SIMBAD: A SIMULATION TOOLBOX FOR THE DESIGN AND TEST OF HVAC CONTROL SYSTEMS

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ABSTRACT

The need for a decrease in the energy consumption of buildings implies an adequate understanding of control strategies. This requires an intensive use of simulation tools for the design and test of controllers of HVAC equipment. It is noticed that simulation software commonly used in control engineering do not provide any model of HVAC equipment. The SIMBAD project has been set up to develop a toolbox of such models adapted to the needs in the control field. As the toolbox is mainly conceived for users who are not necessarily "experts" in HVAC equipment, the user-friendliness of the models is a major concern in the development work. This includes a hierarchical structure for the description of systems, an insight of physical phenomena involved in the models visible on the graphical interface, an enhanced parametering mode and availability of parameters of models.

INTRODUCTION

This paper presents the progress in the SIMBAD project. The aim of this project is to develop a toolbox of models of HVAC components and plants for the design and test of control systems. It is noticed that current mathematical software (Matlab/ SIMULINK [7], XMath/SystemBuild [6]...) do contain toolboxes on control systems or adaptive control which can be used at the design stage of controllers. However if the controllers are specific to HVAC equipment, it is impossible to carry out test of these controllers on HVAC installations as no models of buildings and HVAC systems exist in such environments.

SIMBAD (SIMulator of Building And Devices) was developed by the CSTB to test Building Energy Management Systems (BEMS). It was based on existing software (TRNSYS [8], HVACSIM+ [3]) and set up in the frame of a working group of the International Energy Agency (IEA) [2]. This first version of SIMBAD had the following drawbacks :

- The models were barely suitable for simulation in dynamic conditions.
- The parameters of models were not easily obtained.
- The assembly of models was tedious and frequently "bugged".
- The man-machine interface was not user-friendly.

To tackle these problems the following steps have been defined :

- Use of a commercial software for its technical computing environment and interface.
- Use of existing robust models with improved parametering modes and model structure.
- Definition of a topology of buildings and HVAC systems with the appropriate data requirements of the models used for simulation.
- Setting up of rules to construct relevant HVAC systems for simulation.

To ensure an effective development work, a survey has been carried out among manufacturers on their needs of simulation tools. It showed that one of their major concern is the parametering of models. This work lays a particular emphasis on the facility of use of models.

WHY A COMMERCIAL SOFTWARE ?

The development of any simulation tool is basically divided into two main parts :

- the scientific aspect (in this case thermal phenomena in buildings and equipment, numerical methods...)
- the computer-environment aspect (interface, links with other software, retrieval of data...)

Generally the development of the environment is very time consuming and takes about 75% of the total development time. Besides scientists involved in the development of the tool, frequently do not show great interest in this work or do not have the necessary skills in this field. This results in powerful tools that have very poor interfaces and difficult to use. To overcome this problem in the development of SIMBAD, a general bloc diagram environment has been chosen [7]. SIMBAD therefore benefits from its user-friendliness and will automatically integrate any improvement that is brought about in the simulation environment.

Furthermore, the environment offers links to C-language and FORTRAN files through predefined templates. This enables **re-use** of existing codes without the need of translation into the bloc diagram language. Secondly it allows the developer to choose the best way for the implementation of his model. For the description of thermal phenomena, the classical procedural methods are most appropriate and thus C or FORTRAN languages are preferred. Regarding control systems modelling, the simulation software provides predefined blocs (integrals, derivatives, logic...) for their description.

STRUCTURING AND PARAMETERING OF MODELS

SIMBAD is now implemented in the bloc diagram environment and contains a library of VAV components :

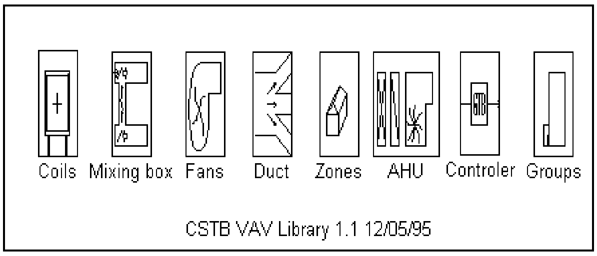

Figure 1 SIMBAD VAV library

From the graphical interface the user can drag the required components onto a new window to build the system needed for simulation. The information given to the user on the interface concerns the inputs and outputs of each bloc for linking purposes. The user does not have any idea of the physical concepts of the models. He usually has to prompt in a large number of parameters on a single command line. This task is very tedious in an assembly of blocs and is greatly liable to errors (inversion of the order of parameters, mis-typing the names of parameters...) which create bugs in the simulations.

The structure and parametering of models need to be reviewed to provide models that can be more easily used. The restructuring process aims at enhancing the understanding of the physical concepts involved in the model and providing a better interface for the input of parameters.

LEVELS OF HIERARCHY IN THE BLOCK DIAGRAM ENVIRONMENT

The basic blocs in the current library are the HVAC components or the building zone. The first level of hierarchy contains the models of HVAC components as they are found on the market. These basic blocs are called "Component-Blocs" that can be assembled to give "Macro-Block", on the second level of hierarchy. The "Macro-Block" corresponds to a complex component of the HVAC plant that is commercialised on its own. One such complex component is the air handling unit. A combination of component-blocks and macro-blocks give a "system-block" which may not necessarily represent a real system. This is the third level of hierarchy. It is noted that for the HVAC equipment, the classification in two levels is made according to the complexity of the component as it is available on the market (Figure 2).

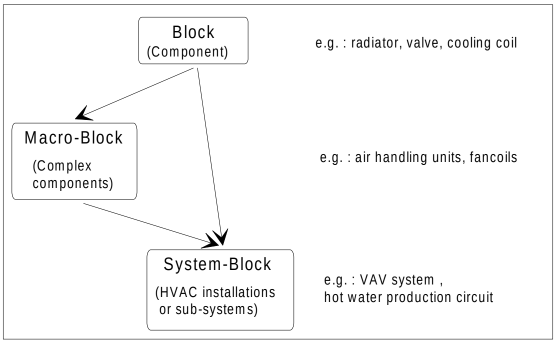

Figure 2 Levels of hierarchy in the library

A component bloc contains the algorithms for the physical concepts involved in the model. The algorithms can either be implemented in the bloc diagram language or in C/FORTRAN languages. They are not accessible to the user. To overcome the "black box" impression that the user has at the "bloc level" an additional level has been introduced and is termed "Physics level". It is now the innermost level that the user can manipulate graphically.

THE "PHYSICS LEVEL"

The aim of this level is to bring the "functional scheme" of the model on the graphical interface. This will give a first insight of the physical concepts used in the model to the user. The blocs found at this level are called "Physics-Blocs" The source code now lies beneath these "physics blocs". Some guidelines have been set up for the structuring process.

1) The basic parameters of the model, that is, the minimum number of parameters required to characterise the phenomena being modelled, should be identified. At this stage there is no concern about how to obtain these parameters.
2) While defining the constituent blocs, special attention should be paid to the ease to shift from a detailed model to a simple model. In this approach, the terms detailed and simplified refer to the means of calculating the basic parameters of the model.
3) The models that are being structured take into consideration both the static and dynamic conditions. If these two conditions are considered separately in the algorithm, they should appear in the functional scheme.

4) Similarly, the models usually involve thermal and hydraulic/air flow calculations. The latter are modelled by simple approaches and are considered independent of the thermal phenomena. It is therefore wise to distinguish between those calculations by carrying out the hydraulic/air flow computations in a specific bloc.

5) It may happen that the model of a component A includes a simple modelling of another component B that is usually connected to the main component A in a real plant. This is the case, for example, in models of radiators with a thermostatic valve. The model of the existing component B should be isolated in a bloc and strictly speaking should not appear at the "physics level" but at the "component bloc level" although it is part of the functional scheme of component A.

PARAMETERING AT THE "PHYSICS LEVEL"

Apart from bringing forward the functional scheme of the model on the graphical environment, the "physics level" also provides an easier parametering of the model. It is found that parametering of a model is the main concern of the users. They need to be guided to give relevant values to parameters. On graphical interfaces, users find it difficult to fill in list of parameters. It is therefore necessary to minimise the number of parameters per bloc. As the "physics level" has been introduced, the number of parameters per bloc is automatically reduced. Besides the simulation environment provide a masking function that enables the creation of a dialogue box for the parameters and an on-line help.

LINKS BETWEEN BLOCKS

The structuring work also considers the description of links between blocs. The flow of information between blocs has to be structured to avoid the excessive use of links. Too many links increase the risks for wrong connections and lead to illegible bloc diagrams. The simulation environment provides vectored links which enable the transfer of multiple information in a single link. As the data can be grouped in the links, it is important to formalise the ordering of data in links so that linking among models can be done easily. This also standardiseS the description of inputs and outputs of models developed by different teams so that exchange of models or calculation blocs is possible.

1) Following a survey of different air conditioning systems, it has been found that two links appear frequently in the components namely air and water characteristics. These are, in fact, the "energy conveying" fluids in these systems. The *air vector* contains the following data: temperature, humidity ratio, pressure, and mass flow rate. The *water vector* carries its temperature and mass flow rate. The data order in the vectors is fixed. In some case a refrigerant is the "energy conveying" fluid (in chillers). A *refrigerant vector* should be formalised.

2) Similarly, in the control system there is a flow of information. A *control vector* needs to be defined to carry the measured signal and the command signal.

3) On the "physics level" the links between the physics bloc do not necessarily have some meaning in the real plant. They may correspond to flow of intermediate calculation values. In this case the links cannot be predefined and it is up to the developer to group the data in a relevant way.

AN EXAMPLE OF MODEL STRUCTURING: THE HEATING/COOLING COIL

The source code of the model is the Type 63 of the AIE annex 17 [2]. This model is a detailed heating and cooling coil model which operates in both static and dynamic conditions. In this model, the total heat transferred and the offcoil characteristics are calculated given the overall heat transfer (referred to as UA) coefficient, the bypass factor (referred to as BF) and the incoil characteristics of air and water. The algorithm is given in the flowdiagram (Figure 3).

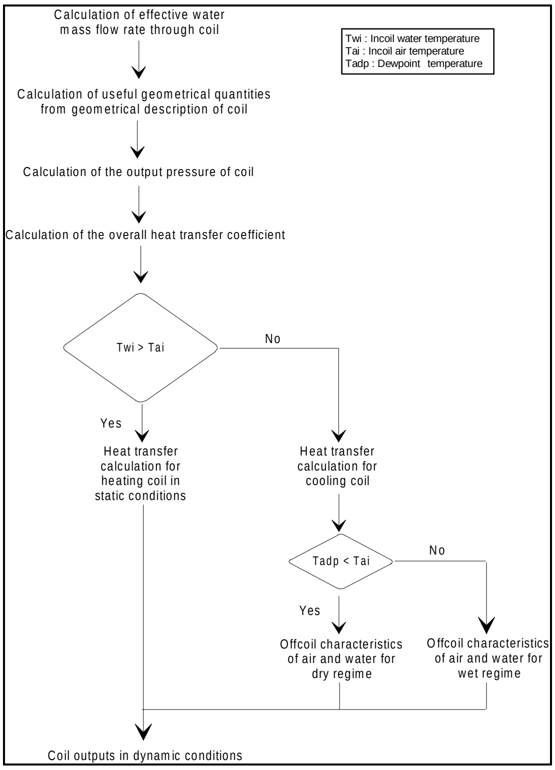

Figure 3 Flow diagram of heating/cooling coil model

The heat transfer calculation is the main part of the model. It is different for the heating coil and the cooling coil. In the former case, one UA value and one BF value are required to define the heat transfer. In the case of the cooling coil, the model considers two working regimes: dry and wet (or partially wet) with a specific value for UA and BF in each case.

Using the rules stated above and the flow diagram the following constituent blocs are obtained:

1) *3-way valve*:

Calculation of the effective water mass flow rate through coil.

2) *Fin data, Tube data and Geometrical calculations*:

Calculation of the useful geometrical quantities and the coil capacity from a detailed description of the coil.

3) *Pressure calculations*:

Gives the output pressure of the air stream. This is the only air flow calculation in this model.

4) *Exchange coefficients* :

Calculation of the overall heat transfer coefficient and the bypass factor in both dry and wet regimes.

5) *Static offcoil (heating)* :

The heat transferred and the offcoil characteristics of air and water are computed in static working conditions. This bloc is used only for the heating coil.

6) *Static offcoil (cooling)* :

The heat transferred and the offcoil characteristics of air and water are computed in static working conditions. This bloc is used only for the cooling coil.

7) *Coil dynamics* :

The dynamic response of the coil is computed here to follow the offcoil characteristics of air and water.

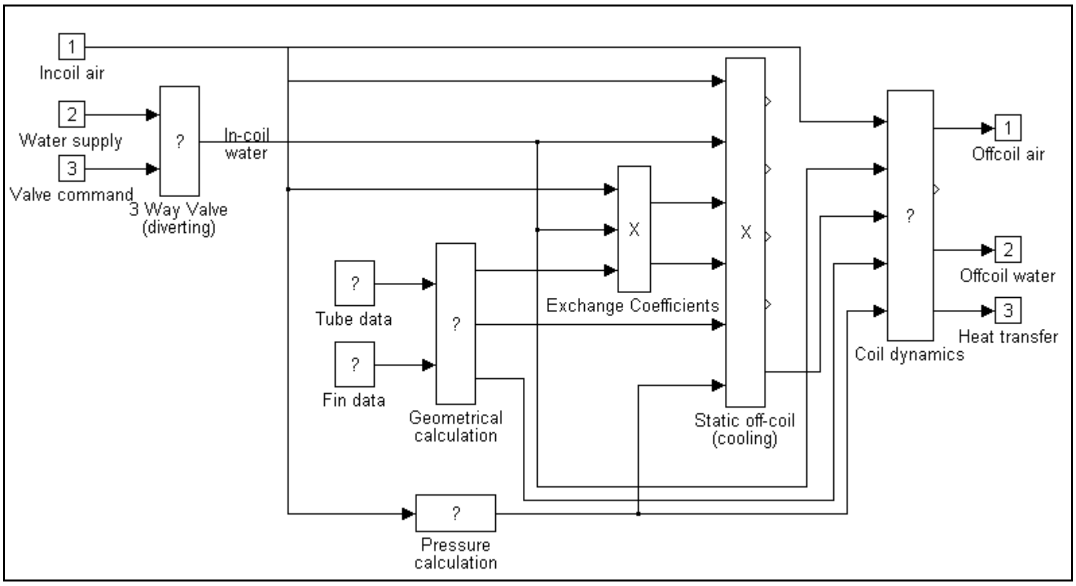

Figure 4 Detailed dynamic cooling coil

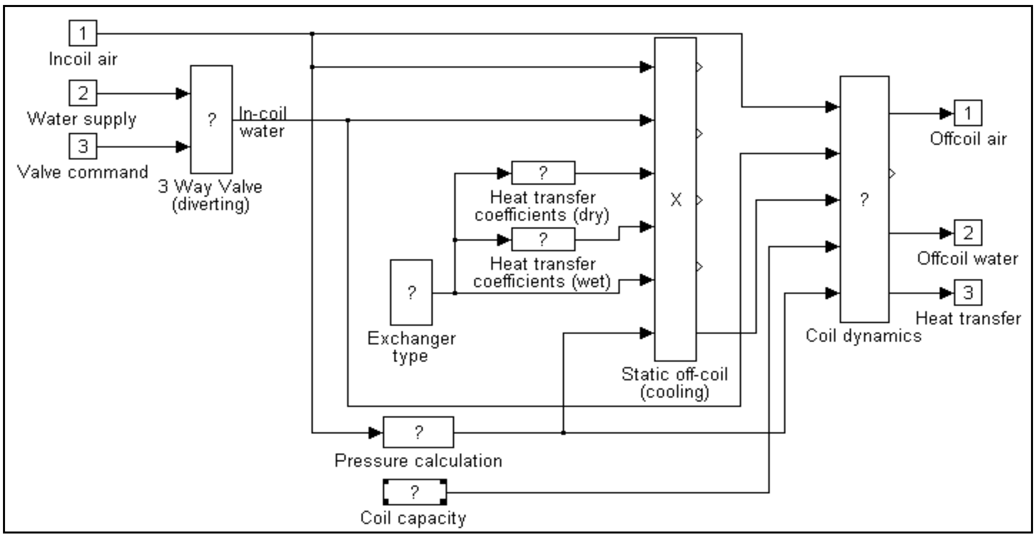

Figure 5 Simple dynamic cooling coil

This model is a very detailed one as the user needs to enter the exact geometrical description of the coil. Figure 4 gives the functional scheme of the detailed dynamic cooling coil as seen on the graphical interface.

In the algorithms available, it is found that the values of UA and BF can be calculated from ratings data available in the manufacturers' catalogues. The coil capacity can be approximated from the water content of the coil given in manufacturers' data. Three further blocs have been added to give a simplified model of the coil. They are :

1) *Heat transfer coefficients* :

Calculation of UA and BF from ratings.

2) *Coil capacity* :

Calculation of the coil capacity from an empirical correlation with the water content of the coil.

3) *Exchanger-type* :

Prompt in of the type of exchanger parameter.

To shift to the simplified model (Figure 5) from the detailed model, the blocs dealing with the calculation of UA and BF from geometrical data are removed and replaced by the blocs "Heat transfer coefficients", "Coil capacity" and "Exchanger type".

The functional scheme of the heating coil is similar to that of the cooling coil except that the "Static offcoil (cooling)" bloc is replaced by the "Static offcoil (heating)" one.

Similarly to shift to the static model, it suffices to remove the "coil dynamics" block and link the "Static offcoil" bloc to the outputs.

There are 12 possible configurations from these constituent blocs for the heating coil, the cooling coil and the heating or cooling coil.

It is important to pinpoint that the ease to shift from the detailed model to the simple model lies in the fact that the correct characteristic parameters of the coil (UA and BF) have been identified. In the detailed model UA and BF are calculated at each time step with the variation of incoil air and water characteristics. In the simple model, they are fixed for one working point of the coil (nominal conditions) and are good approximations if the simulations are carried around this point. If further simplification is needed, a typological study of coils is required to give typical UA and BF values of coils for nominal conditions and sizes of coils. In this case the user will have fewer parameters to enter for the model.

TYPOLOGICAL STUDY TO GENERATE PARAMETERS

We have mentioned, in the above section that typological studies can be helpful to generate typical values of parameters. Such a method has been applied to obtain the parameters of a building zone model.

In fact, the study of HVAC systems requires typical buildings representative of the residential park, the commercial one, hotels, schools... The user who has to test a BEMS for VAV systems, for example, does not need the data of one particular building but a typical building representative of a class of buildings, for example, secondary schools. It is therefore necessary to provide data of typical buildings. Besides it is observed that the building models available have a very tedious descriptive phase. At this level, errors are very common.

The typological study has been carried out on the residential park in France with the following aims :

1) *Give a set of buildings representative of the residential park (main residence) in France for study-cases.* The data can be used by different working teams so that exchange and comparison of results may be relevant.
2) *Give the parameters of a second order building zone model*. The second order building model [1] is supplied in the library of models. It is characterised by 3 resistances and 2 capacitors. The resistances and capacitors are obtained from a detailed description of the walls of the zone, the position of the zone in the building, the orientation of the zone...

The principal criteria for the classification of the residential buildings are :

1) *Type of lodging*

The residential park is made up of individual housing and flats. Semi-detached houses are included in the "individual housing type". In the case of flats the energy consumption depends on the position of the flat in the building. 3 cases are considered : ground floor flat, intermediate floor flat and top floor flat.

2) *The size of the lodging*

The energy consumption is influenced by the size of the lodging. In the case of individual housing, the typical sizes chosen are :

i) Small (~80m^2) and semidetached (2 party walls)
ii) Medium (~110m^2) and semidetached (1 party wall)
iii) Big (~140m^2) and individual

Concerning flats, the size refers to the number of rooms namely :

i) Small (1 room)

ii) Medium (3 rooms)

iii) Big (5 rooms)

3) *Period of construction*

The period of construction of building also plays an important role in the typological study. In fact, the French thermal regulation which specifies the "heat loss calculations" in buildings has been modified several times over the past decades. Thus the construction standards have changed. 3 periods of construction have been considered :

i) before 1974 (old)

ii) between 1975 and 1988 (recently built)

iii) after 1989 (new)

Furthermore, in the new thermal regulation, the calculation of heat losses is different following the source of energy used for heating (gas or electricity). So the "after 1989" group is subdivided into two types. As the thermal regulation changes, there has been a change in the construction material used and it is found relevant to single out 3 insulation materials for the recently built houses (75-88). Regarding the old ones (before 1974), there was no regulation and they had undergone refurbishment to abide to the thermal regulation. This category has been subdivided into 5 cases following the refurbishment carried out. Thus the "period of construction criterion" gives 10 cases of study.

There are in all 120 possible building configurations from the 3 criteria and subdivisions summarised in Figure 6.

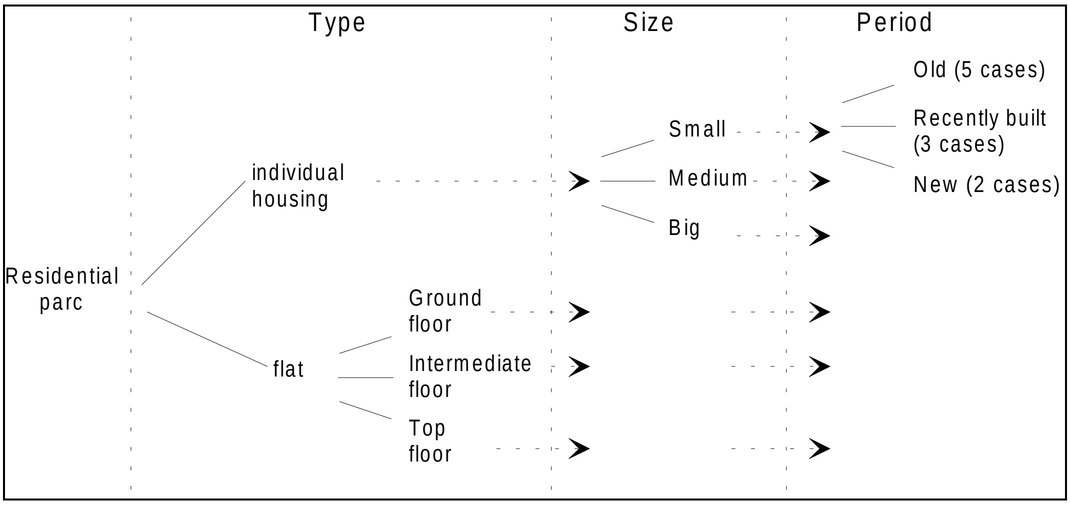

Figure 6 Typology of the residential park

The data (size, material type, glazing...) for these 120 residential lodgings have been pre-processed to give the corresponding 3 resistances and 2 capacitors for the building zone model in the SIMBAD library. The user will have to specify the building type at the initialisation process and the model will be completely parametrised for the chosen typical building. Note that the user can also give the detailed description of the building if he has to study a particular building.

TYPOLOGICAL APPROACH TO DETERMINE RELEVANT PARAMETERS OF MODELS

So far, different means have been used to facilitate the parametering of models. The structuring method gives a greater user-friendliness of the graphical interface and enables the shift to simple models to use data readily available from manufacturing catalogues.

A typological study has been used to provide typical parameters to a model. In this case, the typological study is carried out before the modelling phase of the component. It enables the definition of the parameters of the model with respect to the different settings of the component that the user can adjust (e.g. speed of a variable speed fan). This approach is mainly used in the modelling of controllers and other devices in control systems.

A survey has been carried out among manufacturers of controllers to list the controllers that are commonly used in heating and air-conditioning systems. The controllers have been divided into four main groups (list is not exhaustive):

i) hydronic heating systems

ii) electric heating system

iii) fancoils

iv) air handling units

The library of controllers in SIMBAD follows the same classification.

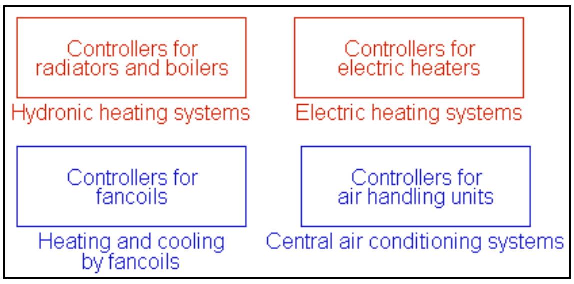

Figure 7 Library of controllers

In each group a general model is derived for the different types of controllers found in real installations. For example in the hydronic heating systems category, 5 controllers have been considered as the most common. They act on the primary and secondary circuits as follows :

1) Controllers for the correction of zone temperature by commanding the three way valve with respect to :
   i) external temperature
   ii) internal temperature
   iii) external temperature with compensation for internal temperature
2) Controllers for the primary circuit of the heating system using :
   i) boilers sequencing with strict working order of the boilers
   ii) boilers sequencing with variable working order of boilers.

The models have the same inputs and outputs as the corresponding real controllers. The most important characteristic of these models is that their parameters correspond to the tuning parameters found on the real counterpart. The user will parametrize the model in the same way as he has to tune the real controller.

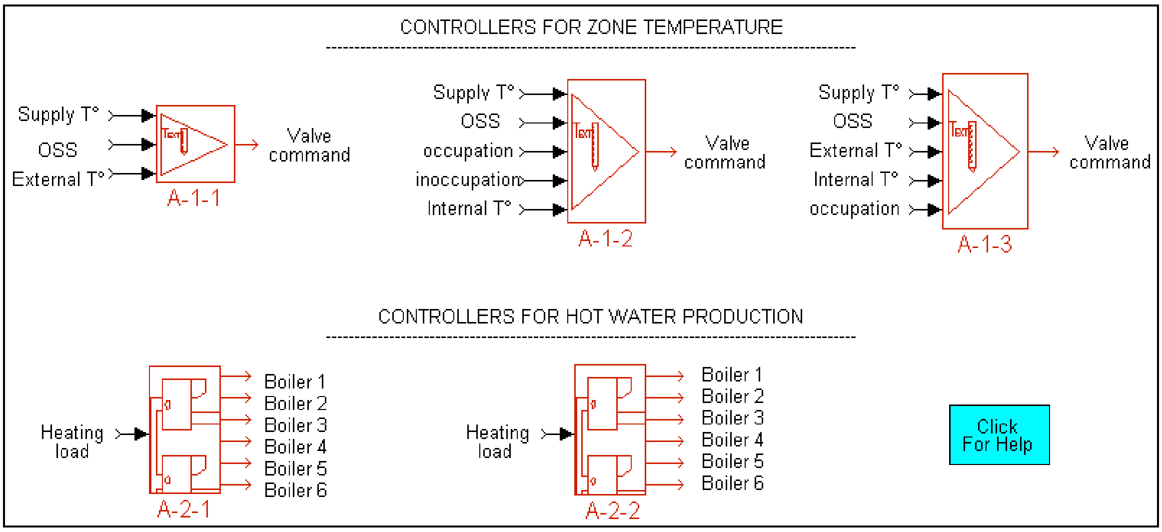

Figure 8 Controllers for hydronic heating systems

Using the same approach optimal start stops and programmable timers have been modelled and included in the library of controllers. These components are vital for all strategies involving intermittent heating.

This library enables the user to test different control strategies and carry out tuning of regulation systems virtually. Commonly found models of controllers did not offer this tuning facility which is essential in the choice of the control strategy.

CONCLUSIONS AND PROSPECTS

In this development work, the main aim has been the facility of parametering and use of models. A method for the structuring of models on graphical interfaces has been developed. It enables a better understanding of the model being used and gives the user a modular aspect for the choice of the complexity or the working mode of the component. In other environments, these choices have to be made through parameters. It has been shown how a typological study can be useful for the determination of typical parameters. This facilitates the use of a model and reduces the risk of errors which are common in descriptive phases of the model. The typological study serves also to determine relevant parameters that obviously enhance the use of models.

Further work includes the development of a library of heating component library in the graphical environment, containing convector heater, electric heating floor and ceiling, radiant heating panels, storage heating floor and low temperature radiators. This is currently being carried out either by re-use of existing models or development of new models.

The improvements have been done at the component level. The next step will deal with the assembly of the components to give virtual systems that resemble the actual layout of the installation. The rules will guide the user to build up systems relevant to his problem and to the data available. They will also ensure a coherence in the links between blocs. This needs a normalisation of links that will follow those described at the physics level, a proper dimensioning and tuning of the systems, a typology of relevant systems...

This toolbox has been developed for the test and design of control systems and BEMS in buildings. It is quite logical that it can be adapted for the training of BEMS's operators so that they can optimise the use of BEMS to reduce energy consumption.

ACKNOWLEDGEMENTS

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REFERENCES

[1 "Annex 10 : System Simulation - Components models", IEA ref. : AN10 860430-01, University of Liège, BELGIUM, April 1986.

[2] "Annex 17 : Simulation and Emulation of HVAC systems" (meeting in Liège), CSTB ref. : GEC/DGE 93.009R, Centre Scientifique et Technique du Bâtiment, FRANCE, September 1992.

[3] Clark D.R., "HVACSIM+ Building Systems and Equipment Simulation Program - Reference manual", NIST ref. : NBSIR 84-2996, National Institute of Standards and Technology, USA, January 1985.

[4] François C., E. Hutter J. C. Visier, "Etude sur les formalismes de modèles simplifiés de Bâtiment", CSTB ref. : GECn°89.4971, Centre Scientifique et Technique du Bâtiment, FRANCE, March 1990.

[5] François C., R. Lahrech, "Typologie des résidences principales françaises", CSTB ref. : GEC/DGE 95.086R, Centre scientifique et Technique du Bâtiment, FRANCE, November 1995.

[6] "MATRIXx - User's guide", Integrated System Inc., USA, June 1995.

[7] "SIMULINK Dynamic System Simulation Software", Mathworks Inc., USA, November 1994.

[8] "TRNSYS, a Transient System Simulation Program", Solar Energy Laboratory, University of Wisconsin, USA, September 1990.