IMPLEMENTATION STRATEGIES FOR DISTRIBUTED MODELING AND SIMULATION OF BUILDING SYSTEMS

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ABSTRACT

This paper describes implementation strategies for external coupling of distributed building system component models. This approach differs from the traditional way of developing software, where additional models are added by incorporating new modules in an existing program. This results in a simulation environment that is more flexible, practical, and powerful than the sum of the individual software programs.

This paper presents the most recent results of an ongoing project that focuses on developments and implementation of the approach. The realization of the first prototype, i.e. the coupling mechanism, is discussed in detail. This paper concludes with a case study that highlights the necessity and potential of the approach.

INTRODUCTION

The traditional (manual) methods for designing heating, ventilation and air-conditioning (HVAC) systems are being surpassed by simulation tools because:

- buildings get more and more complex in terms of shape, lay-out, functionality and services;

- increasing requirements for flexibility and adaptability;

- modern building standards and codes are performance based rather then prescriptive; i.e. questions to answered include: How many hours per year will the temperature rise above a certain value? What will be the energy consumption per square meter floor per year?

Advances in hardware and software resulted in a flood of building simulation tools. However, each tool is applicable only to a subset of the overall problem, and is limited both in scope and resolution.

We believe that a promising way forward would be to enable run-time communication between tools. This will enable immediate sharing of software improvements, allowing distributed independent development and increasing the overall applicability and scope of existing tools. This is illustrated in Figure 1.
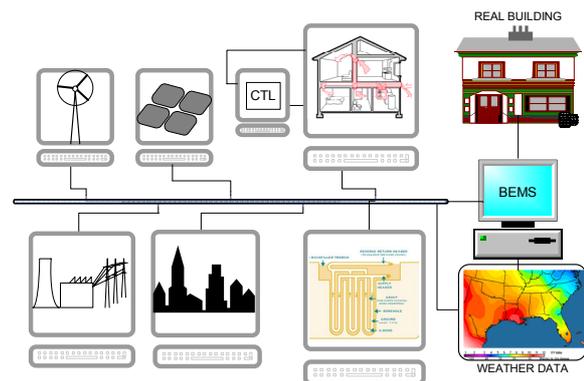

Figure 1 Distributed modeling and simulation

Each sub-system could be modeled in the appropriate software and simulated, potentially, using different computers, while intermediate results would be communicated over the network during execution time. The possibility to model various interdependent aspects over a wide range of applicability and resolution will allow much greater flexibility in the use of building energy simulation.

The work described in this paper is a step towards such a framework. The aim is to resolve the communication between various HVAC component or system simulation software packages. The goal here is to define the coupling methodology in terms of content and frequency of the data exchange.

EXTERNAL COUPLING

The traditional way of sharing developments, such as information sharing [Lockley et al., 1994], information exchange [Bazjanac and Crawley, 1999], or generic model description [Bring, Sahlin et al., 1999] takes place before the simulation starts. External coupling, on the other hand, stands for run-time communication between separate programs (Figure 2). The programs exchange data in a user-predefined or automated manner, while keeping a high level of results consistency.
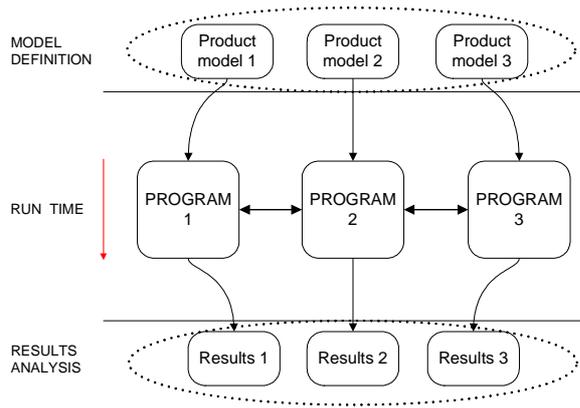
Figure 2 External run time coupling

There are at least three reasons supporting the concept of external coupling in the building systems domain:

- there will never be a single software environment that incorporates all system components models;

- distributed developments in the various packages can be used immediately, allowing efficient and flexible use/reuse of building systems simulation tools;

- external coupling allows to incorporate black box models; so parties may contribute models without sharing the source code.

Master-slave, server-client and peer-to-peer are common terms in inter-process communication configuration. Here we use the term base program to indicate the one which takes the role of master program, or merely the one which contains the majority of components. A program that is externally connected to the base program is referred to as an external program.

DATA TO BE EXCHANGED

The minimum number of variables that defines the thermodynamic state of a working fluid is theoretically known from Gibbs phase rule. These variables together with a variable that quantifies a flow uniquely determine the coupling set of variables among components in the HVAC system. However, in many HVAC component modeling approaches, the mass flow is a known quantity and thus there in no need to consider pressure drop.

For moist air the temperature and first and second phase mass flows are to be exchanged between the programs. In case of water, temperature and mass flow will be sufficient. More discussion on this subject including the quality of the coupled variables can be found elsewhere [Radosevic et al. 2006].

In case the control of an external component or sub-system is based on a sensed variable defined in the base program (or the other way around), it is also necessary to communicate the value of this variable between the coupled programs.

DIFFERENT IMPLEMENTATIONS

The current work starts from specific building simulation environments, such as ESP-r. However, the developed mechanism and generated knowledge should be software and platform independent are thus more widely applicable.

Depending on the context, time dependent behavior of HVAC components can be regarded as dynamic, quasi-static or steady state. This distinction is important for the choice of coupling mechanism. In case of dynamic behavior it is important to keep track of the evolution of the results over time.

Figures 3 and 4 show two principally different coupling mechanisms. Figure 3 illustrates the coupling mechanism for a discontinuous running external program. The base program invokes the external program and waits until that is finished before it continues itself. This mechanism is applicable for steady state component models. If applied with a dynamic external model, a results history mechanism has to be implemented.
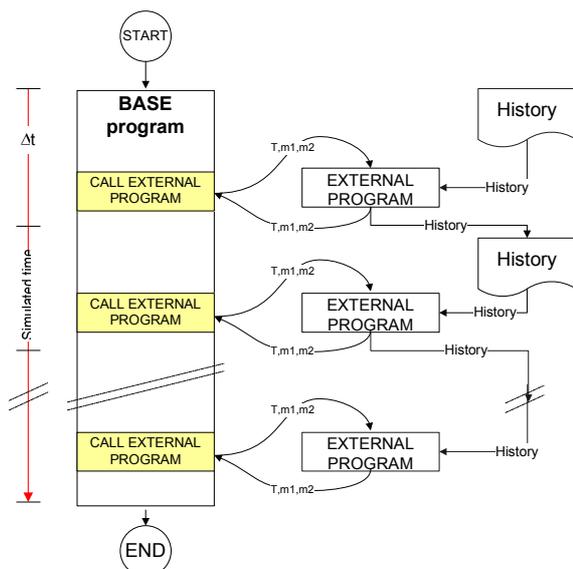

Figure 3 External coupling mechanism for a discontinuous running external program
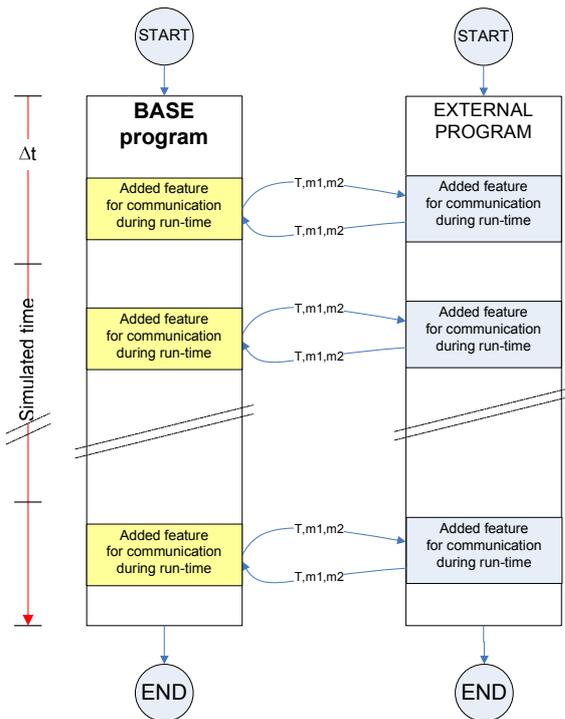
Figure4 External coupling mechanism for a continuous running external program

Figure 4 illustrates the coupling mechanism for a continuous running external program. Both programs run in parallel and exchange data in a certain user-predefined manner. This mechanism is more suitable for dynamic component models. However, if iteration would be needed it requires a more complicated implementation because it would necessitate (time-step) rewind of the external program. Therefore we recommend to use this coupling mechanism with shorter time steps to avoid iteration.

ACCURACY ISSUES

Coupling strategy

In the run-time coupling approach each application runs separately, while they interact through their boundaries. There are two different external run-time coupling strategies:

- quasi-dynamic coupling [Zhai, 2003], or loose coupling [Struler, et al., 2000], or ping-pong coupling [Hensen, 1999] and

- fully-dynamic [Zhai, 2003], or strong coupling [Struler, Hoefligeret al., 2000], or onion coupling [Hensen, 1999].

Accuracy as well as stability constraints limit the simulation time step length in case of the first strategy. The second strategy allows longer time steps for the same accuracy, but it requires an iteration procedure to ascertain user defined convergence criteria.

Due to the more complex inter-software iteration procedure in case of the second coupling mechanism, the first coupling strategy has been chosen for the prototype presented in this study.

Inter vs. intra time step data exchange

In terms of individual component models two main approaches can be distinguished: input-output based (each component is represented by an input/output relationship), and conservation equation based (each component is described with time-averaged discretised heat and/or mass conservation statements which are combined to form a plant system matrix, and which are solved simultaneously for each simulation time step using either an implicit, explicit or mixed numerical scheme). Advantages and disadvantages of these approaches are addressed elsewhere [Hensen 1996].

External coupling will result in different time step variable exchange depending on which approach is used, as shown in Figures 5, 6 and 7. The circles represent the component state and its output at a specific moment in time. The arrows indicate the information flow, which (in terms of location) follows the fluid flow; i.e. from sending to receiving component. By the grey boxes the placement of the external component is indicated.
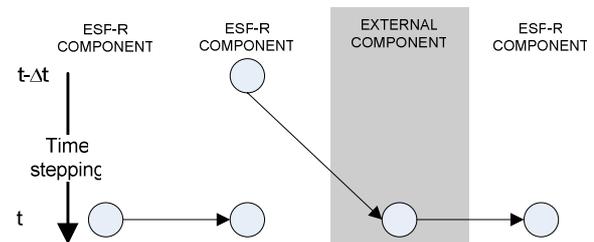

Figure 5 Inter and intra time step data exchange with an external component assuming that the base program uses a fully implicit numerical scheme

When the base program uses fully implicit numerical scheme, it solves a system of equations – a plant system matrix at each time step. However, when an external component is interconnected its dynamical and physical behavior is unknown and component-dependant. Therefore, it is not possible to uniquely define its dependences with other parts of the system and only an explicit determination of temperature, first and second phase mass flows that are calculated from the external program can be used.

Further, if the exchange of data takes place before the solving of the plant matrix, when the external program is invoked, the thermodynamic state of the incoming connection for the future time step of the component is unknown and is yet to be solved. This means that the values of the variables that describe the thermodynamic state of the incoming connection, calculated for the last time step, will be forwarded to the external program. Based on these values external

program performs the calculation and sends the data back to the base program.

Inter programs time step variable exchange will disturb the original intra time step variable exchange of the base program that uses implicit numerical scheme (Figure 5).

However, if explicit numerical scheme is used (Figure 6) the external coupling will keep the original intra time step data exchange consistent. The same applies for input-output based component modeling approach (Figure 7).
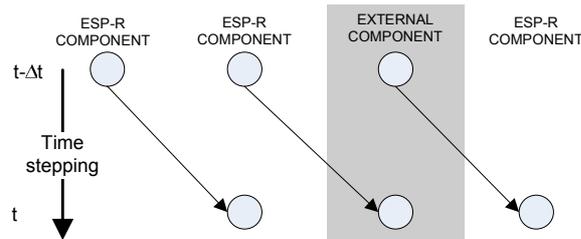

Figure 6 Inter and intra time step data exchange with an external component assuming that the base program uses a fully explicit numerical scheme
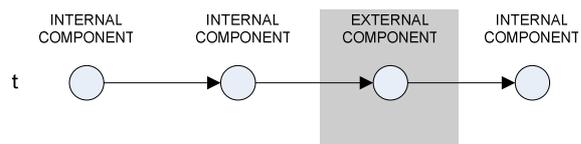

Figure 7 Inter and intra time step data exchange with an external component assuming that the base program uses an input-output based approach

However, small coupling time steps, which are required by the chosen coupling strategy (ping-pong), will result in neglecting the discrepancy between the inter and intra time step variable exchange schemas and ensure the stability and accuracy of the obtained results.

CHANGES WITHIN ESP-R

Four additional plant components have been developed within the ESP-r simulation environment in order to implement and test coupling of continuous and discontinuous running external models of either air or water systems. (Additional connections could have been used as well. However, from the solution point of view both approaches are identical. Only, a care of the order in which the connections are defined would be very important.) The mechanism for the discontinuously running external program uses intermediate files. In case of the continuously running external program, data transfer is via so-called named pipes. In both cases it would be possible to use other inter-process communication (IPC) mechanisms as well.

In case of the named pipes IPC, process blocking and synchronization is provided as part of the pipe services. For IPC mechanisms which do not provide this service, a time-stamp variable could be added to the set of exchanged data for checking and synchronization purposes.
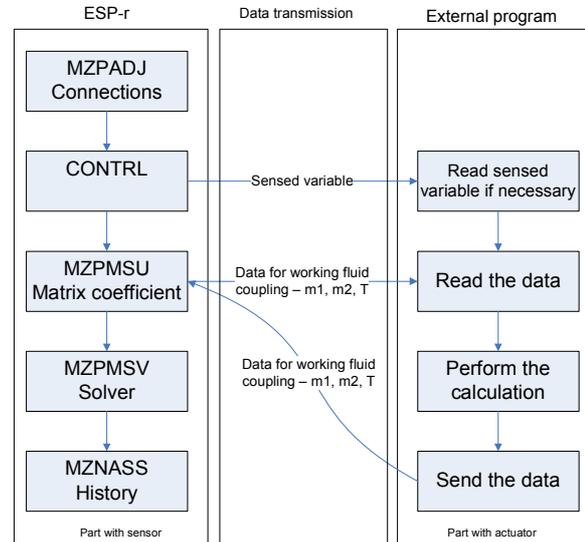

Figure 8 External coupling implementation in ESP-r within one time step

WHEN IS COUPLING NECESARRY – DECISION METHODOLOGY

The use of building simulation should be led by the problem at hand rather than by the available simulation tool. Due to the increasing requirements in terms of knowledge and skills, as well as increasing computing resources, it is generally advisable to obey the Einstein principle applied to modeling *"A scientific model should be as simple as possible, but no simpler."* In the current context this means that it is advisable to define minimum model resolution and complexity level relative to the building performance indicator or problem of interest; e.g. as in Table 1.

Table 1
Potential questions/problems in design and maintenance of HVAC systems

1	Maximum load calculation
2	Inquire about comfort condition
3	Energy consumption - gross
4	Energy consumption - global
5	Fuel consumption
6	Component effect on building energy performance
7	Fault detection and diagnosis
8	Optimisation of the control

A decision-making procedure is schematically shown in Figure 9. The numbers in the figure correspond to the questions/problems in Table 1. Each has its own minimum resolution level, which does not

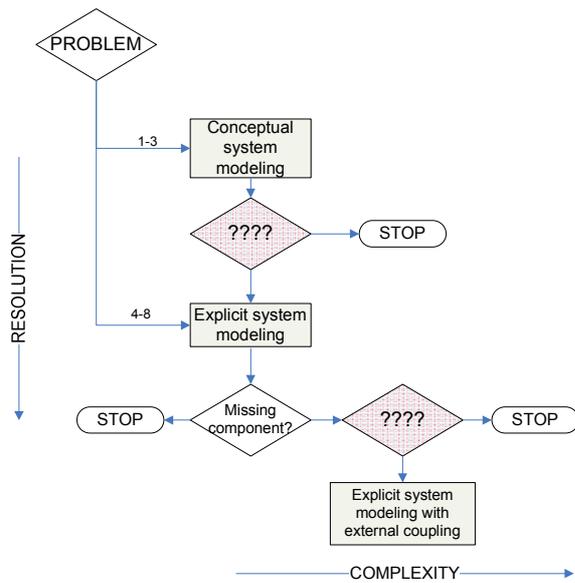necessarily have to be sufficiently accurate for a specific design at hand.

Figure 9 Flow chart of the decision-making methodology

For example, if information about maximum temperature is required (question 2), pure conceptual system modeling would initially be the minimum resolution level. If there are potentially influencing interactions between the building and system, there is a need to perform sensitivity analysis (shaded area in Figure 9), i.e. check how the range of change of interacting variables influences the performance indicators in question.

If the influence is higher than allowed then the level of system modeling should be brought one step higher on the resolution scale to the level of explicit system modeling.

However, it may happen that no model exists for one or more system components in a particular simulation environment. Going to a higher level of complexity and implementing external coupling is quite demanding. That is why the sensitivity analysis is also important when making such decision. Again, defining the range of change of coupled variables and comparing their influence on change of the values of performance parameters in interest would facilitate the decision-making process. However, such definition of sensitivity analysis would not represent influence of transient changes of coupling variables, neither is it straightforward to define the range of their change. Therefore, a simpler check for necessity is adopted in this work as follows.

Decision making methodology – external coupling of HVAC components

Firstly, the external coupling is justified only if:

- the model for a component does not exist in a particular environment,

- or the existing model is not adequate for the specific study, or

- the component represents a real building and/or system.

If justified, there are potentially two distinct ways of running the simulations of the base and the external programs: they can be coupled or decoupled. The decoupled solution means that once one program is finished the output will be redirected to the input of another program. The coupled approach requires run-time exchange of coupled data between the programs.

In open systems, if the coupling data are constant, or if they vary only as a function of input to the first part of the system then the system can be analyzed decoupled. This is not the case if the coupling data changes not only as a function of input to the first part of the system, but also by what is going on in the second part of the system. This is normal in closed systems where there is inherent feed back from the second part of the system to the first part. It doesn't matter whether the loop is closed because of the working fluid or due to control signals. There will be dynamic interactions between the components and thus coupling is required in these cases.

Table 2 shows possible interconnection cases in terms of necessity for coupling. Only in special cases a decoupled approach will be sufficient. Most cases will require a coupled approach.

TEST CASE STUDY

As an illustration, consider the greenhouse with air recirculation through an earth-to-air heat exchanger from [Ghosal, et al. 2004]. The objective here is to assess the energy saving potential of the ground-coupled heat exchanger consisting of buried pipes.
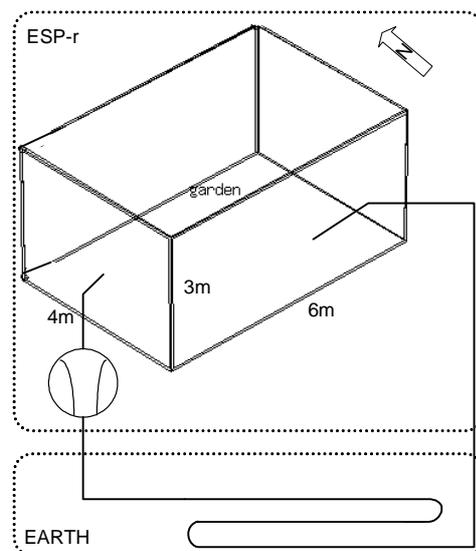

Figure 10 Greenhouse coupled to an earth to air heat exchanger

Table 2
External coupling necessity

	System sescription	Coupling data description	Sytem schema	Coupled	Decoupled
1	Open system	Function only of input data to Program 1	Program 1 SYSTEM PART I → Coupling data → Program 2 SYSTEM PART II	o	+
3	Open system	If each connection is as in 1	Program 1 SYSTEM PART I/a → Program 2 SYSTEM PART II → Program 1 SYSTEM PART I/b	o	+
2	Open system	Influenced by changes in Program 2	Program 1 SYSTEM PART I ← Coupling data → Program 2 SYSTEM PART II	+	-
4	Open system	If even one connection is as in 2	Program 1 SYSTEM PART I/a → Program 2 SYSTEM PART II → Program 1 SYSTEM PART I/b	+	-
5	Closed system	Working fluid cooupling	Coupling data — SYSTEM PART I — Coupling data → SYSTEM PART II	+	-
		Control feed back	Control data — SYSTEM PART I — Coupling data → SYSTEM PART II		
		Control feed back	Feed back — Program 1 SYSTEM PART I/a → Program 2 SYSTEM PART II → Program 1 SYSTEM PART I/b		

The greenhouse itself is modeled in ESP-r which currently lacks a model for an earth-to-air heat exchanger. EARTH, a program that models and simulates earth-to-air heat exchanger is run-time coupled to overcome this deficiency.

Some simulation results are presented in Figure 11. These are for three one-day simulations using climate data for New Delhi, India: one without coupling the external exchanger, and two coupled simulations with either 350m^3/h air volume flow rate and 50m pipe length (design 1) or 700 m^3/h air volume flow rate and pipe length 120m (design 2).

As expected, the air temperature in the greenhouse varies less when it is coupled to the earth-to-air heat exchanger. The variations are smaller with design 2. The greenhouse is heated during the night and cooled during the day. For higher volume flow rates the difference in temperatures can be as high as 7 degrees Celsius.

The variations of the outlet temperature of the ground coupled heat exchanger depend on a specific heat exchanger design and variations of the temperature within the zone. The heat exchanger and the greenhouse are strongly coupled and only by coupled simulation these interactions can be taken into account.
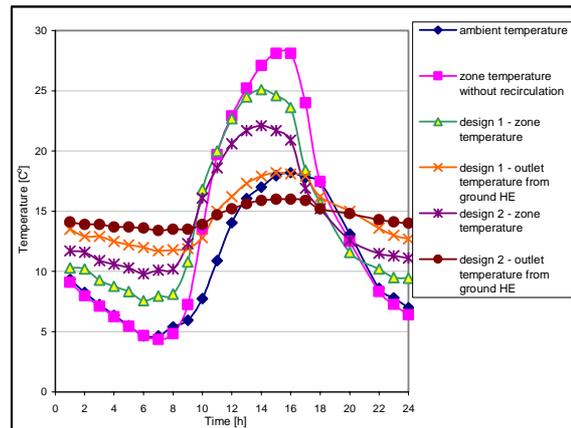

Figure 11 Air temperature profiles: ambient temperature, zone temperature for free floating conditions, zone and outlet temperatures from ground coupled heat exchanger for design 1 and 2

The heating/cooling potential of the exchanger is shown in Figure 12. It is calculated from the difference in temperature inside the house and temperature at the outlet of the heat exchanger. As can be seen, it depends on the design and varies over the day. In the early and late hours the greenhouse is heated by the earth to air heat exchanger and in the mid day it is cooled down.
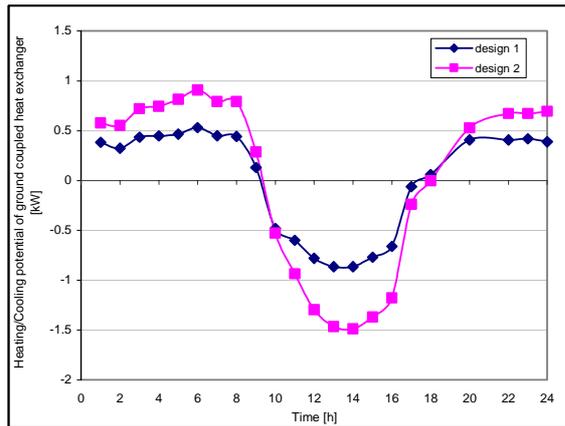
Figure 12 Change in ventilation heat capacity provided by the ground heat exchanger, calculated on the basis of difference in zone and outlet temperature of the exchanger

IN CONCLUSION

It may be argued that a simulation environment able to address all the questions which may come up in the design, operation and maintenance of HVAC systems, is like a giant puzzle. We see the work presented here as a small part of this puzzle, which aims to enable the communication between existing tools and in doing so a more flexible use of simulation.

This paper presented coupling strategies implemented in a prototype. The advantages and disadvantages of each coupling strategy and methodology were considered. The implementation of the working prototype has been demonstrated on an example case study.

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