MULTI-DOMAIN MODELLING USING THE ESP-r SYSTEM

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ABSTRACT

Prediction of building performance is inherently a multi-domain problem. This is particularly true of many modern buildings where the aim is to provide energy efficient operation and high levels of comfort (thermal, visual, acoustic) and indoor air quality. Such buildings may employ sophisticated environmental control systems, and/or energy efficient design features such as natural daylighting, natural ventilation and building-integrated renewables.

The ESP-r system allows the analysis of coupled, inter-domain processes, e.g, detailed air flow and dynamic building temperature variation. The program has the capability to model, in an integrated manner, the following domains to variable levels of resolution: thermal, lighting, ventilation (network air flow and CFD), moisture, HVAC, electrical power flow (including renewable energy sources). All of these domains can be subjected to user-defined control action. The modeller can select, based on the particular design, which domains to include in the analysis.

This paper discusses the importance of multi-domain modelling and illustrates this with an example of an application where it is important to model interactions between different domains: the detailed modelling of an HVAC system, coupled with the building it serves. The model highlighted is one developed in support of HOT3000 developments at Natural Resources, Canada (NRCan).

INTRODUCTION

Buildings are an inherently complex energy system, whose constituent energy-related sub-systems (fabric, HVAC, lighting, etc.) interact and evolve dynamically with time due to environmental excitation, human occupation and control action. Capturing this complexity in a simulation program requires a coherent and integrated mathematical model of the problem.

This paper describes an integrated approach to building simulation, applied in the ESP-r simulation program. The building is modelled as a set of domains, each representing a sub-system. Coupling the domains together in a single model and solving simultaneously with real climate data allows a solution to be obtained of the dynamic performance of the whole building. This simultaneous solution can only be undertaken if the domains of the model are fully compatible, requiring a common approach to the representation of all the constituents of the model. However, in order to avoid over-complexity, it is important to ensure that only those domains relevant to the particular design issues of interest are selected for study.

There are many examples of building performance where the different domains interact and where the use of multi-domain models would be advantageous. Examples include:

- thermal/lighting interaction: using light sensors to control light switching;
- thermal/airflow interaction: using air flow through a double facade to provide pre-heating of building ventilation air;
- thermal/CFD interaction: studying dynamic variations in local comfort conditions in a large glazed space;
- thermal/HVAC interaction: using thermal mass to moderate heating/cooling requirements;
- thermal/power flow interaction: using electrical power and thermal heat recovery from hybrid photovoltaic modules on a building facade;
- thermal/moisture flow interaction: studying local condensation and mould growth potential.

MULTI-DOMAIN MODELLING

ESP-r applies the same basic modelling principle to all aspects of the building, which is broken down into many small control volumes. A control volume is a region of space, represented by a node, to which the principles of conservation of mass, energy and momentum can be applied. A building modelled using this technique may require the use of many thousands of control volumes to describe its fundamental components: opaque and transparent structures, plant components, fluid volumes, etc. The technique may be summarised thus [1]:

"*... ESP-r will accept some building/plant description in terms of three-dimensional geometry, construction, usage and control. This continuous system is then made discrete by division into many small, but finite volumes of space. These finite volumes then represent the various regions of the building within and between which energy can flow.*"

An energy conservation equation can be derived for each control volume describing the fundamental physical processes, e.g. heat conduction and storage, air flow, moisture flow, convection, etc. Sets of these equations can be extracted from the building model and grouped according to the physical process they represent. Solution of the equation sets, with real climate data and user defined control actions as boundary conditions, allows the determination of the transient energy and fluid flow processes occurring within the building.

The Form of the Multi-Domain Model

A typical ESP-r model of a building consists of a number of coupled polyhedral zones that describe the geometry and fabric. Augmenting these zones are a series of networks, each of which describes an individual domain: heating and air conditioning plant, air flow, water flow and moisture flow. This multi-domain modelling approach is efficient in terms of both the complexity of the model and the numerical solution. In a multi-domain ESP-r model, each domain adds functionality and detail. The requirements of a particular simulation will dictate the form and complexity of the model, with extra domains being added by the modeller as needed. Table 1 describes the functionality added by the various domains within ESP-r.

The multi-domain approach to modelling allows flexibility in both the types of system that can be modelled and the level of detail to which they are defined. The modeller can describe a building and its systems abstractly and then add more detailed domain descriptions as required. For example, the most basic energy simulation would involve only one domain in a model, e.g. the geometry and fabric of the building. If more functionality were required, the model could be augmented with air flow, CFD, plant and electrical networks, etc.

This flexible approach to the problem definition is made possible by the consistent application of the control volume in the description of every constituent of the building model. Hence, while the model can be constructed from many different and diverse domains (e.g. moisture flow, electrical networks, air flow networks), each domain is based on the same elemental components: control volumes. When the domains of the building model are connected together, they form a consistent mathematical description of the building.

Numerical Solution of the Multi-Domain Model

ESP-r's solution method complements the program's flexible approach to model description in that it can be tailored to suit the constituents of any particular model. ESP-r employs a range of solvers to process each domain of the building model using the most appropriate and efficient means. These solvers are essentially individual blocks that can be linked together to form a unified solution process for the entire model. The exact form of the solution process is variable: different combinations of solvers may be used at any one time. The number and type of solvers used will depend upon the characteristics of a particular model. The domains of the model (fabric, plant, flow, CFD, etc.) will use the relevant solver as required (Figure 1).

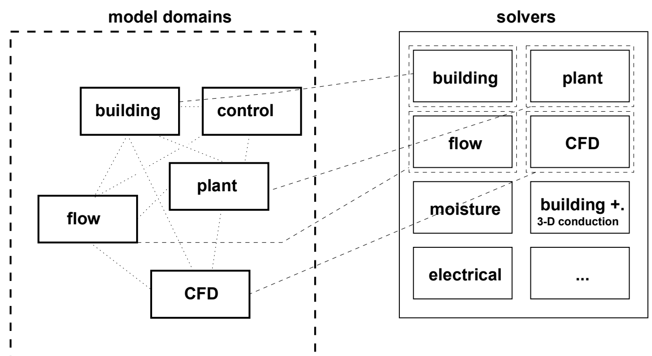

Figure 1: A multi-domain model and associated solvers.

The framework upon which the ESP-r solution process is built is provided by a governing control algorithm: a simulation controller (this is described in [1]). The combination of the solvers and the simulation controller forms ESP-r's "numerical engine", which is able to simultaneously solve all of the subsystems of the building model. This controller determines the structure of the solution process for a particular model, both in terms of the solvers that are employed, their couplings, and their temporal relationships. The use of both a simulation controller and solvers was designed to be flexible enough to enable such functionality as variable frequency processing of the equation sets, iteration and variable time-stepping within an ESP-r simulation. All these functions are useful for the successful execution of an integrated simulation, accounting for the complex couplings between the various domains.

CASE STUDY: CANADIAN BUILDING

The case study discussed here demonstrates the multi-domain modelling approach discussed above when applied to a typical Canadian dwelling. The domains involved in this particular model are described in the following paragraphs.

The Building

The building is described using 14 thermal zones, describing the basement, ground floor rooms, first floor bedrooms and roof space. The basic zone geometry is augmented with details of the constructions and occupancy schedules. A wireframe geometry of the building is shown in Figure 2.

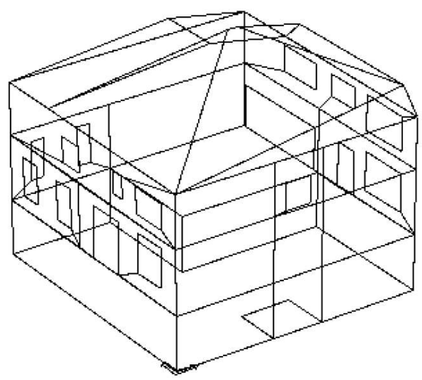

Figure 2: ESP-r Canadian building model.

The development of the original building model is described in [2]; the model shown here has been enhanced with CFD and HVAC domains to allow the investigation of local room conditions resulting from HVAC operation. The model enables accurate representation of the interacting heat transfer processes. Although it is possible to include enhanced resolution such as 3-D conduction and detailed sun-patch analysis, it was not considered necessary in this model.

Plant Network

Plant is represented within ESP-r in two complementary ways. Firstly, conditions can be controlled using abstract control: essentially an idealised representation of coupled HVAC systems. Secondly, a more detailed representation of plant can be integrated into the model: a plant network with a detailed representation of each plant component.

In this case, detailed plant modelling was used. The building was modelled with an advanced integrated mechanical system (AIMS). Such systems are being developed by a consortium of Canadian companies with Government support - they are domestic systems that integrate space and water heating with ventilation, fuelled by natural gas. They can also include air conditioning and heat recovery components. The intention is, by integrated design and intelligent control, to achieve high levels of energy efficiency and performance.

The AIMS system is shown in Figure 3. This system combines the functions of domestic hot water storage and supply with mechanical ventilation and warm air heating. In the corresponding ESP-r plant network 16 components are used to model the AIMS system; these describe ductwork, heat exchangers, mixing boxes, heating coils, fans, etc. These components are adapted from the basic plant component templates available in ESP-r's plant component databases. The network also includes a heated water storage component (described in detail in [3,4]), which serves the heating coil and also supplies the scheduled hot water demand of the building. The plant network is augmented with several control loops, which govern the operation of the system. These are summarised in Table 2.

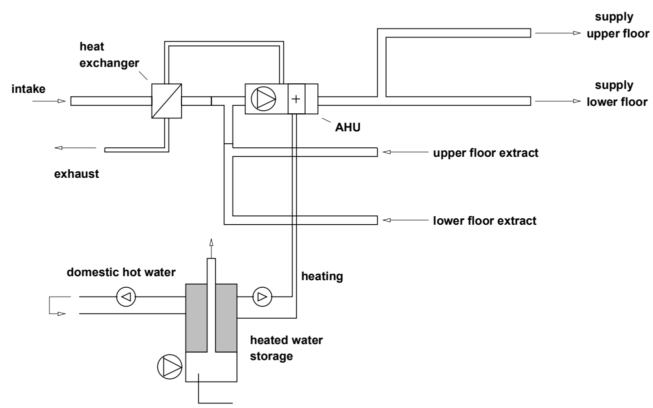

Figure 3: The AIMS system

Flow Network

The flow network, consisting of fluid components and control volumes, describes the air flow through the building and plant domains. In the building domain, the fluid control volumes correspond to the thermal zones, while connections represent doors, windows, etc. In the plant system the connections represent the individual plant components, and the control volumes represent the coupling points between the components. Air flows throughout the network are calculated as a function of pressure difference between control volumes and connecting component characteristics.

CFD

To facilitate detailed analysis of air temperature distributions, the living room zone is augmented with a CFD domain. The integration of CFD within the ESP-r model is achieved by replacing the single control volume describing the air inside a room with the CFD equivalent comprising many hundreds of smaller control volumes [5]. The CFD model facilitates the extrapolation of surface temperatures to the interior of the zone. The ability of CFD to calculate temperature distributions, air velocities, humidity and contaminant concentrations enables more detailed environmental performance analysis than would be possible with a simple homogeneous zone air volume model. It allows, for example, investigation of local thermal comfort, air quality and ventilation system performance.

Inter-Domain Couplings

The individual domains described above are all coupled together. The nature of these couplings is as follows.

building-plant: Plant components can supply and extract air to and from a zone (in convective plant systems). Hydronic systems can supply a mixed radiant/convective heating flux into a zone (e.g. radiators), or a heating flux to a structural element in the case of chilled/heated ceilings and floors. Plant interaction is integrated into the overall zonal energy balance calculations. Similarly the air temperature of the zone determines return air temperatures in convective systems and convective output from radiators and chilled/heated ceilings and floors; zone surface temperatures influence the radiant output from the same components.

flow-building-plant: The flow network calculates the flows in the building and plant network. On the building side, the flow network calculates buoyancy and wind pressure driven air flows between the building and outside and between zones. On the plant side, the flow network calculates inter-component air flows and can be used to represent the action of dampers and valves. The flow network is also used to calculate the flows between the plant and building (in convective systems) and so explicitly couples these two domains. Finally, temperatures calculated in the plant and building domains are used in the calculation of buoyancy driven flows in the flow network.

CFD-building-plant-flow: The CFD domain relies on the building plant and flow domains for the supply of its boundary conditions, and in turn provides temperature and flux data back to these other model domains. The flow domain supplies boundary flow rates to the CFD model, either from connected plant components (supply and extract) or other openings such as doors and windows. The building and plant domains supply the temperatures of these boundary flows. In addition, the temperatures of surrounding surfaces are also boundary conditions for the CFD domain, with convective heat transfer occurring between the surface and air. The convective heat transfers into and out of the CFD domain are calculated using the local surface-to-air temperature difference and a heat transfer coefficient h_c. New empirical correlations for the calculation of h_c, appropriate to the flow regimes found in buildings, have recently been added to provide more accurate estimations of convective heat transfer to and from the CFD domain [6].

Additionally, the new expressions for h_c enable the modelling of mixed natural and forced convection regimes. For the model in question both flow regimes operate: forced flow when the AIMS system is active and natural convection during quiescent periods.

Finally, as mentioned previously, control action pervades all the participating domains and as such is a major coupling mechanism in an ESP-r model. In the case of the Canadian building, model control spans the flow, plant and building domains:

- the flow rate of the pump supplying the heater coil (part of the plant network) is controlled based on the temperature of the lower floor living room in the building domain.
- the flow rate of the combustion air supply fan (calculated by the flow network) is controlled based on the heated water storage burner status (again located in the plant network).

In summary, the linkages between the various domains of the model take the form of "handshaking" of critical coupling variables: temperatures and flow rates. Control also acts as a coupling mechanism between variables in different domains e.g. flow in plant and temperature in the building.

Simulation of the Integrated Model

The model of the Canadian dwelling presented here uses 4 of ESP-r's customised domain solvers: the building solver, plant solver, flow solver and CFD solver. Note that the solution process employs the use of both iterative solvers to process the flow network and CFD equations and direct solvers to process the building and plant domains.

The solution of the CFD domain is a special case as the user has the option of activating the CFD solution for each time step of the simulation period (this is computationally expensive) or for shorter periods of interest, e.g. during plant ON state and OFF state. Outside the active period, the CFD domain is replaced by a single control volume representing the air in the living room. The advantage of this "swapping" mechanism is that the computational overhead associated with the CFD solution is reduced.

The integrated model was simulated using Ottawa climate data over the course of a winter week (8th - 14th January). The simulation was conducted using 5-minute time steps on the building side and 1-minute time steps on the plant and flow-side. These short time steps allow the dynamics of the HVAC system and associated control to be captured in the simulation output. This allows a detailed picture of plant performance to be gained from the simulation, both in terms of the performance of individual components, but also the overall performance of plant and control on environmental conditions. A more detailed picture of environmental conditions in the living room is gained using the CFD model, which is activated during a plant ON and plant OFF state to examine the prevailing temperature distributions.

Analysis of the Integrated Model

The results presented here demonstrate the detail that can be obtained from an integrated simulation. Figure 4 shows the variation in temperatures of the living room (located on the ground floor) and an upstairs bedroom along with external temperatures. The output clearly shows the effect of the ON-OFF control strategy employed in the plant system. Also evident is the effect of night-time set-back on the temperatures.

Figures 5 to 7 show output from the plant domain, with heating coil and duct temperatures shown in Figures 5 and 6 respectively. The output indicates that air is occasionally delivered to rooms at temperatures up to 40°C, a value that may have implications for occupant comfort. This temperature could be reduced in a number of ways, e.g. down-sizing the heating coil or reducing the set point temperature of the hot water storage. Figure 7 shows the variation in temperature of the hot water storage. Again the effect of the ON-OFF cycling of the heating coil pump is evident. However, the temperature of the hot water is maintained at close to the 60°C set point.

Figure 8 shows infiltration into the living room zone, as calculated using the flow network. More detailed output regarding living room conditions is shown in Figures 9 and 10, which show output from the CFD model with the heating system active. Figure 9 shows the temperature distribution in a cross-section through the room and shows a thermal plume rising above the heating outlet (located at floor level below the living room window). Figure 10 also shows the thermal plume for a length-wise cross-section. The near uniformity of room air temperature (in the regions outside the thermal plume) and the absence of a cold down-draught indicate that, in terms of homogeneity of air temperatures, the system performs well in this room.

CONCLUSIONS

The intention of this paper was to demonstrate the need for multi-domain modelling to permit proper study of whole building performance. Given that the simulation program has the capability for such modelling, users then need appropriate skills to identify the required domains for the design questions in hand, to construct the models and to interpret the large data volumes resulting from simulations of the model.

By way of example, the paper has presented the development of a detailed model focussed on the investigation of local conditions within part of a residential building, as influenced by the heating, ventilation and control system, together with the building fabric. Such models allow designers to optimise the design of such systems without unnecessary simplification of the real building response.

REFERENCES

[1] Clarke J A, 'Energy Simulation in Building Design', Adam Hilger, Bristol, 1985.

[2] Swinton M C, Moussa H, and Marchand R J, 'Commissioning Twin Houses for Assessing the Performance of Energy Conserving Technologies', to be published in Proceedings of Integration of Building Envelopes, Performance of Exterior Envelopes of Whole Buildings VIII, Clearwater USA, December 2-6, 2001.

[3] Kelly N J, 'Development of a Heated Water Storage Plant Component Model ', Technical Report TRE 150/01, ESRU, University of Strathclyde, Glasgow, March 2001.

[4] Parent M, 'Combo/AIMS Model Description', Technosim Report for CANMET, Buildings Group, Natural Resources Canada, May 2000.

[5] Negrao C O R, 'Conflation of Computational Fluid Dynamics and Building Thermal Simulation', PhD Thesis, University of Strathclyde, 1995.

[6] Beausoleil-Morrison I, 'The Adaptive Coupling of Heat and Air Flow Modelling Within Dynamic Whole-Building Simulation', PhD Thesis, University of Strathclyde, 2000.

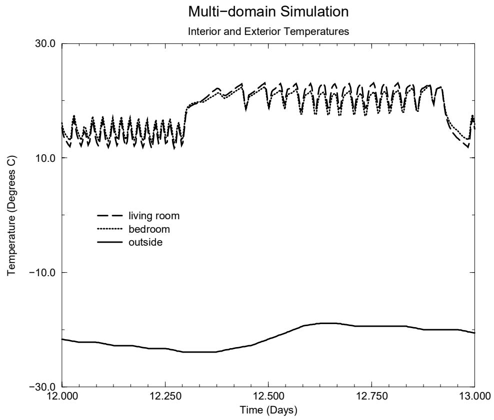

Figure 4: Internal and external temperatures

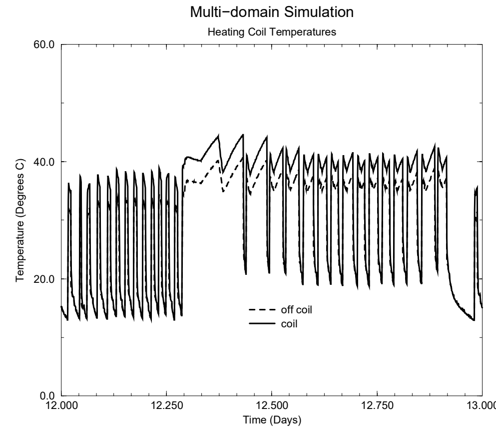

Figure 5: Heating coil temperatures

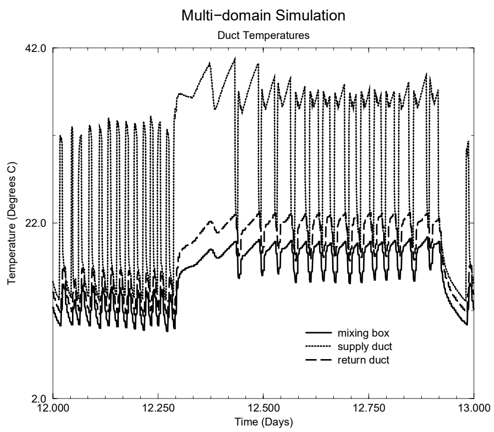

Figure 6: Duct temperatures

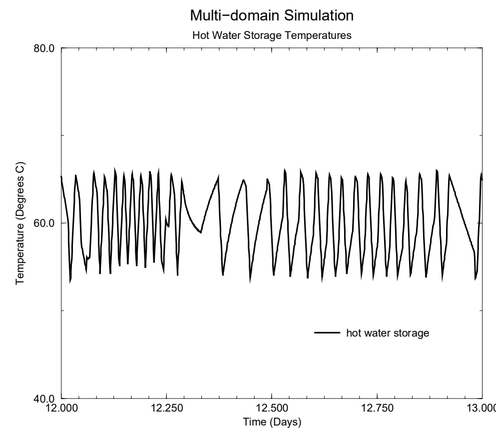

Figure 7: Hot water temperature

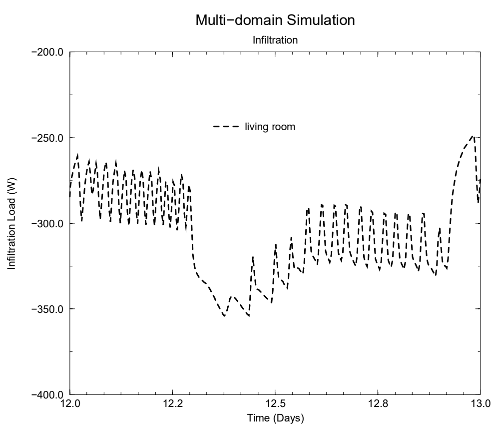

Figure 8: Infiltration

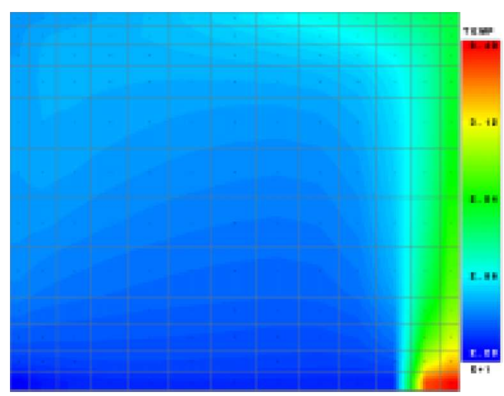

Figure 9: Temperature distribution

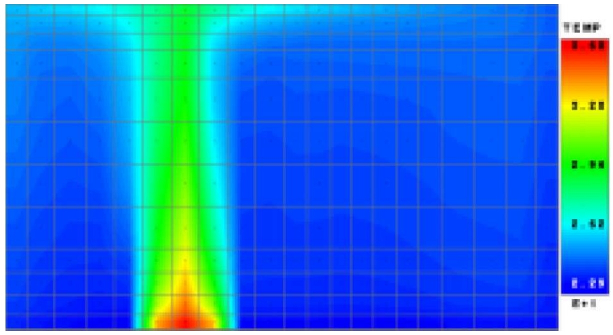

Figure 10: Thermal plume

Table 1 The added functionality from different domains of an ESP-r model.

Model Domain	Functionality	Typical Uses
the essential model "core": building fabric, climate, occupancy, idealised ventilation and infiltration	basic fabric thermal energy flows, air, surface and fabric temperatures	free floating environmental conditions driven by climatic and internal excitations, daylight factor calculations, solar distribution, overheating and summer comfort analysis, basic lighting studies
+ zone based control	logically and temporally controlled heating, cooling, lighting, etc.	control strategy testing, heating/cooling loads, plant sizing, lighting control, heated/cooled floor and ceiling models
+ enhanced fabric modelling: 3-D conduction, non-linear material properties, special materials	three dimensional conduction, detailed fabric thermal and non thermal (i.e. electrical energy) flows, advanced materials	thermal bridging, detailed floor heat flows, phase change materials, photovoltaics, advanced glazing studies
+ air flow network	pressure driven air flow and ventilation, inter-zonal air flow and moisture transport, detailed fan models	natural and forced ventilation studies, detailed overheating analysis, passive/ambient cooling strategies, e.g. night flushing
+ HVAC and component level control	detailed component-based plant descriptions, component temperatures and energy flows, local component-based control loops	detailed air conditioning systems modelling, control strategy analysis, etc.
+ CFD	air velocities and momentum, temperature distributions, surface boundary layer information	detailed forced and natural ventilation studies, convective heat transfer coefficient calculations, displacement ventilation modelling, detailed heating or cooling studies, atrium airflow patterns, indoor air quality etc.
+ moisture network	humidity distribution	local condensation, mould growth studies
+ electrical power network	voltage and current levels, power factors	building-integrated renewable energy studies, load control

Table 2: Control loops used with the plant network.

loop 1	ON-OFF and timer control on the pump supplying the heater coil: the pump is ON if the temperature in the ground floor zone is less than 19°C during the day and ON below 14°C at night.
loop 2	Timer control on the ventilation fan.
loop 3	ON-OFF control on the HWS burner, maintaining the water temperature at 50°C ± 5°C.
loop 4	ON-OFF control on the combustion air supply fan (ON when the burner is activated).