THE USE OF BUILDING EMULATORS TO EVALUATE THE PERFORMANCE OF BUILDING ENERGY MANAGEMENT SYSTEMS

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ABSTRACT

Three complementary approaches may be used in the evaluation of the performance of building control systems - simulation, emulation and field testing. In emulation a real-time simulation of the building and HVAC plant is connected to a real building energy management system (BEMS) via a hardware interface. Emulation has the advantage of allowing controlled, repeatable experiments whilst testing real devices that may contain proprietary algorithms.

Building emulators have been developed by the authors in the context of IEA Annex 17, which is concerned with the use of simulation to evaluate the performance of BEMS. The paper discusses different approaches to the design of building emulators and describes the different architectures, hardware and software used by the authors.

The problem of evaluating the overall performance of BEMS is discussed and results are presented that illustrate the use of emulators to investigate the influence of the tuning of local loop controls on building performance.

INTRODUCTION.

The commercial airline industry uses flight simulators to train its pilots. Although flight simulators can not completely replace actual flight experience, they can drastically reduce the amount of real flying time required. The airlines have found flight simulators to be safer less expensive, and provide a more thorough training experience over a wide variety of flight conditions. Flight simulators can be used to evaluate pilot performance, to refresh flying skills, and to develop standardized procedures to be followed in case of emergency.

In the building industry, the analogue of a flight simulator is an emulator/tester for Building Energy Management Systems (BEMS). Just as a flight simulator simulates an airplane in real time, an emulator/tester for BEMS simulates a building and its HVAC system in real time. The emulator/tester is connected to the BEMS in place of its sensors and actuators and the BEMS controls the simulated building and HVAC plant as if it were an actual building. The emulator/tester can be used to evaluate the BEMS' performance in terms of the energy consumed, the degree of comfort maintained in the simulated space, the response time of the system, and the amount of control activity [1].

Other important uses of an emulator/tester are the training of new BEMS operators, the commissioning BEMS software, the development and debugging of new control algorithms, and the tuning of control loops [2].

A number of different emulators have been constructed as part of an International Energy Agency collaborative research project on the use of computer simulation to evaluate the performance of BEMS (Annex 17 of the Energy Conservation in Buildings Program). The configurations of the four emulators constructed by the authors are described in the following section. The remainder of the paper then describes the use of emulators to study real control systems and presents the results of a study of the effect of loop tuning on building performance.

DESCRIPTION OF EMULATORS.

Building emulators used for testing building control systems consist of a real-time simulation of the building shell and HVAC plant together with a hardware interface that connects the simulation to the BEMS. The function of the interface is to couple the control equipment to the sensors and actuators of the simulated plant. Analogue to digital converters are connected to the analogue outputs of the controller, which would normally be connected to the plant actuators. The digital to analogue converters are connected to the analogue inputs of the controller in place of the plant sensors. Digital inputs and outputs are used for the plant switching and status signals.

The emulators described here all use component-based simulation programs, either HVACSIM+ [3] or TRNSYS [4]. The flexibility provided by such programs is important for two reasons :

the component-based architecture facilitates the substitution of the dynamic plant models required for the stable sequential solution of the plant and controls [5]

the communication between the simulation and the hardware interface can be implemented much more easily than in a "monolithic" program.

The emulators described below were developed in the context of IEA Annex 17 but the hardware and software used were determined mainly by local practice and preference.

Liège University Emulator.

Figure 1 shows the configuration of Liege University emulator. It consists of a microcomputer 386 (33MHz) with math-coprocessor, which runs the simulation (in real time), the graphics routine and manages the I/O interface, and an I/O interface (DMS 541), which links the simulated system and the BEMS to be tested.

The I/O interface (DMS 541) is a built-up data acquisition system. In this case, it has 32 chanels of analog-digital input and 16 chanels digital-analog output.

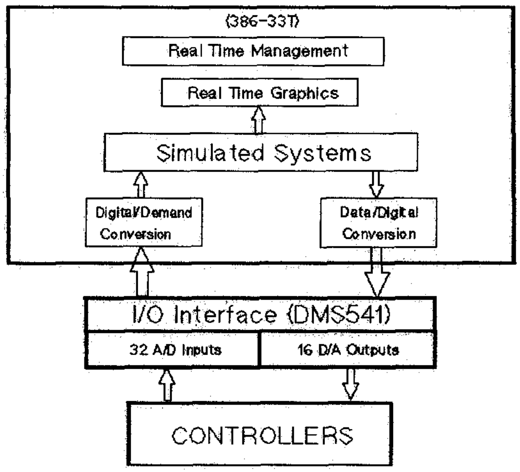

Figure 1 : The configuration of the Liege University Emulator.

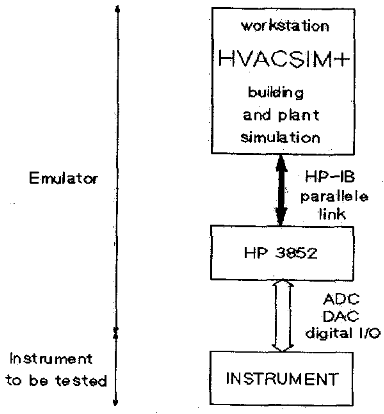

Figure 2 : The configuration of the CSTB Emulator.

A TRNSYS module is especially developed to manage the real time of the emulation and the communication between simulated systems and the BEMS [6].

This module manages the real time of the emulation by frequently checking the clock of the computer. When the correct time comes, the computer sends the system's state values to the BEMS and recieves the control values at the very begining of each step. If the simulation computation of a step ends before the real time, the computer will wait until it reaches the real time. In case the simulation computation of a step is longer than the time step, it results a drift in time, the computer begins the next step immediately and a time error message is written into a file.

This module also assists the I/O interface for communication with BEMS by calling the C routines which are especially developed to be suitable for the DMS541. The module includes the functions to convert the data for the simulation and BEMS.

Another TRNSYS module is developed for drawing the graphics on the screen of the computer during emulation. This module draws two figures for the system variables. Each figure can have the maximum twelve curves. The sum of the curves for two figures is twenty, which is limited by the number of maximum inputs of a TRNSYS module. The current simulation time and current values of the system variables of each curve are printed on the right of the figures, which are refreched at every time step. This module reads the names for each curve, the titles and the units fort two figures from three text files which can be easily modified due to requirement. The curves of variables and their current values differ from each other by different colour. The scales of Y-axes of each figures can be modified by the paramters of this module.

CSTB emulator.

The CSTB emulator, shown in Figure 2, uses the HVACSIM+ simulation program running on an Unix workstation. The use of a multi-tasking workstation provides an efficient development environment and also facilitates the changing of parameters such as the heat gain to a particular zone while the simulation is running. The interface is composed of an autonomous data acquisition and control system produced by the manufacturer of the host computer and linked to it by an IEEE 488 bus. This configuration is expensive when compared to the PC implementation described above but has the advantages of convenience and flexibility.

The communication between the simulation program and the interface is controlled by a Fortran subroutine that is incorporated in the simulation in the same way as the models of the physical components. The routine reads the system clock and initiates analogue to digital and digital to analogue conversions and data transfers between the work station and the control system at fixed intervals. It is run in a separate "superblock" in HVACSIM+ so that it does not participate in the iterative solution of the simulation equations. The routine is based on the corresponding routine used in the Oxford University emulator, as is the routine used to plot graphs of flow rates, temperatures and control signals as the simulation proceeds.

Oxford University Emulator.

The configuration of the Oxford University emulator is shown in Figure 3. A unique feature is the implementation of the interface in a dedicated distributed computer system based on single-board microcomputers. Each microcomputer includes a programmable logic array that provides eight digital input lines and eight digital output lines and also implements the digital interface logic to connect to a multiplexed eight channel twelve bit integrating ADC and a separate eight channel analogue output interface.

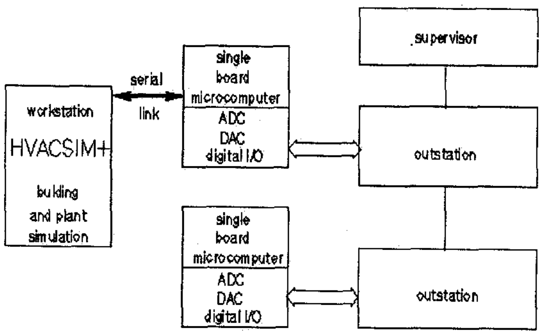

Figure 3 : The configuration of Oxford University Emulator.

The microcomputers are programmed in an extension of PASCAL that supports real-time execution, multi-tasking, and transparent communication between microcomputers and with the analogue interface. The use of a high-level language allows the interface to be reconfigured easily to meet the particular requirements of the BEMS under test. The interface program is compiled on a workstation and the executable code downloaded across a network to each of the microcomputers.

The interface has the ability to perform part of the simulation as well as transferring data to and from the BEMS. In particular, the short time scale dynamic response of the actuators and sensors may usefully be simulated in the interface since a shorter time-step than is required for the rest of the plant may easily be used. Effects that may be treated include non-linearities, faults, measurement noise, offsets and drift.

NIST Emulator.

The NIST emulator/tester, shown in Figure 4, employs a data acquisition/control system (DACS), a 25 MHz 32 bit personal computer and a 20 MHz 32 bit personal computer. The NIST developed HVACSIM+ program runs on the 25 MHz personal computer and simulates the performance of the building and HVAC system. HVACSIM+ shares computer memory with the software drivers for a local area network (LAN) and uses a special component for data communication which in turn calls routines written in the C language. The shortage of runtime memory space, resulting from the memory sharing, is overcome by using a commercially available memory manager program. The interface between the user, the HVACSIM+ program, and the BEMS is a commercially available process management and control software (PMCS) package running on the 20 MHz personal computer. The software has been customized using user-developed C code that handles the data flow and some data manipulations, including the conversion of engineering units to/from the electric currents or voltages required by the connected hardware. It is also possible to intercept and change the numerical value of sensor data and/or control signals in a program window of the PMCS during runtime. Up to four selected data point values cans also be plotted simultaneously on the screen as a time series graph.

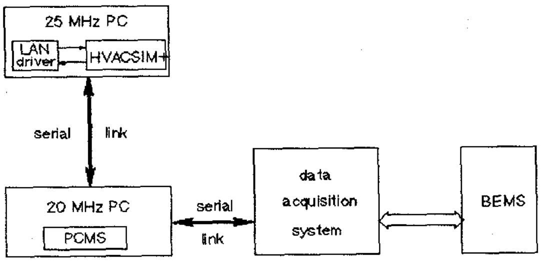

Figure 4 : The configuration of the NIST Emulator.

Comparison of the emulators.

In the emulators developed at the University of Liege and at CSTB the interfaces are more closely integrated with the simulation computer. Advantages of this approach include :

- high data transfer rate between the computer and the data acquisition system ;
- communication between the computer and the interface could be easily effected by software supplied by the manufacturer.

The more distributed systems developed at NIST and the University of Oxford have greater flexibility but require greater effort and expertise to set up and are significantly more expensive.

USE OF THE EMULATORS TO STUDY CONTROL PERFORMANCE.

The overall aim of BEMS testing is to evaluate the effect of the BEMS on the performance of the building. Measures of building performance include energy consumption, comfort conditions, and wear/failure of the plant. These measures will be weighted differently for different buildings by different people; the problem of making an overall assessment of building performance from different indicators is discussed in [7,8,9].

In evaluating the performance of BEMS hardware the speed at which tests can be performed is presumed to be limited to real time for some equipment, and to some modest factor of speed-up from real time for most other equipment. Thus prediction of annual energy consumption using Test Reference Years (365 days) or even Short Reference Years (56 days), appears somewhat impractical. If the simulation has to run in (near) real time, then this time is most profitably used to run a detailed simulation of the plant and perform a realistic evaluation of the lower level control performance and its effect on overall performance.

Results of two studies are presented here. The first is a simple study of the effect of changing the zone temperature control strategy on the overall performance of the building and is included to illustrate some issues that arise in the assessment of performance. The second study is concerned with the effect on building performance of the choice of tuning parameters for various control loops. It would appear that in practice most controls are poorly tuned or use "standard" values. The question then arises as to the influence that (poorly tuned) local loops have on overall performance in general, and on the assumptions of ideal lower level behavior commonly made when studying the performance of buildings using simulation.

Building an Plant Simulation.

A simulation of a building and plant whose behaviour is taken to be representative of an air-conditioned office building was used in the studies presented here. The simplified building has a variable-air-volume HVAC system with a single air-handling unit and three zones, as illustrated in Figure 5. The air handler consists of fresh, return and exhaust air dampers, a pre-heating coil, a cooling coil, and a fan. Air is supplied to the zones by ducts that run through a return air plenum. Each zone has a reheat coil and a variable-air-volume (VAV) box to vary the temperature and flow rate of the air supplied to that zone. The central plant consists of an oil-fired boiler, a reciprocating chiller and a cooling tower.

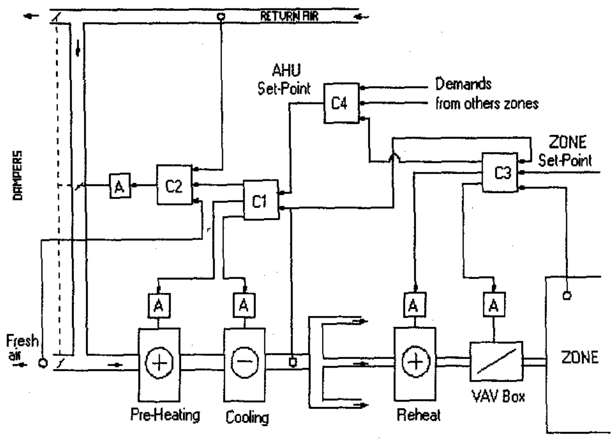

Figure 5 : An overview of the air-conditioning system simulated in the study

The simulation makes use of building and plant models developed from the specifications produced by the International Energy Agency project on plant modeling (Annex 10) [11]. The models of the components of the distribution system have been modified and supplemented to treat dynamic and non-linear operation in a more realistic manner [5].

A realistic test of a BEMS involves subjecting it to disturbances typical of those found in actual buildings. In the absence of field measurements, simple schedules of internal gains with step changes at various times of day are used. The weather data used for the test run are hourly temperature and minute by minute solar radiation measurements made near London.

Two different days are used for the tests, a March day that is cold enough for the cooling load to be met entirely by free cooling, and a June day during which the chiller is required to operate throughout most of the operating period. Both days have been selected for their rapid fluctuations in solar radiation, which provide disturbances for the control system over a wide range of frequencies.

Control scheme.

The BEMS under test consisted of four, software configurable, outstations; one to control the air handling unit, and the other three to control the re-heat coils and VAV boxes in the three zones. The control scheme, which is typical of those used in commercial office buildings, has two main types of control loop. One controls the temperature of the air supplied by the air handling unit and the other controls the temperature of the air in the zones.

PERFORMANCE ASSESSMENT

Table 1 shows the results of a simple study conducted using the University of Oxford's emulator to examine the effect on the overall performance of the building of changing the strategy that defines the set-point for the zone temperatures [9]. In one case, fixed set-points of 20 C for heating and 24 C for cooling were used. In the other case, the cooling set-point was determined by a linear reset schedule based on outside air temperature. The cooling set-point is 20 C when the outside temperature is 0 C and 24 C when the outside temperature is 25 C. The heating set-point is 0.5 C lower than the cooling set-point.

		Energy (MJ)	Dissatisfaction (%)	Maintenance (hr-1)
March	OAT reset	886.8	7.4	11.8
	4 C deadband	320.2	11.9	3.0
June	OAT reset	1665.9	5.6	9.4
	4 C deadband	1473.9	6.4	7.9

Table 1

There are a number of measures of performance that can be used in the evaluation of the control performance of environmental systems in buildings. Here, the assessment of the overall performance takes account of discomfort, energy costs and maintenance costs. Fanger's Percent Persons Dissatisfied (PPD) [12] is used as a measure of the dissatisfaction with the thermal environment. The energy costs considered here are the costs of operating the oil-fired boiler, the chiller, the cooling tower fan and the supply fan. The cost of electrical energy is taken to be three times that of fuel oil energy. In the absence of any empirical data on the relationship between control activity, wear and maintenance costs, the hourly average number of starts, stops and reversals of every actuators is used as an indicator of probable maintenance costs.

The significantly greater energy consumption on the June test day is due to the continous operation of the chiller plant, whereas the cooling load is met by using outside air on the March day. The energy consumption is lower when the large dead-band is employed because the cooling set-point is then higher, resulting in a slightly smaller cooling load and a greater use of free cooling. The dissatisfaction is greater on the March day than the June day because there are larger fluctuations in solar gain on a time-scale similar to the response time of the zone (i.e. approximately 1 hour).

The use of the large dead-band strategy also results in lower maintenance costs. The total control activity is significantly reduced on the March test day since the cooling load is such that the zone temperatures can be maintained within the dead-band without opening the VAV boxes beyond their minimum airflow position.

The results presented in Table 1 illustrate the problem of deciding whether one system or strategy is better than another. It is not possible to maximize all aspects of performance simultaneously and 'trade-offs' are therefore required. In particular, for the March day it is a matter of judgement as to whether considerable savings in the cost of energy and maintenance justify the somewhat higher discomfort obtained from the 4 C deadband strategy. An approach to this problem that allows linguistic statements abtained from facilities managers etc to be used in evaluating building performance is described in [7,9]. Fuzzy logic is used to relate these statements, cast in the form of rules, to the quantitative indicators of performance obtained from simulation or field measurements.

EFFECT OF TUNING ON BUILDING PERFORMANCE.

A systematic study of the behaviour of the simulated building has been performed by varying the parameters of the control system around a set of nominal values (table 2: test 1).

The variatious were carried out gradually so as to reduce/increase the dynamic performances of the system (Table 2: test 2 to 8 and 9 to 15). The last two tests (ie. test 17 and 18) were included to examine the degradation of the dynamic performances of the final control caused by the addition of a dead band.

The measures of performance used are energy cost, maintenance costs, dissatisfaction and control stability. The results of the tests are shown in Figure 6. The total distance travelled by all the actuators in system is used as a relative measure of control activity. Excessive control activity can be taken to be an indication of actual or potential instability.

	PID Zone 1, 2, 3 dampers			PID AHU	
	GAIN	INTEGRAL TIME	DEAD BAND	GAIN	INTEGRAL TIME
TEST 1	12.5	900	-	1.0	120
TEST 2	12.5	900	-	1.0	240
TEST 3	12.5	900	-	0.125	120
TEST 4	12.5	900	-	0.125	240
TEST 5	12.5	1800	-	1	120
TEST 6	3	900	-	1	120
TEST 7	3	1800	-	1	120
TEST 8	3	1800	-	0.125	240
TEST 9	12.5	900	-	1.0	60
TEST 10	12.5	900	-	5.0	120
TEST 11	12.5	900	-	5.0	60
TEST 12	12.5	450	-	1.0	120
TEST 13	50.0	900	-	1.0	120
TEST 14	50.0	450	-	1.0	120
TEST 15	50.0	450	-	5.0	60
TEST 16	12.5	900	0.5°C	1.0	120
TEST 17	12.5	900	1°C	1.0	120

Table 2 : Parameters values in PID for the tests.

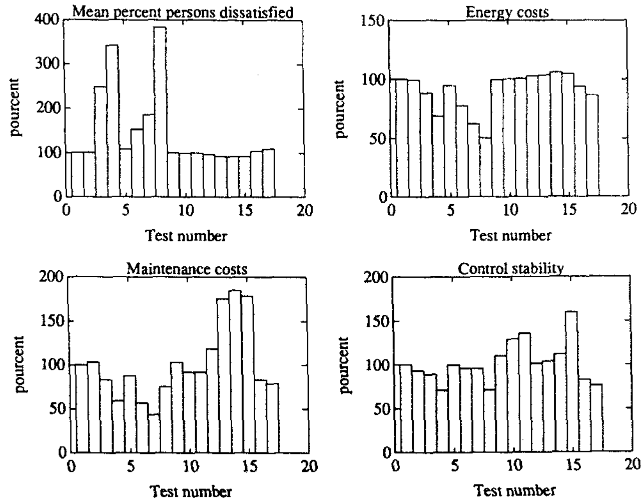

Figure 6 : The relative performance measures obtained for the different tests, expressed as a percentage of the results for test 1.

The results show the significant effect of control tuning on the overall operating costs (energy and maintenance costs), as well as on the quantative performance (PPD and control stability). Moreover, the demonstrate criteria (PPD, energy cost, maintenance cost and stability) when tuning controllers.

The two main results that derive from this study, are as follows:

- the importance of proper control tuning to improve the performance of the HVAC system;

- the type of control tuning to ve chosen depends on the desired dynamic performance, as well as on the energy and maintenance costs of the system.

CONCLUSIONS.

The use of an emulator to evaluate control systems provides the advantages of building the plant simulation while allowing real BEMS hardware, firmware and software to be tested. With an emulator, a BEMS may be tested with any type of building/HVAC system for which a simulation model is available, and tests may be repeated on different BEMS under identical conditions. User developed control algorithms and proprietary software provided with the BEMS can both be evaluated using a rating criteria that includes energy consumption, occupant comfort, and maintenance costs.

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