

## FROM SIZING AND HYDRAULIC BALANCING TO CONTROL USING THE SIMBAD TOOLBOX

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### ABSTRACT

This paper demonstrates one step forward in the development of virtual laboratories that can be used for the development and test of HVAC control systems.

While predefined parameters are used for standard tests, individual tests of controllers on different building construction and types or for different boundary conditions need, for each test, new sizing of the components of the HVAC system. This means, that the emitter (HVAC terminal system), tubes, valves and pumps have to be sized and the controllers to be tuned when the test case is changed.

An automatic sizing procedure has been developed that is called before each simulation or emulation. Starting from the emitters, tubes, valves, pumps and controllers are then sized, parametered or selected from a predefined list from catalogue data.

The advantage of such a procedure is the reproducibility of the tests, independent from the user. It can be seen as a first step to quality assurance of building controller tests.

Different laws, applied for the sizing, can be changed separately in the sizing procedure and their impact on the system performance can be studied. This extends the usability of the virtual laboratory to the study of sizing and balancing problems.

If controllers shall be tested, the impact of sizing and balancing of the HVAC system on the control performance or the overall system performance can be analysed.

Some first results are shown, using the SIMBAD Building and HVAC toolbox for a building with six zones equipped with hot water radiators in serial and parallel connection. The effect of flow balancing on the flow rates in the system is shown in order to compare a hydraulically balanced with an unbalanced system.

### INTRODUCTION

Modern buildings are actually equipped with more and more complex products. One example is the use of integrated control strategies combining the control of HVAC, blind and lighting applications. These complex

systems can be on the zone level (terminal) or on the building level (e.g. building Management Systems etc.).

The necessity of innovation on this field imposes on the control industry to develop new products while managing perfectly the quality of the products. To date, field tests are carried out in order to make sure the correct function of the product under different conditions.

Besides these important tests, virtual laboratories (Visier, 2000) represent a very suitable approach in order to allow this faster development. It reduces the necessary time for field tests that are long, expensive and in many cases even impossible. These virtual laboratories can be based on simulation (Haves, 1998, Husaunndee et al., 2000) as well as emulation technologies (Annex17, 1993, Vaézi-Néjad et al., 2000, Vaezi-Nejad et al., 1991).

The aim of this paper is to continue the development of test benches that are able to deal with different problems from questions of integrated planning, sizing (e.g. HVAC terminal system, flow rates, tubes, valves and pumps), hydraulic balancing or control.

These test benches can also be used in order to optimise parts of the commissioning process which is the aim of task 40 of the IEA (Visier, 2001).

The test benches developed in this paper are based on a library of models (SIMBAD Building and HVAC Toolbox) of HVAC components (Husaunndee, 1997).

### SIMBAD BUILDING & HVAC TOOLBOX

#### Generalities

The SIMBAD building and HVAC toolbox is a library of models, suitable for the development and test of HVAC control systems on plant, terminal and building level (cf. <http://simbad.ddd.estb.fr>).

The toolbox consists of models, necessary to simulate building phenomena of conduction, radiation and convection, models for the production part (hot water, storage and air conditioning), distribution, emission on the terminal level as well as some other groups of

useful models (controllers, weather data files, occupancy profiles...) as shown in Figure 1.

The toolbox benefits from the user friendliness of the Simulink graphical environment and uses the "drag and drop" method of the graphical environment to select the components required. The latter are linked together to build the systems.

The models available in this toolbox are structured using a methodology of modelling in a graphical simulation environment (Husaunndee et al., 1999, and Husaunndee, 1999).

One characteristic of the toolbox is the definition of connection vectors to transfer data from one block to another: air vector, water vector, information network, weather vector... These connection vectors enable the user to build the systems following the actual layout of the plant either on the air-circuit or water circuit.

To facilitate the use of the toolbox, different zone models are provided: from one with a predefined list of buildings over others with individual wall description up to zonal models, dividing the room air into sub-volumes.

Users of simulation tools can have various knowledge of thermal building simulation. Therefore, the models in the library are structured in order to allow experienced users the access to all parameters and source code while the beginner can use the models even without a particular knowledge of modelling. The models are developed in a way that the necessary parameters are easily available or can be obtained from manufacturer data or rating points. These two points are particularly important as the library is mainly developed for the use on the control field where the users do not necessarily have a significant experience in thermal modelling.

The models in the library are mostly dynamic. They can be switched by the user to steady state models if long term simulations are of interest.

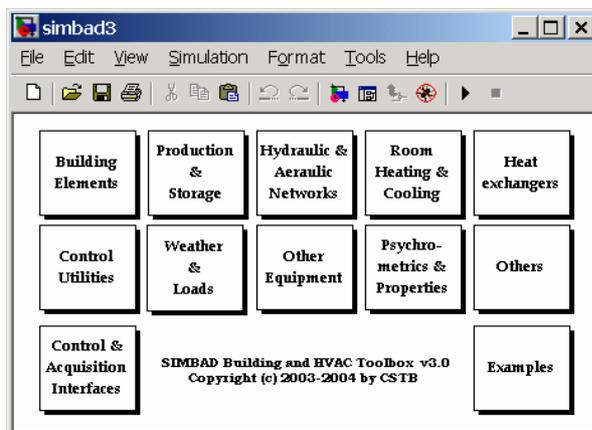


Figure 1: Structure of the SIMBAD toolbox

## The hydraulics library

One new feature of the toolbox is a group of models permitting to describe hydraulic circuits (Figure 2) realising a direct coupling between hydraulic and thermal phenomena.

The effect of hydraulic balancing and control is thus taken into account.

Hydraulic components as well as predefined circuits are available in the toolbox (cf. Figure 2), permitting to represent various hydraulic circuits. These models are then coupled with the models of plant or terminal units that take also into account the hydraulic phenomena. The equations for the hydraulic calculations are listed in the appendix.

Most models of the hydraulic library are focussed on hydraulic phenomena (e.g. valves etc.) since thermal phenomena are negligible. Only mixing elements and tubes consider thermal phenomena. These are simple for the mixing elements (tees or valves), where a simple heat balance is carried out.

In the case of tubes, a thermal heat balance is carried out on the tube that is divided into a number of segments, defined by the user.

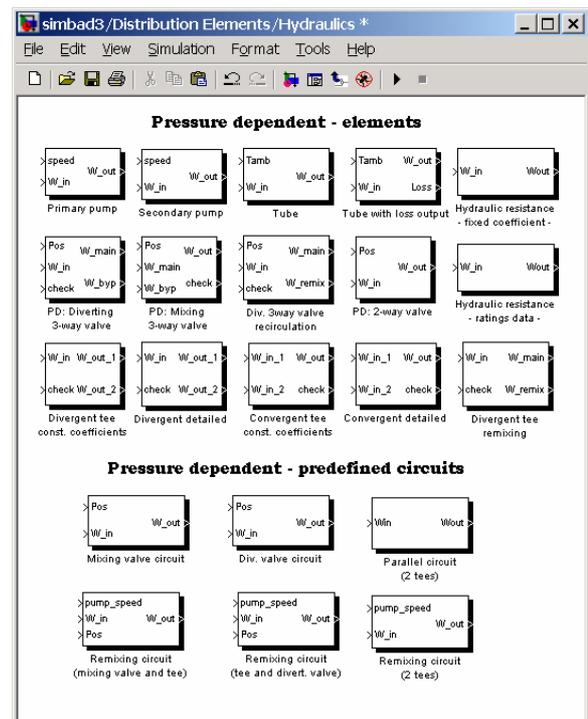


Figure 2: Hydraulic part of the SIMBAD toolbox

The calculation of flow rates is described hereunder.

### Main flow circuit:

The pump model is the main element of the hydraulic circuit (e.g. Figure 11 in the appendix). In this model, the mass flow rate through the main circuit of the

system is calculated, depending on the characteristics of the water circuit and the pump curve: the flow rate is obtained by equalising the pressure drop of the water circuit (circuit of a hydraulic network with parallel and serial resistances) to the pressure generated by the pump.

$$\Delta p_{network} = \Delta p_{pump} \quad (1)$$

Matlab/Simulink environment allows the iteration of the flow rate for each time step. However, in the case of more complex systems with a large number of parallel and serial connections, this method does a) not guaranty convergence in all cases and b) slow down the simulation speed. A simplified method is thus applied, using the resistance coefficients bequiv of the previous time step to calculate the flow rate (Felsmann et al., 2002):

$$\Delta p_{network} = b_{equiv} \dot{m}^2 \quad (2)$$

A comparison between both methods has shown good agreement, if valve positions and pump speed do not change brusquely. This is generally the case since valve actuators are characterised by a non negligible time constant.

Supplementary pumps in the circuit (cf. Figure 12 appendix) are treated as pressure gains.

#### Parallel circuits:

In the case of parallel circuits (cf. Figure 11 or Figure 12 in the appendix), the incoming flow rate has to be divided in the two circuits. This is carried out by equalising the incoming pressure in the tee or valve where both flow paths will join again:

$$\Delta p_{path2} = \Delta p_{path3} \quad (3)$$

The developed method works for any number of serial and parallel connections.

The drag and drop principle of Matlab/Simulink environment allows a simple modelling without a high knowledge of modelling. The models are completely modular and hydraulic circuits can easily be constructed.

On the other hand, meshed circuits (circuits that are not only replaced by simple parallel or serial resistances, e.g. Tichelmann method) can to date not be simulated since they need more complex modelling in order to achieve convergence. A method for these circuits which is also based on the modular structure of Matlab/Simulink, is actually being developed for the next version of the library.

### APPLICATION OF THE LIBRARY TO THE CASE OF A 6 ZONE BUILDING

The studied building is divided into 6 characteristic zones. Each zone is provided with heat by a hot water radiator, controlled by a PI controller depending on air and radiant temperature, measured by a controller sensor.

The radiators are supplied with hot water at 70°C from a boiler in the production part of the building.

The hydraulic circuit is presented in a simplified way in Figure 3.

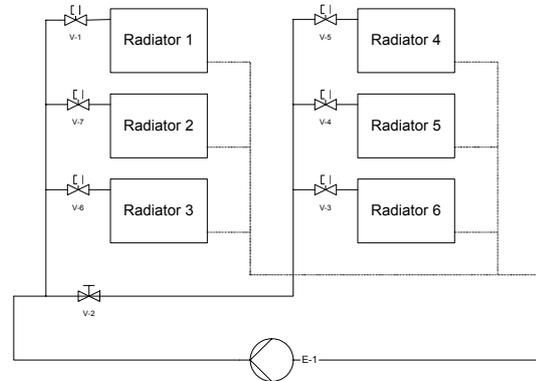


Figure 3: Layout of the hydraulic circuit

The circuit is divided into two parallel groups, containing each three radiators in parallel arrangement. A pressure drop between both groups is represented as a valve in Figure 3. This has been added in order to increase the effect of an unbalanced system.

### THE BUILDING MODEL

The building model has already been presented (Riederer et al., 2001). It divides the simulated building into the following groups of models (Figure 4):

- Building control (zone control, central HVAC unit control, supervisory control),
- Building production (Air and water preparation for building HVAC system),
- Distribution of water and air flows from “production”,
- Mixing of water and air flows returning from emitters (HVAC terminal systems) and zones to the central unit,
- The group “Zones Emitters Loads” where the conditions in the building zones are calculated (models of rooms, heat gains, HVAC terminal systems etc.).

The layout of the different groups of models has been shown previously (Riederer et al., 2001).

The emission part, including radiators and the hydraulic circuit, is shown in Figure 6 (using tubes, tees, singular resistances, valves and radiators from the library).

The graphical environment allows an ease implementation of the circuit as already presented in the schematic of the circuit in Figure 3. This layout can be compared to that of installation plans and the user

can follow and supervise all fluid, heat or control flows at any position in the circuit.

Each radiator circuit in Figure 5 is again represented by a tube, a two way valve, the radiator itself and additional hydraulic resistances (bows, singular resistances etc.) as shown in Figure 5. The valves are

here positioned by an actuator model which represents the time delay and time constant of the actuator.

The valves position is driven by an actuator that is commanded by the PI controller, positioned in the room.

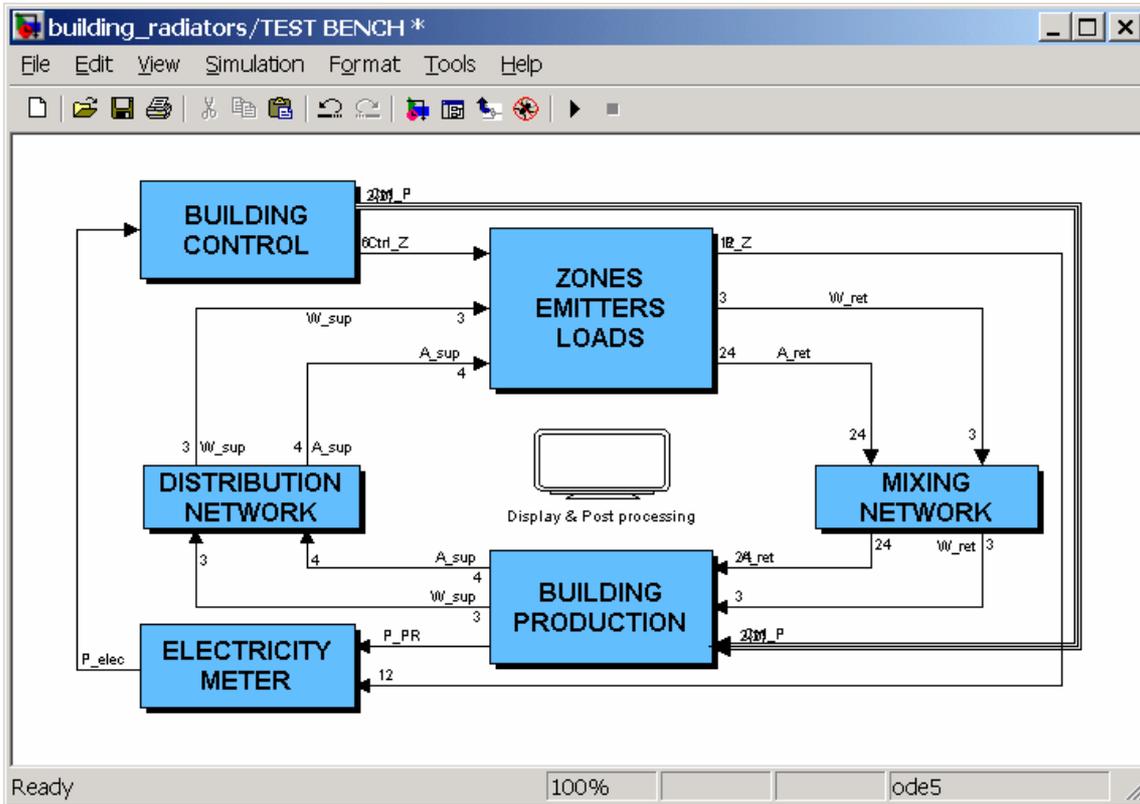


Figure 4: Structure of the building model

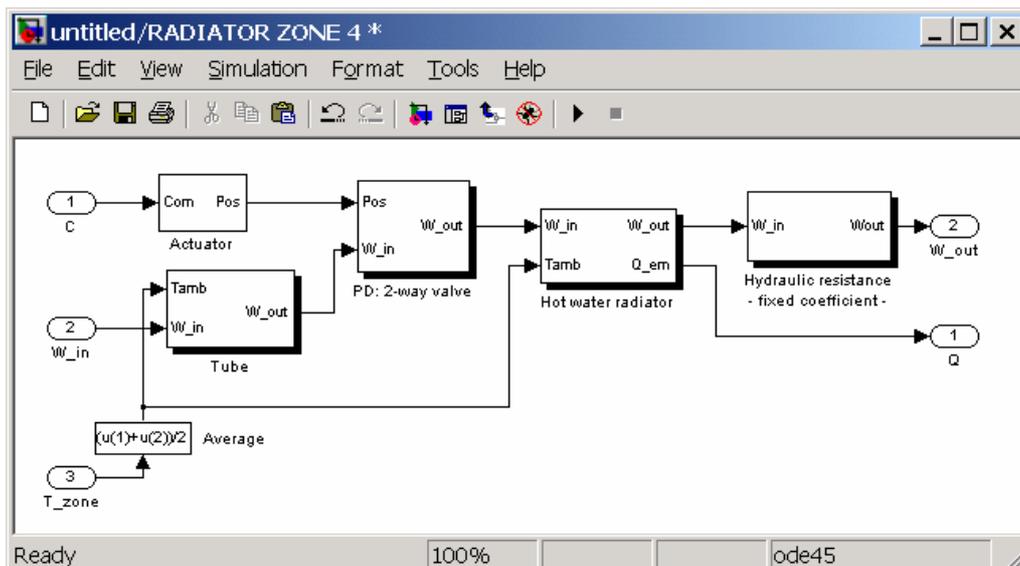


Figure 5: Single radiator circuit on the terminal level

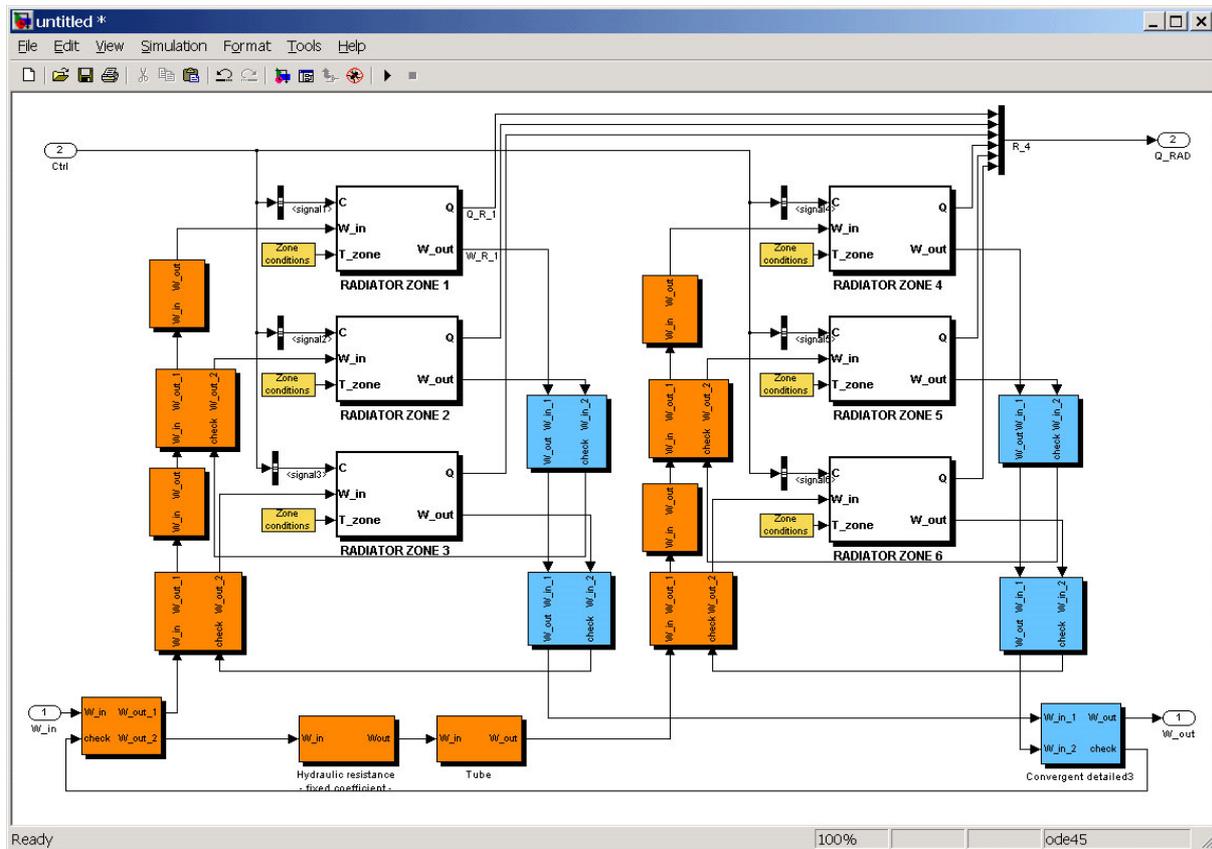


Figure 6: Structure of the hydraulic network of the building

## SIZING PROCEDURE

An automatic protocol has been written for the sizing of the different components and the hydraulic balancing. This allows obtaining a reproducible procedure for all sizing steps. The simulation result is then independent from the user.

The procedure can be based on classic rules (e.g. ASHRAE Handbook of Fundamentals, 2001) or on optimisation criteria. The latter will be carried out in further studies using the various capabilities of the Matlab/Simulink environment as for example an optimisation toolbox (Matlab, 2002). This will be necessary when different sizing approaches shall be compared to a reference case (optimal case).

For each step in this procedure, a command file is written. These are then called by a general sizing program. The advantage of this approach is that the rules for one step can easily be changed and the impact of different sizing methods can be compared.

In this study, a simple sizing procedure is applied to demonstrate the approach.

In a first step, a data base is constructed, listing catalogue data for all components of the system

(radiators, tubes, valves, tees and pumps). For simplification, standard values are taken in this study that will be changed to a real data base in a next step.

It includes the steps described hereunder:

1. Definition of thermal heat demand in each building zone: in this case, the heat demand is obtained by a first simulation with constant boundary conditions (external temperature and radiation). The same building model as used for later simulations is used for this step.
2. Conversion of a data base of heat emission of emitters to the system temperatures available in the treated building (selected supply and return temperatures) that can be different to those given by the manufacturer. The command file calls only the emitter model in order to obtain the values for the whole range of catalogue data.
3. Selection of an appropriated emitter dimension from the modified data base of heat emissions. The new list of modified thermal outputs of the emitter is compared to the real heat demand from step 1. The closest value, superior to the real demand is selected in our case.

4. Calculation of the new “nominal” flow rates in order to match the exact heat demand of each room. The emitter model is again used to obtain the flow rate matching with the needed system temperatures. The flow rates in all circuits of the system are then known.
5. Selection of tube dimensions in all circuits (depending on the structure of the circuit) in order to prevent excessive water velocities for the flow rates obtained in step 4. Tube dimensions are again selected from standard values for the internal tube diameter.
6. Selection of valves with suitable kvs values for the emitters. The building model is used without previous balancing and while imposing the nominal flow rate (step 4) on the main pump of the HVAC system. Each radiator circuit is then opened separately in order to calculate the resistance coefficient of the circuit while all other circuits are closed. Then, the highest kvs value in the valve catalogue is chosen for the circuit characterised by the highest network resistance (minimal valve resistance for the path with the highest resistance to reduce pump energy consumption).

To obtain the other kvs values, a thermal approach has been chosen in this study: all other valves characteristics are obtained by thermal balancing. This means, the kvs value of the valves are iterated in order to obtain the design return temperature which is the same for all emitters in the building. If the emitters have been carefully selected an identical return temperature is obtained at the nominal heat emission of the emitter. When all valve characteristics are selected, the system is working at nominal conditions. These data are used to define the nominal point of the “ideal” pump.

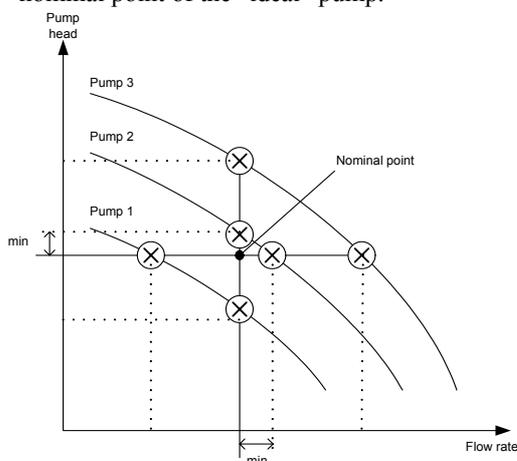


Figure 7: Procedure of pump selection

7. In a last step of the component sizing, an appropriated pump has to be chosen. A simple static approach has been chosen: the nominal point, characterised by the sum of the nominal flow rates in all radiators as well as the pressure drop at the inlet and the outlet of the pump (step 6), is compared to the characteristic curves of the different pump sizes (Figure 7).

The pump with the closest result has been chosen with the constraint that the pump curve has to furnish higher pressure as needed at the nominal point (cf. Figure 7).

8. Tune terminal controllers.

The last step, the tuning of the controllers is actually being implemented into the procedure.

The sizing of a production part including different heat sources (boilers, heat pumps, combined solar systems etc.) is also in progress.

## RESULTS OF SIZING PROCEDURE

In this paper, the sizing is carried out for 6 identical rooms with the same boundary conditions. This permits to compare the impact of sizing and balancing of the final result, the verification of the hydraulic balance in the 6 rooms that must be identical as well.

All components are selected from the predefined lists that are just an example. As already mentioned previously, these lists will be replaced by real data bases from manufacturer data.

The results of the sizing procedure are presented hereunder.

Step 1: The heat demand is obtained for an external temperature of  $-7^{\circ}\text{C}$  without internal heat gains in the rooms. The nominal heat demand in each room is found to about 870 W.

Step 2: The nominal heat output of the radiators as well as the heat output of the same radiators for the changed system temperatures ( $70\text{-}50^{\circ}\text{C}$ ) with different room set point temperature is given in Table 1:

Table 1 : Heat output of the radiators

	1	2	3	4	5	6	7
Heat (90/70) [W]	500	750	1000	1250	1500	1750	2000
Modified heat (70/50) [W]	271	405	539	672	804	926	1067

Step 3: Radiator 6 has been chosen by the program.

Step 4: The flow rates in all 6 radiator circuits are adjusted in order to get the nominal heat demand by each radiator. It is found to 33.6 kg/h.

Step 5: The tubes are then selected in order to prevent water velocities above 0.1 m/s. The results can be found in Figure 8.

Step 6: The range of kvs-values has been limited between 0.25 and 1.5 m<sup>3</sup>/h. The obtained values are shown in Figure 8.

Step 7: The smallest pump has been selected by the program since the circuit is very small.

Step 8: This step, the tuning of the controllers, has not been implemented yet.

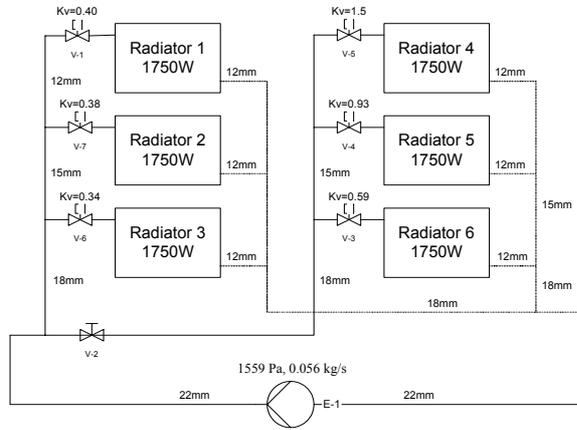


Figure 8: Results of the automatic sizing procedure

### EFFECT OF HYDRAULIC BALANCING

The effect of balancing using the selected pump is shown for fully opened valves. Since the heat demand in all zones is identical, all flow rates must be the same. Table 2 shows the results of the test in the balanced and in the unbalanced case.

Table 2 : Effect of balancing on flow rates

	1	2	3	4	5	6
Balanced [l/h]	31.7	31.6	31.6	31.8	31.7	31.7
Unbalanced [l/h]	36.9	43.1	52.9	24.2	28.0	34.4

It can clearly be seen that the balancing allows a more equal distribution of flow through the different radiators. While the flow rates vary from 24.2 to 52.9 kg/h (relative difference of 90.5%, compared to the flow rate obtained in the balanced case), the difference is negligible in the balanced case (0.6%).

The more interesting result of this balancing is the impact of balancing on the final system performance in terms of terminal control. Since the tuning procedure has not been finished yet, the results are not shown in this study. This will be presented in a future paper.

### PLANNED APPLICATIONS OF THE MODEL

After optimisation of the presented sizing procedure and resolution of last problems concerning the usability and validity of such a simulator, it can be applied to a large range of applications. Studies on the influence of the following points on control performance and system efficiency can be undertaken:

- sizing of components (emitters, tubes, valves, pumps etc.),
- hydraulic balancing,
- selection of control utilities (controllers, sensors, actuators).

These points can be treated point by point but also simultaneously. When the points are treated step by step, faults can be detected in the commissioning process. When all points are treated simultaneously, the building with its system can be optimised and rules can be given especially for dynamic sizing and balancing methods.

A difficult point to solve for these studies is the definition of criteria for the comparison. These criteria are actually being developed.

### CONCLUSION

In this paper, a test bench for impact of sizing, balancing and control parameters is developed.

The test bench is developed in Matlab-Simulink environment that has the following advantages:

- The Simulink environment allows an easy modelling as well as a detailed system monitoring (access to all data transfers),
- The environment is very suitable for any kind of optimising procedure.

In order to study the impact of the listed parameters, an automatic sizing procedure has been developed where step by step all necessary sizing and parametering of the models is carried out. The different steps are based on rules that can be changed in order to study the effect of the sizing on system performance.

The developed test bench can easily be adapted to other hydraulic circuits or zone numbers.

The demonstrated approach is particularly interesting for parametric studies of controllers installed in different buildings with different use.

The new hydraulic part of the SIMBAD toolbox permits the simulation of different hydraulic circuits.

First results have been shown for an exemplary building.

In a next study, the effect of different sizing and balancing methods will be compared and the impact on control performance and energy consumption will be analysed. Criteria will be developed in order to carry out these comparisons.

Especially when variable speed pumps shall be used, this tool will be very helpful to analyse the effect of sizing on the final result.

The automatic sizing procedure has been successfully applied to the terminal part. In a next step, the production part will be sized in the same way.

## BIBLIOGRAPHY

- Annex17, 1993. Development of emulation methods, VTT research notes, ISBN 951-38-448-X
- ASHRAE Handbook of Fundamentals, 2001. SI Edition, American Society of Heating, Refrigerating and Air conditioning Engineers
- Felsmann, C., Werdin, H., Knabe G., 2002. Simulation of domestic heating system by integration of TRNSYS in a Matlab/Simulink model, System simulation in buildings SSB, Liège, Belgium
- Idel'cik, 1960. Momento des pertes de charge – coefficients de pertes de charge singulières et de pertes de charge par frottement, Eyrolles, Editeur Paris
- Haves, 1998. A standard simulation test bed for the evaluation of control algorithms and strategies, ASHRAE Transactions, 1998, Vol. 104, Part1
- Husaunndee, A., Bolher, A., Jandon, M., Millet, J.R., Visier, J.C., 2000. Improving the SIMBAD Toolbox for the Development and Assessment of integrated control Strategies, Proceedings of Sustainable Building 2000, Maastricht, the Netherlands, October 2000, pp494-496
- Husaunndee, A., Visier, J.C., 1997. SIMBAD: A simulation toolbox for the design and test of HVAC control systems. Proceedings of the 5th international IBPSA conference, Prague, CZECH REPUBLIC, 2 : 269-276
- Husaunndee, A., Visier J.C., 1999. The building HVAC System in control engineering- A modelling approach in a widespread graphical environment, ASHRAE transactions, 1999, Vol. 105, Part 1
- Husaunndee, 1999. Modélisation des installations de génie climatique en environnement de simulation graphique, Thèse de Doctorat, Ecole nationale des ponts et chaussées, Paris, France
- Riederer, P., Husaunndee, A., Vaezi-Nejad, H., Bruyat, F., 2001. Development and quality improvement of HVAC control systems in virtual laboratories, P. Riederer, et al., Building Simulation 2001, Rio de Janeiro, Brazil, August 2001
- Matlab, 1998. Matlab. Version 6.1 Mathworks Inc., Ma., USA, 1998
- Simulink, 1998. SIMULINK dynamic System Simulation for Matlab. Version 2.1 Mathworks Inc., Ma., USA, 1998
- Vaézi-Nejad, 2000. Projet QUALISIM: Qualité Assistée par la SIMulation – Définition du Cahier des charges et réalisation d'une première version d'un laboratoire virtuel, CSTB, Marne-la-Vallée, November 2000

- Vaézi-Nejad et al., 1991. The use of building emulators to evaluate the performance of building energy management systems , IBPSA Simulation 91 , Conference proceedings building simulation 91 pp. 209-213
- Visier, J.C., 2000. Virtual laboratories used for climatic engineering, International Journal of HVAC&R research, Volume 6, number 6, October 2000
- Visier, J.C., 2001. Des outils pour le commissionnement des installations de génie climatique, Annex 40, International Energy Agency

## LIST OF SYMBOLS

### *Latin letters:*

$\dot{m}$	Flow rate	[kg/s]
A	Surface	[m <sup>2</sup> ]
b	Resistance coefficient	[
D	Thickness	[m]
H	Height	[m]
kv0	Valve capacity (fully closed)	[m <sup>3</sup> /h]
kvs	Valve capacity (fully open)	[m <sup>3</sup> /h]
L	Length	[m]
p	Static pressure	[Pa]
Pos	Position	[%]
w	pump speed	[rpm]

### *Greek letters:*

$\alpha$	Correction factor	[-]
$\lambda$	Friction factor	[-]
$\rho$	Density	[kg/m <sup>3</sup> ]
$\zeta$	Resistance coefficient	[-]

### *Subscripts:*

100	percentage of valve opening
180°	outlet/inlet path with 180° to inlet/outlet path
90°	outlet/inlet path with 90° to inlet/outlet path
equiv	equivalent
max	maximal
network	network
nom	nominal
out	outlet path
pump	pump
ret	return
singular	singular (resistance)
sup	supply
tube	tube

Note: The appendix is only available in the electronic version of the paper.

## APPENDIX

Hydraulic relationships used are based on [Idel'cik60], they are listed exemplarily hereunder:

1) Tubes

$$\Delta p_{tube} = \lambda \cdot \frac{L}{D_{tube}} \left( \frac{1}{2} \rho v^2 \right) - \rho g \Delta H \quad (4)$$

The friction factor  $\lambda$  is calculated depending on the flow characteristics for the laminar case, the turbulent case or a transition case (Felsmann et al., 2002). Moody relationship is used for the turbulent case.

Height difference between inlet and outlet of the tube is considered in order to allow the calculation of flow, generated by density differences (e.g. solar systems).

2) Singular resistances

$$\Delta p_{singular} = \zeta \left( \frac{1}{2} \rho v^2 \right) \quad (5)$$

In the case of tees, the resistance coefficient is calculated as a function of the flow rates through the two flow paths. It is given exemplarily for the mixing tee with 90° angle between both flow paths (cf. Figure 9 and Figure 10 for definition of the flow paths).

For the straight path (180°):

$$\zeta_{180} = 1.55 \frac{\dot{m}_{90^\circ}}{\dot{m}_{out}} - \left( \frac{\dot{m}_{90^\circ}}{\dot{m}_{out}} \right)^2 \quad (6)$$

For the rectangular path (90°):

$$\zeta_{90} = \alpha \left[ 1 + \left( \frac{\dot{m}_{90^\circ} A_{out}}{\dot{m}_{out} A_{90^\circ}} \right)^2 - 2 \left( 1 - \frac{\dot{m}_{90^\circ}}{\dot{m}_{out}} \right)^2 \right] \quad (7)$$

3) Valves (two-way and three way mixing and diverting valves):

$$\Delta p_{valve} = \left( \frac{\dot{m}}{k_v} \right)^2 \rho 7.716^{-19} \quad (8)$$

Note that  $\dot{m}$  in (8) is in [kg/s] while  $k_v$  is in [m<sup>3</sup>/h].

This relationship is applied for both paths in the case of the three-way-valve. The valve flow rate  $k_v$  at the nominal pressure drop of 1bar is calculated for two different valve characteristics depending on the valve position:

a) Linear valve characteristics

$$k_v = k_{v_0} + k_{v_s} \left( 1 - \frac{k_{v_0}}{k_{v_s}} \right) \left( \frac{Pos}{Pos_{100}} \right) \quad (9a)$$

b) Exponential valve characteristics

$$k_v = k_{v_0} e^{\frac{\log \frac{k_{v_s}}{k_{v_0}} \cdot Pos}{Pos_{100}}} \quad (9b)$$

4) Pumps

A simplified expression for the pump curve is used:

$$\Delta p_{pump} = \Delta p_{max} \left( \frac{w}{w_{nom}} \right)^2 - (\Delta p_{max} - \Delta p_{nom}) \left( \frac{\dot{m}}{\dot{m}_{nom}} \right)^2 \quad (10)$$

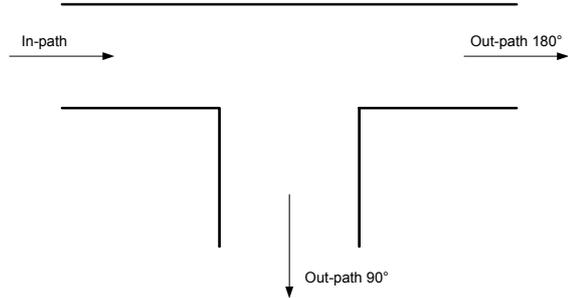


Figure 9: Definition of flow paths in a diverting tee

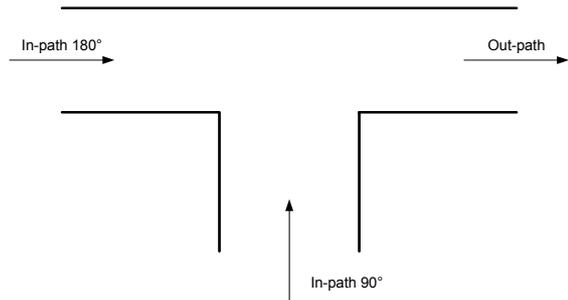


Figure 10: Definition of flow paths in a mixing tee

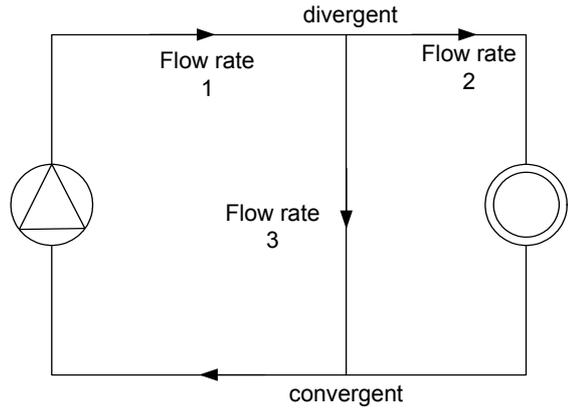


Figure 11: Flow calculation in a parallel diverting circuit

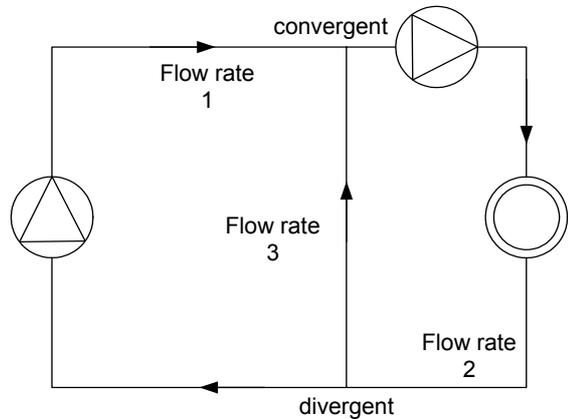


Figure 12: Flow calculation in a parallel remixing circuit