

## Case studies of co-simulation for building performance prediction

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# CASE STUDIES OF CO-SIMULATION FOR BUILDING PERFORMANCE PREDICTION

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## Abstract

*This paper aims to illustrate the usability and benefits of recent developments in co-simulation of building systems by means of several case studies. Co-simulation enables the reuse of models developed in separate simulation tools as well as integration of generic solvers into the computational building performance simulation domain. This in turn facilitates rapid prototype modeling of new and emerging building systems, and thus early performance prediction of innovative systems and concepts, which would not be feasible otherwise.*

## Keywords

Co-simulation, External coupling, Run-time coupling, Integrated building performance simulation

## Introduction

Integrated building performance simulation can help in reducing emission of greenhouse gasses and providing substantial improvements in fuel consumption and comfort levels. This is done by treating buildings and the systems which service them as complete optimized entities and not as the sum of a number of separately designed and optimized subsystems or components. However, available tools in the domain of building performance are not equally suited for modeling and simulation of all relevant aspects and for all possible design analysis. For example, some tools are better suited for building envelope simulation (e.g. EnergyPlus, ESP-r), some for HVAC system simulation (e.g. Modelica, TRNSYS) and others for refrigeration systems (e.g. DOE-2.2 refrigeration version 49a). On the other side, as building technology evolves, there will always be a need to add a new component model into existing tools.

Previously (Hensen 1991, Hensen and Clark 2000), it has been argued that building system modeling and simulation capabilities develop slowly and take up an enormous amount of resources (time wise and financial). So, in order to be successful, tool developers need to focus on the value added by their tool. The investment in already existing should be minimized.

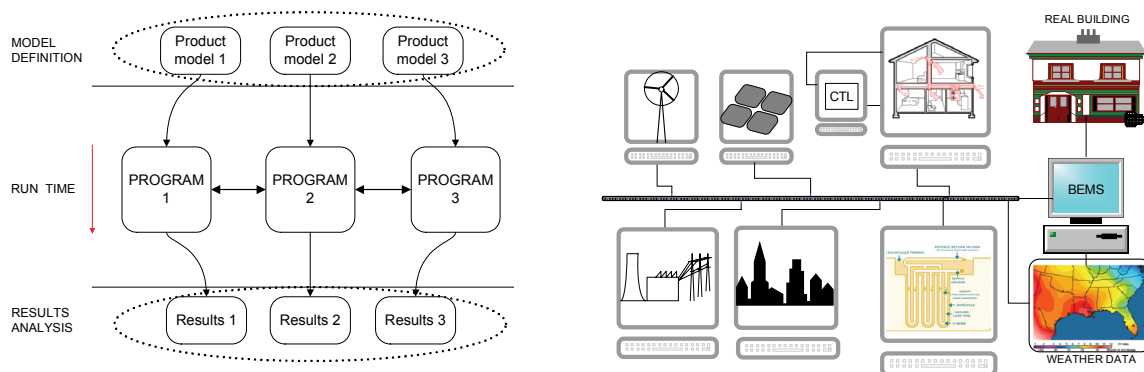


Figure 1: Right: Data flow in co-simulation; Right: Schematic representation of the approach

One way to proceed is by integrating new developments, i.e. new models and tools, with other complementary tools in such a way that the integrated result provides more value to the end user than the individual tools by themselves. This can be achieved by using co-simulation. By co-simulation, we mean a particular case of simulation scenario where two solvers, which originate in different simulators, running simultaneously and exchanging relevant coupling data at the synchronization time points, solve a coupled system of equations (Figure 1). The models in different tools can be combined as soon as they become available and thus, the combination of the tools provides a greater value to the end user than individual solvers if used separately.

A review of research and developments in co-simulation in BPS as well as other fields is given elsewhere (Trcka {Radosevic} et al. 2006a).

In this paper we briefly discuss different co-simulation implementation strategies for building and HVAC/R systems<sup>1</sup>. We will show that the run-time communication between the legacy simulation programs enables modeling across various environments, while exploiting advantages of each.

## **Co-simulation**

In co-simulation there are various issues which need to be addressed, such as the following.

### ***Decomposition strategies***

We implemented two different system-decomposition strategies. The first implementation is called *intra-domain* decomposition. As its name reflects the system is decomposed within one domain, i.e. in our case within either building or HVAC/R system domain only. The second implementation - *inter-domain* decomposition allows a system to be decomposed between different domains, i.e. the building and the HVAC/R system domain.

Intra-domain decomposition in HVAC/R domain allows distributed modeling and simulation of different pieces of HVAC/R equipment, while the intra-domain decomposition in the building domain allows distributed modeling and simulation of building structure, for example when using an externalized model of thermally activated building slab.

Inter-domain decomposition allows for example for a supermarket to simultaneously simulate the refrigerated cases and the HVAC/R system in one tool and in another the building heat transfer.

### ***Coupling strategies***

There are two different simulator coupling strategies:

*Quasi-dynamic* coupling (Zhai 2003), also called *loose* coupling (Struler et al. 2000), or *ping-pong* coupling (Hensen 1999), where distributed models run in sequence, and one model uses the known output values, based on the values at the previous time steps, of the coupled model. The feedback between the programs is lagged one coupling time step.

*Fully-dynamic* coupling (Zhai 2003), also called *strong* coupling (Struler al. 2000), or *onion* coupling (Hensen 1999), where distributed models iterate within each time step until the error estimate falls within a predefined tolerance.

### ***Stability and accuracy***

From the theoretical analysis of the co-simulation approach (which is not shown here due to the limiting length of the paper), one can conclude that even though the accuracy of co-simulation is degraded (a numerical method implementing a general midpoint rule to solve first order differential equations if partitioned has local truncation error one order lower than if non-partitioned), implementing small distretization steps good approximation to the solution of the differential equations can be obtained . Also the analysis shows that the partitioned method is zero-stable. For some partitioning schemes the method can be unconditionally stable as well.

### ***Prototypes***

Early co-simulation prototypes have been developed using TRNSYS 16, EnergyPlus (v1.2.2) and ESP-r (10.6), (Trcka {Radosevic} et al. 2006b, Trcka et al. 2007). The code of each tool has been modified to enable run-time communication with other executables.

Each tool implements the modifications that enable both loose and strong coupling with each decomposition strategy.

Different implementations were compared and the results of the comparison and recommendations for co-simulation were reported in (Trcka et al. 2007).

## **Case studies**

The potential use of co-simulation is best illustrated with case studies.

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<sup>1</sup> The approach is not limited to this domain of implementation. For example, the related work of Djunaedy (2005) tackles the similar issue but in the domain of air flow modeling and energy simulation.

### Active thermal slab

Active thermal slab systems are increasingly used in Europe (for example Melexis Telecom in De Meern, see Figure 2), but some uncertainties still remain, especially as far as the control strategy is concerned (De Carli et al. 2003). Due to its very high thermal mass (using pipes embedded in the concrete slab) the individual room control is not applicable. In most cases a zone control (south-north) is used, where the supply water temperature, the average water temperature or the flow rate may differ from zone to zone. The active thermal slab system usually runs in parallel with an air system which if the system is not designed correctly can result in cooling and heating at the same time. An example of such case was reported by Tian and Love (2006), who found out from the measurements that for the real studied building, reheat coils were activated in the interior areas to prevent overcooling throughout the year. This points out the necessity of having different control strategies not only for south-north areas of a building, but also for core and perimeter zones.

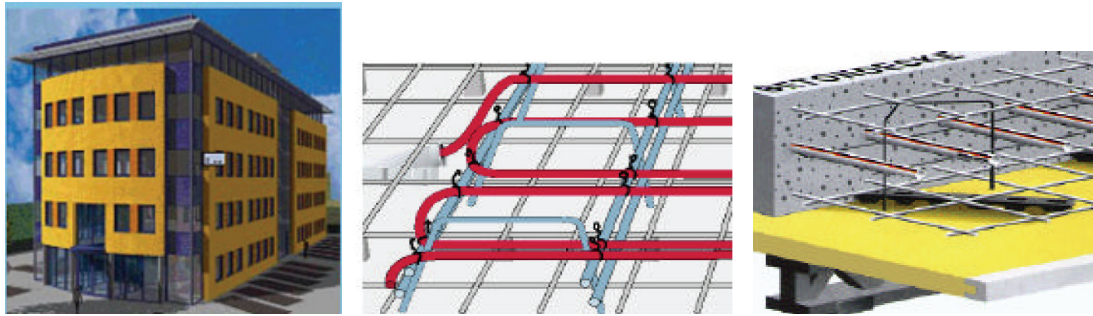


Figure 2: Left: Melexis Telecom building in De Meern near Utrecht; Right: the typical disposition of pipes in thermo-active systems (De Carli et al. 2003)

To exploit different control strategies, building performance simulation tools can be used. However, not all the tools offer the model of such system and what is offered is in general simplified and restricted in terms of control. The radiant slab heating and cooling floor component in TRNSYS 16 (type 712), although very detailed in two dimensions (in the plane parallel to the wall surface), was found to be oversimplified in the very important third dimension. Further, the EnergyPlus module, which is based on conduction transfer function method, has some deficiencies when simulating combined radiant slab cooling and air systems. The radiant system and air system can only be modeled in sequence instead of in parallel, which may differ from actual operating conditions in combined air and radiant systems (Tian and Love 2006).

To overcome the deficiencies of the above mentioned programs and enable parallel operations of two systems we have prototyped the new type in TRNSYS 16 based on the old type. The new type models the heat transfer in the third dimension using three instead of one node. Co-simulating the building in EnergyPlus and the system in TRNSYS the deficiencies of sequential system operation in EnergyPlus is also alleviated as the co-simulation does not pose such restrictions.

Here, a simple case is used to demonstrate the application of the coupled models. Two zones (one peripheral zone having windows on three sides and one attached core zone) are modeled in EnergyPlus and the system consisting of (i) an active thermal ceiling and traditional cooling/heating floors (design motivated by De Carli et al. (2003)) that circulate constant flow of water, which temperature is controlled on the basis of the ambient temperature (minimum water supply temperature is 19°C), and (ii) an constant air system with a cooling and a heating coil is modeled in TRNSYS.

The distributed models interface each other through the separate interfaces for the slab components and the air system which allows for the great flexibility of modeling the system control.

The internal heat gains are set to 1600W (60% radiative) in each zone and scheduled according to the working hours (the nominal office internal gains are adjusted to the low level reported in (Knight and Dunn 2007)).

The air is not conditioned unless the zone operative temperature rises or drops below specified points. The proportional controller is used, for heating the lower temperature is set to 20 °C and the higher to 22 °C, and for cooling the lower is 24 °C and higher 26 °C.

The original design with both pipes in the floor and in the ceiling (slab) show (climate file for Amsterdam used) that for the core zone the ventilation air does not need cooling, but some heating in the morning hours is necessary to stay within the comfort conditions (for 5 working days in summer the energy requirement is 6.4kWh). The cooling of the ventilation air for the peripheral zone was needed only in the peak hours and there was no need for heating.

The suggestion not to use the floor cooling (but only pipes embedded in the ceiling) and to limit the water supply temperature to 21°C for the core zone was made to accommodate the original design in order to avoid reheating of the ventilation air. The alternative design was evaluated again using co-simulation.

The operative temperature is higher for the alternative design option. If there is no conditioning of the supply ventilation air, the operative temperature exceeds 26°C for 0.3 degree hours. To keep the operating room temperature within the comfort requirements, the heating is not required in the alternative design option, but the cooling requirements appear, as shown on the Figure 3.

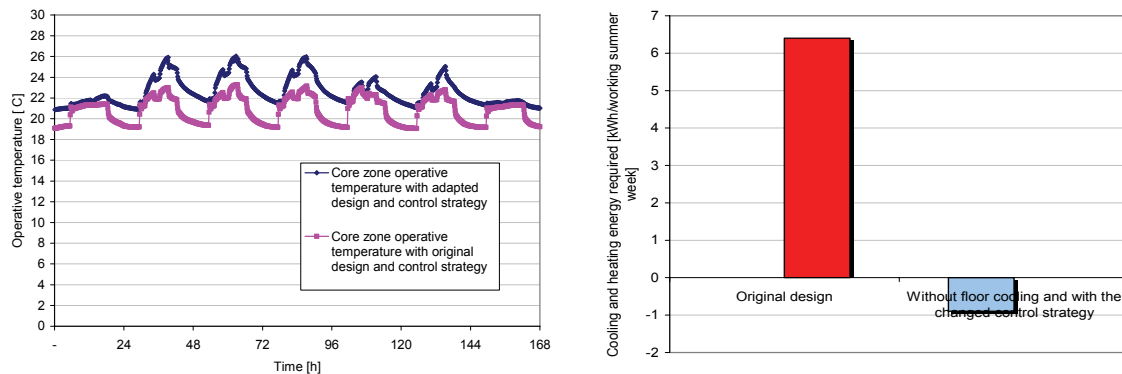


Figure 3: Comparison of original and alternative design options; Left: Core zone operative temperature; Right: Cooling and heating energy requirements for a summer week

Implementing the second design option, the energy consumption can be reduced in comparison to the original design. This study only demonstrates a way of applying the co-simulation approach by which present restrictions of the existing tools can be alleviated.

### Combination of air solar heating for desiccant regeneration and evaporative cooling

This study was inspired by the system proposed by Archibald (2001), and more detail of the system can be found in that publication. The system combines three different technologies and tries to expand their individual usability to more diverse climate conditions.

The system presented on the Figure 4 consists of a desiccant, a heat wheel, an indirect and a direct evaporative coolers and a solar tile roof. The desiccant is regenerated using the hot air from the roof solar system. The hot dry air is then first cooled down in the heat wheel, and then split into two streams. The first stream supports an indirect evaporative cooling of the second stream without adding any humidity to the first stream. The final direct evaporative cooling the temperature and humidity to any point in order to meet the desirable room conditions.

The exhaust air is firstly cooled in the direct evaporative cooler and then passed through the first section of the heat wheel. As the exhaust volume flow rate is lower than the air flow being cooled in the wheel, an extra volume of ambient air is brought to the first section to meet the cooling requirements. The warmer ambient air can then be directed into the solar thermal tile roof system. An additional amount of the ambient air may be necessary to meet the desiccant regeneration requirements. The excess heat from the desiccant wheel can also be used for heating the water for the domestic use to improve the system performance. This is however not considered in this study.

Supplemental gas heat can be added if necessary to support desiccant regeneration during cloudy days, and possibly early evening cooling hours, or other hours when solar heating is not 100% effective at delivering cool dry air for cooling or dehumidification. Desiccant evaporative cooling system with solar regeneration explores benefits of the indirect evaporative heat exchanger, but at the same time consumes more fan and possibly heating energy to regenerate the larger volume of desiccant in the larger wheel.

The comparison study between the system using the traditional compression chiller only, and the alternative system from the Figure 4, without water heater and supplemental gas heat, is done.

A ground floor office (6m x 8m x 2.7m) is modeled in EnergyPlus. Internal gains are set to only 15W/m<sup>2</sup> and are scheduled according to the office hours. The air solar collector model is not available in EnergyPlus, thus the system modeling in that tool is not feasible. Co-simulation however enables us to couple the building model in EnergyPlus with the system model in TRNSYS. Both the traditional and alternative design system options are modeled and simulated in TRNSYS.

The simulations are performed for a summer week and using Chicago climate file. The flow rates in the alternative design approach are not changed. The time step was as low as 1min.

The diagram on the right of the Figure 4 shows the results of the comparison. As it can be seen, due to high pressure loss in the system, and thus required power consumption for the fans, the energy requirements for the

alternative system design is greater than for the system using simple compression chiller cycle. At the same time, the set point temperature is not met by the alternative design. The office temperature exceeds 26°C for 208 degree hours during the simulated period if the combination of solar air heating, desiccant wheel and evaporative cooling is used.

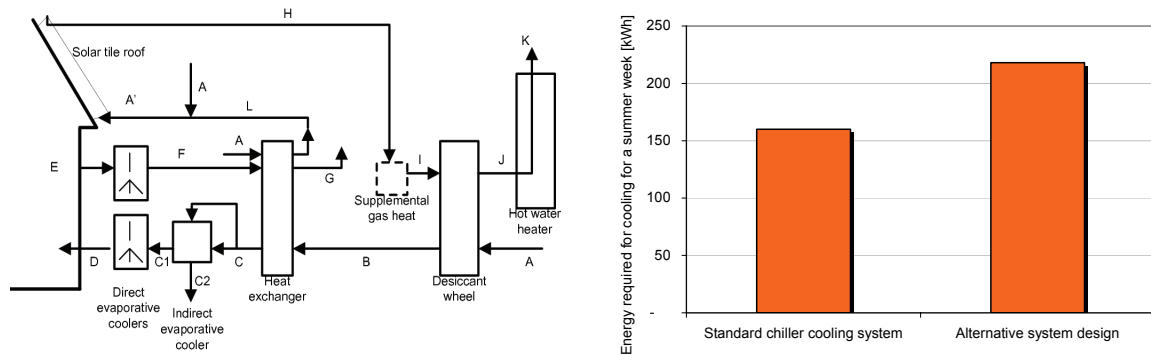


Figure 4: Left: Schematic of the system with solar air collector, desiccant wheel, recovery wheel and direct and indirect evaporative cooling; Right: Energy consumption for cooling for a summer week (Chicago) for two alternative design options

### Earth-to-air heat exchanger coupled to a building

A low energy building in Korea (Yoon et al. 1997) (Figure 5) includes an earth-to-air heat exchanger for pre-heating or pre-cooling fresh air supply, depending on the season. The building incorporates a double-skin south facade, which can act as a solar collector for additional preheating of supply air. In the summer this is bypassed to avoid overheating of the air. In that case the double-skin facade is naturally ventilated. The transient solar behavior and the dynamic nature of the double-skin façade and the ground-coupled heat exchanger affect the building heating and cooling load in a very dynamic way.

The building, including the double-skin façade, is modeled in ESP-r, and the earth-to-air heat exchanger is modeled in another tool called EARTH. Both simulation programs have undergone minimal code adaptation.

This case study involved comparison of the energy-saving potential of several design options of the earth-to-air heat exchanger coupled to the double-skin façade. The simulations assume Korean climate and a period of one winter week. Additionally, the results are compared to those obtained from the approach used in Yoon et al.(1997). There, a simple earth heat exchanger model that uses monthly constant value for the temperature of the air entering at the bottom of the double-skin façade was used. It was estimated that this temperature is equal to the ground temperature, evaluated in Equation 4.

$$T_{g,i} = T_{o,i} + 0.5(T_{m,i} - T_{o,i}) \quad \text{Eqn. 4}$$

where:

$T_{g,i}$  = monthly mean ground temperature;

$T_{o,i}$  = annual mean ambient dry bulb temperature and

$T_{m,i}$  = monthly mean ambient dry bulb temperature (Yoon et al. 1997))

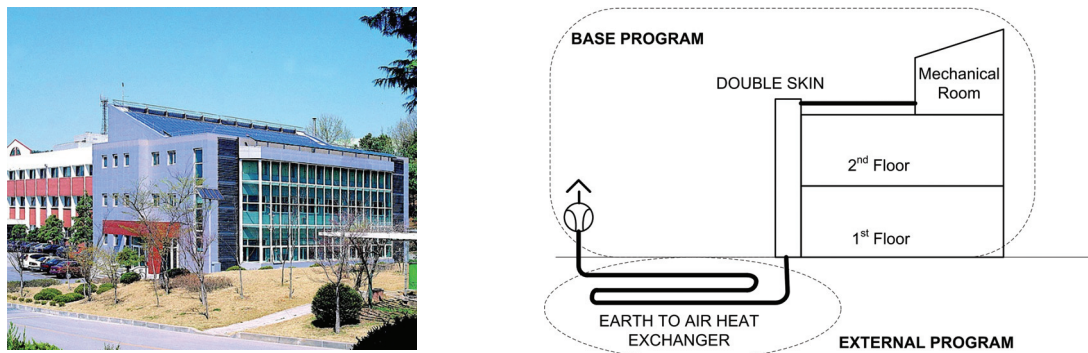


Figure 5: Low energy building in Korea

Different design options are simulated with two volume flow rates: (1) lower - 0,25m<sup>3</sup>/s that would be sufficient for ventilation of the building, and (2) higher - 1m<sup>3</sup>/s, and the results from co-simulation and those obtained by using simplified monolithic simulation approach are compared.

The design volume flow rate resulted in pipe velocities between 2 and 8 m/s. The pipe depth was kept between 1.5 and 3 m and the pipe length between 30 and 150 m. A one-pipe heat exchanger was used in case of the lower volume flow rate, while four parallel tubes were considered for the higher volume flow rate (for details see Tables 1).

The gross heat gain by both the ground-coupled heat exchanger and the double skin is evaluated from the difference between the ambient temperature and the temperature at the upper part of the double skin. It was assumed that system operates between 8 a.m. and 19 p.m. In some hours the heat gain is higher than the overall loss of the building itself. The minimum of these two values at each point in time were used to assess the energy-saving potential. The results are shown on the Figure.

TABLE 1.

*Design parameters for different design options and lower volume flow rate*

	Design1	Design2	Design3
Depth [m]	1.5	2.5	3.0
Length [m]	30.0	70.0	150.0
Radius [m]	0.2	0.11	0.12

The temperature difference of the incoming air at the bottom of the double skin does not have significant influence on the overall result in the first case (Figure 6). With the lower volume flow rate, the ventilation loads have less impact on the resulting temperature of the double skin compared to solar heat gain and loads due to conduction through the construction. However, if the volume flow rate is increased, (Figure 6) the temperature difference of incoming air will have much more impact on the simulation results.

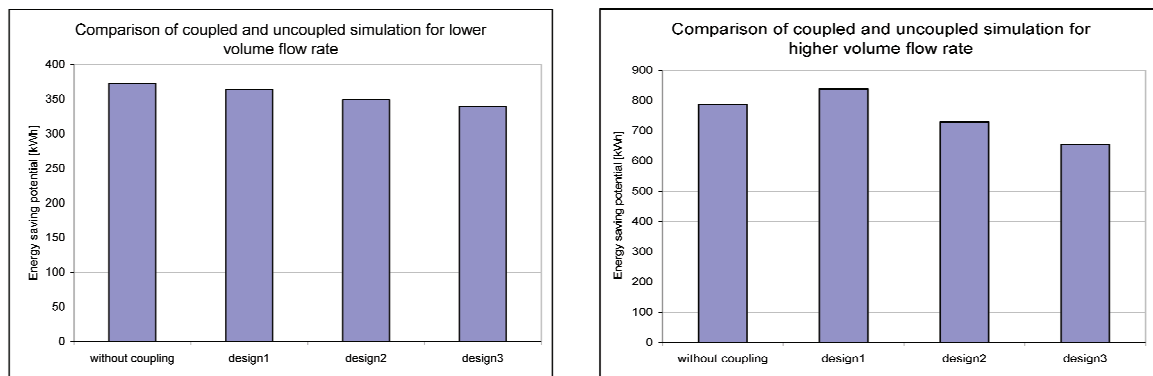


Figure 6: Left: Estimated weekly energy saving for several design option and lower volume flow rate, including the result for the uncoupled simple earth-to-air modeling approach; Right: Estimated weekly energy saving for several design options and higher volume flow rate, including the result for the uncoupled simple earth-to-air modeling approach

It can be concluded that for low volume flow rates, the simplified model reasonably well predicts the energy-saving potential (in this specific case the difference is less than 10%). In this particular case the incoming temperature, hence, earth-to-air heat exchanger itself, does not have a big influence on the results. However, the simplified, monolithic approach does not allow evaluating the influence of different design options when the volume flow rate is higher. The deviation here rises up to 25%. The co-simulation approach is necessary to predict the energy-saving potential in this case.

### **Fuel cell example**

Legacy building performance tools, such as ESP-r and EnergyPlus are not easy to use if something (new component or subsystem) needs to be prototyped quickly. However, tools such as Matlab, Modelica, or even TRNSYS (in some cases) are suitable for fast prototyping.

An example is a big retail store in US. The building envelope model was already available in EnergyPlus, and an evaluation of fuel cell heat usage needed to be investigated in an integrated fashion. Due to the lack of the fuel cell model in EnergyPlus the analysis would not be feasible without co-simulation. Instead of expanding the capabilities of EnergyPlus, a quick prototype of the fuel cell thermal capacities was made as a function of

the incoming water temperatures using the equation adding mechanism in TRNSYS. Co-simulation approach allowed the system performance prediction using already existing building envelope model.

## Conclusions

We showed how legacy BPS tools can be linked in co-simulation and how the co-simulation adds the value to the end-user. For example, a building can be modeled in different domain simulation tools, such as ESP-r and EnergyPlus, taking advantage of the latest developments on the building side. A coupled HVAC/R system can be modeled in one of the drag-and-drop environments, such as TRNSYS or Modelica, making the overall modeling process easier and faster, and exploiting the application of advanced controllers and innovative building components/systems that are difficult or not feasible to model in the previously mentioned tools. The end-user is able (i) to combine features/options between available tools, (ii) to use equation based tools to quickly prototype new technologies and (iii) by that enlarge the applicability scales of individual tools.

The simple case studies presented in the paper, demonstrated the benefits of the co-simulation approach. We were able to predict behavior of systems which could not be done using one single tool (EnergyPlus) due to the lack of a subsystem model or due to the limitation in control modeling flexibility, by coupling it to another tool.

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