A NEW CO-SIMULATION ARCHITECTURE FOR MIXING DYNAMIC BUILDING SIMULATION AND AGENT ORIENTED APPROACH FOR USERS BEHAVIOUR MODELLING

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ABSTRACT

This paper deals with an interoperability solution based on co-simulation that ensures tools collaborative working for building's global simulation. The proposed solution couples two specialized tools from different domains and characterized by different modelling approaches in order to simulate a low energy building. A dynamic thermal envelope model in SIMULINK is coupled to a multi-agent based occupants' behaviour model realized in BRAHMS. The co-simulation of these two tools has been established to take advantages of their specific capabilities for a detailed simulation using physical and inhabitants' behaviour (cognitive abilities) models. This work is realized to simulate an efficient building control, taking into account the system's complexity. A co-simulation architecture based on software component standard is also proposed. The use of this technique helps to unify programming interfaces of several BPS[1] tools in order to facilitate and generalize co-simulation use cases.

KEYWORDS: **Co-simulation, software component, human behaviour, multi-agent modelling.**

INTRODUCTION

In order to reduce energy consumption, to respect national and international restrictions and to better manage the electrical grid, many resolutions have been taken in the buildings' field; as it is the most energy consuming domain. These actions can be synthesized around two principal concepts:

- Low energy buildings: In these buildings actions comprises of improving buildings' insulation and using efficient energy systems (double flow ventilation, heat exchangers…).
- Smart buildings: In such buildings the energy management is more and more entrusted to automated systems named BEMS[2] (Nikolaou & al., 2004) that generate loads reports and facilitate energy exchange with the grid.

These evolutions have led to the development of more efficient buildings in which internal actors like occupants became more and more influential as they take part in the buildings' heating due to their thermal import i.e. the thermos effect. This role is beneficial in winter as it reduces energy bills. In the summer, however, it deteriorates comfort resulting in more energy use for air conditioning.

Moreover, the introduction of BEMS to ensure an efficient energy management requires a global modelling of the whole building taking into account its different actors, especially internal ones e.g. the occupants and their interactions.

The need to establish a global simulation is confronted to BPS tools' limitations. These tools allow a satisfactory thermal envelope modelling, HVAC[3] system studying and energetic analysis; however, they are not adapted for occupant behaviour modelling.

In fact, the need for global modelling taking into account occupants' behaviour and interactions has recently emerged, whereas most of the building simulation programs were developed 20 to 40 years ago (Attia, 2011).

In this paper, we demonstrate BPS tools' limitations and propose an efficient solution based on the co-simulation for occupants' modelling with dedicated tools.

BUILDING'S OCCUPANTS MODELING: ACTUAL LIMITATIONS AND PRPOSED SOLUTION

Occupant importance on building simulation and BPS tools limitations

So, in this new context of efficient and smart buildings, occupants have more influence on buildings' thermal behaviour then on the global energy balance (Turner & al., 2008). This influence can be classified under three main categories:

- Thermal power injection: occupant produce thermal power that participates in heating up the building.
- Action on its equipments like laptops, lights, heaters…: The occupant can act on building's equipments and then influence its thermal sources.
- The envelope structure modification: by opening and closing its doors and windows.

[1] Building Performance Simulation
[2] Building Energy Management Systems
[3] Heating Ventilation Air conditioning

On the other side, occupants' comfort becomes more important in office design studies and must be taken into account during the design phase (envelope, equipments and control strategies) to avoid expensive modifications at a later stage.

For these reasons, newly developed tools give more emphesis on occupants' modelling. Nevertheless, several existing BPS tools, mainly dedicated for envelope simulation, are neglecting the occupant modelling and do not take into account the variation and the complexity of its behaviour (Hoes & al., 2009). These tools do not completely neglect this actor since they generally take into account his thermal power through predefined scenarios. This method is based on predefined occupancy and thermal power profiles that can be derived from occupants traces (energy consumption or CO2 measured) or schedules and also from real behaviour observation (observation, questionnaires (Le & al., 2010). These profiles are widely used in BPS tools like TRNSys (TRNSys, 2007), Energy Plus (Holly & al., 2009), ESP-r (Bourgeois, 2005) and COMFIE (Peuportier & al., 1990) (Gaaloul & al., 2012).

Although it allows an easy description able to represent a realistic behaviour of users, this method does not take into account the variation and the complexity of user's behaviour, nor his interaction with its environment. The static profile based simulations are not compliant with the current need for global energy simulations, because they neither respect the users' comfort nor accommodate the new situations.

The occupants are a major source of uncertainty in building's energy consumption where its variation can considerably affects results. In fact, Clevenger and Haymaker's study (Clevenger & al, 2006) shows that estimated energy consumption can be changed by more than 150% when using two different typical profiles of occupant behaviour and also that "Relationships and dependencies exist between parameters (loads and schedules) that may further contribute to variability in energy modelling results".

That is why more detailed occupant's behaviour modelling methods should be used in order to ensure more precise energy estimation and robust control strategies. These objectives can be achieved by using multi-agent based modelling methods. These method are based on agents' states and behaviour rules to simulate different occupants' behaviours by changing their characteristics and interactions.

Occupants' multi-agent modelling

The multi-agent modelling is widely used in complex environments characterized by complex interactions between multiple agents (Gilbert, 2004) (Bertels & al., 2001). It is used for various purposes like prediction (e.g. demographic changes, consumer behaviour), understanding errors (e.g. nuclear disasters), design (e.g. evacuation), and entertainment (e.g. video games).

This technique establishes users' behaviour rules by using autonomous agents (agent based modelling) that automatically computes their behaviour, without following predefined profiles. These agents are more interactive as they interact with other agents and with their environment.

Software agents described in a multi-agent environment have the distinction to be:

- Autonomous: they decide what action they will perform (distributed decision-making Ability (Schneeweiss, 2003), by referring to fixed rules....
- Receptive and reactive: they are aware of their environment and able to respond and react to its objects.
- Able to communicate: can send and receive messages from other agents.

Although the agent based modelling was already used to assist BPS tools (Erickson & al. 2009) (Azar & al., 2010)…, the use of multi-agent frameworks has recently started but its use still limited (Klein & al., 2011) (Le & al., 2010).

In computer science, several multi-agent environments have been developed and can be used for buildings' field e.g. JADE (jade.tilab.com), Repast (repast.sourceforge.net/repast_3/index.html) or BRAHMS (www.agentisolutions.com/) etc.…

BRAHMS is chosen for the study done in this paper to ensure a multi-agent modelling of occupants' behaviour for several reasons. Besides its modelling approach's characteristics that will be described in the next section, this tool allows agent building (unlike repast) and presents a simulation structure (unlike Jade) (Castro, 2010).

BRAHMS tool for occupant modelling

BRAHMS tool is an agent platform that can be used for occupants' behaviour simulation. The feasibility and the usefulness of using this tool in buildings' applications has been already proven in Kashif's work (Kashif & al., 2011).

Human behaviour is modelled in BRAHMS according to to the BDI[4] (Belief, Desire, and Intention) structure (Georgeff & al., 1998). An agent (e.g. occupant) is defined, in the context of a group of agents, by its thoughts (e.g. feeling hot), activities (e.g. moving) that can be linked with other objects (e.g. turning off the heater), knowledge, geographic location and time constraints that determine its behaviour (Figure 1).

Agent's behaviour can be described in a deterministic or, more used in building simulation, in a stochastic way (Parys & al. 2011) (Haldi & al., 2011) by specifying the probability of occurrence of a given action.

[4] Belief, Desire, Intention

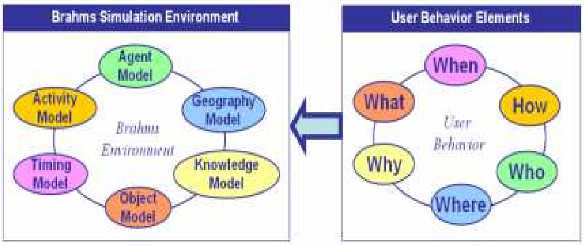

Figure 1: Agent modelling approach in BRAHMS environment

For these reasons, the use of BRAHMS for building's occupants behaviour modelling will allow more detailed global modelling that benefits from the multi-agent approach capabilities by the use of autonomous, reactive and deliberative agents.

Co-simulation solution

As many tools have already been developed and several users are used of using them, it is more practical to adapt existing ones rather then redeveloping new tools.

Nevertheless, changing these tools requires significant efforts in terms of methodology as well as programming, however, there are other existing tools that could be complementary, such as the BRAHMS software.

That is why; the co-simulation represents an efficient solution that is able to ensure the coupling between existing BPS tools and dedicated occupant behaviour ones in order to benefit from their mutual capacities. This co-simulation can be realised directly between two tools (master-slave technique) (Trcka & al., 2007) or by using dedicated environments like the BCVTB[5] (Wetter, 2011).

As an illustration of these technique, a co-simulation will be realised in this paper, between MATLAB/SIMULINK (www.mathworks.fr) that implements a classical model of a thermal envelope (electrical equivalent circuit), and BRAHMS that implements a multi-agent occupant model.

The co-simulation offers several advantages like (Fujimoto 2003) (Trcka & al., 2006):

- A collaborative work: by using multiple tools specialized in different areas and thus going beyond existing ones (like BPS tools).
- Combining multiple modelling paradigms like a multi-agent approach (BRAHMS: occupants) and differential equations (ODE[6]) (SIMULINK: dynamic envelope model).
- Easy maintenance and improvement because models are dynamically reconnected to the system due to the co-simulation structure.

These advantages will be shown through a use case of an efficient building simulation: the "PREDIS" building (Gaaloul, 2012). We will focus on the established co-simulation architecture and different interactions between occupants' and the building's envelope.

USE CASE STUDY

Building description

In this part, the PREDIS smart building will be used to illustrate occupant's behaviour influence on building simulation. This building was constructed under another building in order to reduce external factors impacts (outside temperature, solar fluxes, wind…). PREDIS is a low energy building (efficient insulation) which makes it sensible for internal actors' variation.

It is composed of two principal thermal zones: a research space for researchers and a computer classroom. Two PhD students working in this platform will be studied with a focus on their interaction with each other and with their environment. These students are moving in the building, using laptops and acting on the heating system.

Envelope modelling

The research space envelope is modelled in SIMULINK by an equivalent electrical circuit (Figure 11 at the end of this paper) which parameters are identified from measurements, collected and stored in the energy management system (Dang & al., 2013). The neighbouring area temperatures (voltage sources: Tinfo, Tshed…) are also issued from measurements whereas internal flows (current sources) will depend on occupants' behaviour as a result of BRAHMS simulation. These fluxes corresponds to:

- *Phichauf*: heating loads.
- *Phielec*: electrical systems thermal loads (only laptops are considered).
- *Phiusage*: occupants' thermal load.

Occupants' modelling in BRAHMS

Due to BRAHMS modelling capabilities, this scenario can be implemented:

PREDIS occupants are able to move from a room to another (→ internal power modifications) depending on their profile and the simulated time. When they are in the research space, they use principally their laptops and act on the heater (→ action on equipments).

They can also turn off the heater when they feel hot (→ reactive agents) when the perceived temperature exceeds tolerated levels (→ receptive) (22° for PhD student 1) (23.5° for PhD student 2) (Figure 2).

[5] Building Virtual Control Test Bed
[6] Ordinary Differential Equation

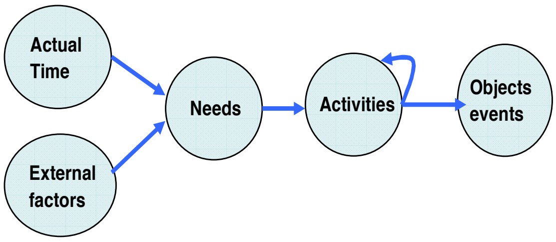

Figure 2: Inhabitant behaviour evolution in BRAHMS

However, this action on the heater requires taking other inhabitants' approval (Figure 3), which induces a mutual communication between these agents (→ deliberative agents) to communicate their needs and intentions before doing some activity (Figure 4) (Brahms, 2008). The other agent can accept or decline this request depending on its comfort (tolerated temperature level).

```
workframe wf_ReactionResearchSpaceHighTemperature {
  repeat: true;
  priority: 1;
  when(knownval(current.wantToTurnOffHeater = true)
  and knownval(PhdStudent2.location = ResearchSpace)
  and knownval(PhdStudent2.acceptToTurnOffHeater = true) )
  do
  {
    conclude((current.wantToTurnOffHeater = false), bc:100, fc:100);
    conclude((current.communicationStarted = true), bc:100, fc:100);
    conclude((objectResearchSpaceHeater.newState = extincted), bc:100, fc:100);
    simpleActivity("Extinct the heater",1);
  }
}
```

Figure 3: Turning off the heater conditions in BRAHMS

```
communicate communicateDemandToTurnOffHeater() {
  max_duration: 1;
  with: PhdStudent2;
  about:
    send(current.wantToTurnOffHeater);
  when: end;
}
```

Figure 4: Communication between two PREDIS agents in BRAHMS

The BRAHMS virtual machine will decide on events depending on their priority order.

Global modelling

The interaction between occupants and the building envelope, described in the previous scenario, is implemented in SIMULINK. The following figure represents the global simulation schema in SIMULINK (Figure 5).

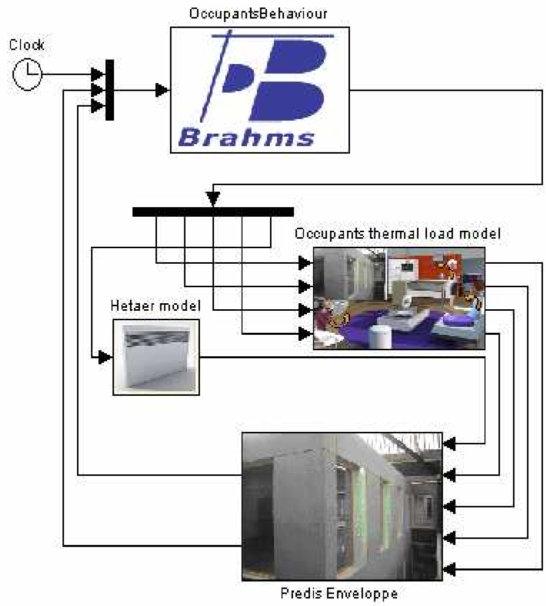

Figure 5: co-simulation schema in SIMULINK

Simulation results

A simple fixed step co-simulation strategy (60 seconds) was adopted to ensure this orchestration, as the purpose of this paper is not to study advanced algorithms. Results obtained are shown in the following figure (Figure 6).

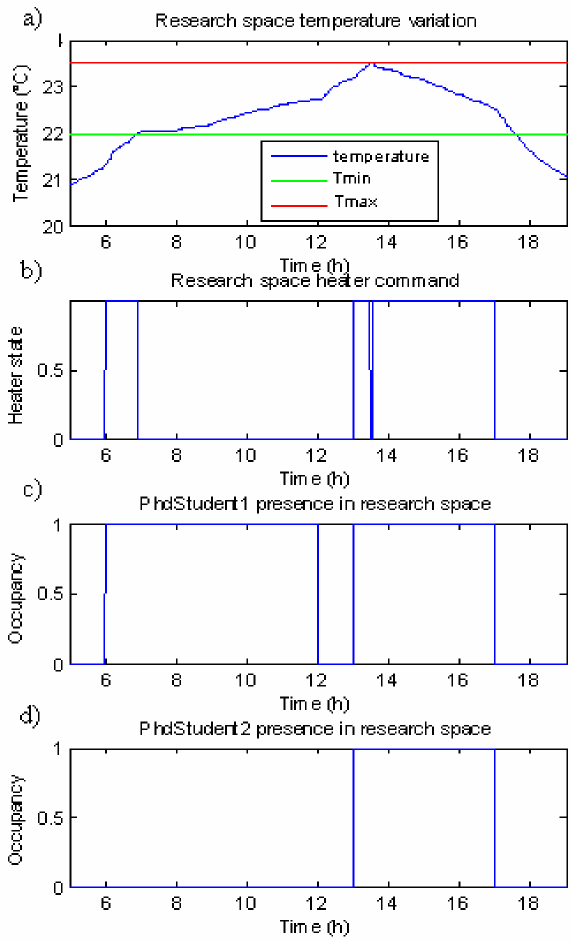

Figure 6: co-simulation results

In the graph 6(a), we can observe the temperature variation: Tmin and Tmax represents respectively the maximal tolerated temperature levels respectively for Phd student 1 and PhD student 2 at which they start feeling hot and want to turn off the heater. A slight increase can be observed when an occupant comes in the research space, which is due to its power and laptop (about 100 W). As the heater power is more important, the observed temperature' increase is higher.

In the first part of the working day (from 6 am to 12 am), the PhD student 1 is working alone on the research space 6(c), so he decides independently for the heater state. When the inside temperature reaches Tmin level, he automatically turns off the heater 6(b) i.e. around 7 am. At that time, even if the heater is turned off (its power is never injected in the building envelope) the temperature keeps growing due to its surrounding areas' high temperatures.

In the second part (from 1 pm to 5 pm), the PhD student 2 joins the PhD student 1 in the research space 6(d). In this case, the heater is only turned off when PhD student 2 gives his approval i.e. when temperature level reaches Tmax.

Before leaving for a long period, any PhD student turns off the heater. This is what happens at the end of the day (5 pm).

Various profiles can be then studied and their impact on energy consumption can be compared, taking into account their interactions.

The simulation of one day (24 h) of the whole-system has taken about 25 minutes. This is because of a slow communication between SIMULINK and BRAHMS (essentially stopping and resuming the BRAHMS virtual machine), which multiplies the simulation duration by ten. Therefore, even if the co-simulation solution presents several advantages (easy to establish, to maintain…), it slows down the simulation significantly.

Use case improvements

As said previously, a co-simulation between two tools makes it easier to improve the models. In fact, to improve occupants' behaviour models, it is sufficient to modify their description in BRAHMS and then re-launch the co-simulation.

For example, occupants' activities, in this use case, were deterministically described. A stochastic description can be easily performed by changing events' probabilities, by modifying "*bc*" i.e. belief certainty value (Figure 3). So, when temperature level limits are reached, the heater can be turned off or not depending on the fixed probability.

PREDIS occupants are also able to modify the thermal envelope structure by opening the door (when they have hot sensation). This action induces "*Rp*" value modification (infiltration resistance) as presented in the figure 11.

CO-SIMULATION ARCHITECTURE

Co-simulation based on software component standard architecture

A simulation tool can play the role of a co-simulation actor if it can provide communication interfaces with its solver. However, interfaces provided by different tools are very different in terms of syntax and data nature…, which requires a special treatment and development for each studied case. For example, the implementation of a co-simulation between an orchestrator X1 (master) and two actors X2 and X3 (slaves) is usually made separately (Figure 7 left): form one side, the connection between X1 and X2 and the connection between X1 and X3 from the other side.

In order to facilitate and generalize co-simulation implementation, a technique based on software component standard can be used. A software component standard dedicated for co-simulation consists essentially on a normalization of communication interfaces. It will make their use in other environments easier, more automated and more generic.

In this way, the co-simulation treated previously can be developed as follows: X2 and X3 are encapsulated in two software components due to dedicated plug-outs (Gaaloul & al., 2011). Therefore, they will have the same communication interfaces that will be called by X1. That is why it is sufficient to develop a single software component connector to X1 (plug-in), that will allow the communication with both X2 and X3 (Figure 7 right).

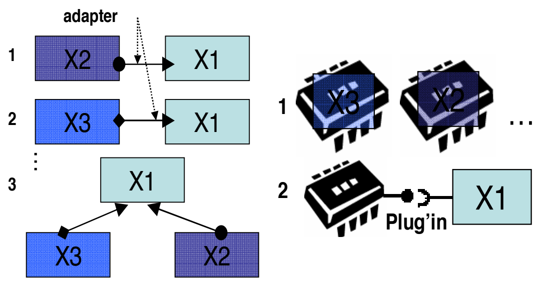

Figure 7: Co-simulation without and with software component standard use

Several communities have identified the need to make actor's standardization to facilitate co-simulation implementation. In the automotive sector, for example, considerable efforts have been made to allow collaborative work between several partners, that led to the development of the FMI[7] standard for co-simulation (www.fmi-standard.org). Other co-simulation standards have also emerged in other communities e.g. OpenMI[8] for hydraulics (www.openmi.org) and CCA[9] (www.cca-forum.org)

[7] Functional Mock-up Interface
[8] Open Modeling Interface
[9] Common Component Architecture

for applications requiring large computing capacity like earth science.

For many reasons that will be explained later, the ICAr[10] standard (Delinchant & al., 2004) will be used to ensure the co-simulation between BRAHMS and MATLAB tools in the specified use case.

ICAr component standard use

The ICAr standard was initially defined for electrical engineering fields but was, after that, adapted and adopted for building simulation field (Gaaloul & al., 2011).

This multi-facet pattern is able to offer several services like optimisation, predictive control and simulation. A specific facet dedicated for co-simulation has been defined to be able to support co-simulation actor's (Gaaloul & al., 2012) (Figure 8).

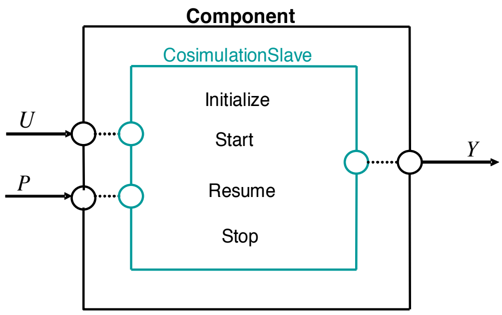

Figure 8: ICAr component facet for co-simulation (U: inputs, P: parameters and Y: outputs)

Besides its generic structure (multi-facet), the ICAr standard has the specificity to be java described unlike FMI standard (C) or openMI (C#). The Java language offers to ICAr norm portability capabilities: platform independency and compatibility with web services technologies and OSGI[11] (Delinchant & al., 2012).

Moreover, as BRAHMS is based on Java language, its encapsulation in a Java software component was easier. The use of JNI[12] is not then required, which will avoid not only connecting difficulties but also portability deterioration (by native libraries import).

This co-simulation facet, adapted for several orchestration will be used to encapsulate the BRAHMS tool and import it in MATLAB, thanks to dedicated and automated plug-out and plug-in.

Co-simulation establishment: BRAHMS plug-in and MATLAB plug-out

BRAHMS offers several Java APIs[13] (JAPI) to control its solver BVM (Brahm's Virtual Machine). So its dedicated plug-out consists of syntax adaptation between BRAHMS and ICAr interfaces (Figure 9).

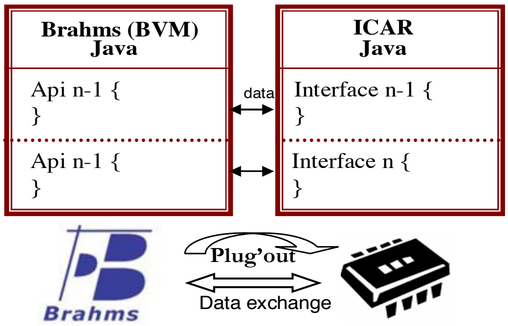

Figure 9: BRAHMS plug-out

On the other side, MATLAB tool owns its proper virtual machine, which remarkably facilitates the Java component ICAr import at its interfaces call from the corresponding S-function in SIMULINK (Gaaloul & al., 2011) (Figure 10).

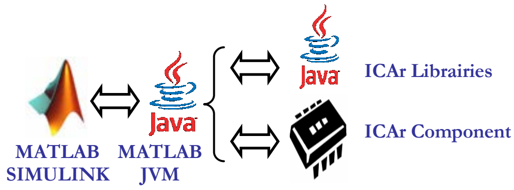

Figure 10: MATLAB plug-in

Software component standard-based architecture advantages

The used technology offers generic co-simulation architecture. In fact, a developed plug-out generates a software component that can be used in several tools that support the ICAr standard. On the other side, a developed plug-in is able to import any co-simulation component.

These programmes (plug-in and plug-out) allow component import and export automation. Even if their development can be hard, their use afterwards is automatic.

CONCLUSION

This paper has shown, through a specified use case of coupling between MATLAB and BRAHMS tools, co-simulation interests and its capacity to go beyond BPS tools' limitations at occupants' behaviour modelling level. This co-simulation has also ensured the coupling between two different modelling paradigms i.e. multi-agent and ODE.

A technology based on software component standard has been explored. This technique has several advantages as it offers generic and automated architecture.
Several plug-ins and plug-outs have already been developed from and to BPS tools in order to construct a rich software component bus. In future works, we aim to develop other connections with other tools like EnergyPlus and BCVTB, in order to benefit from their complementary capabilities.
In this paper, we have demonstrated software component-based architecture' benefits in the building simulation field. As a perspective of this

[10] Interface Component Architecture
[11] Open Services Gateway Initiative
[12] Java Native Interface
[13] Application Programming Interfaces

work, several control strategies will be tested regarding different occupants' profiles and their real impact on energy consumption will be studied.

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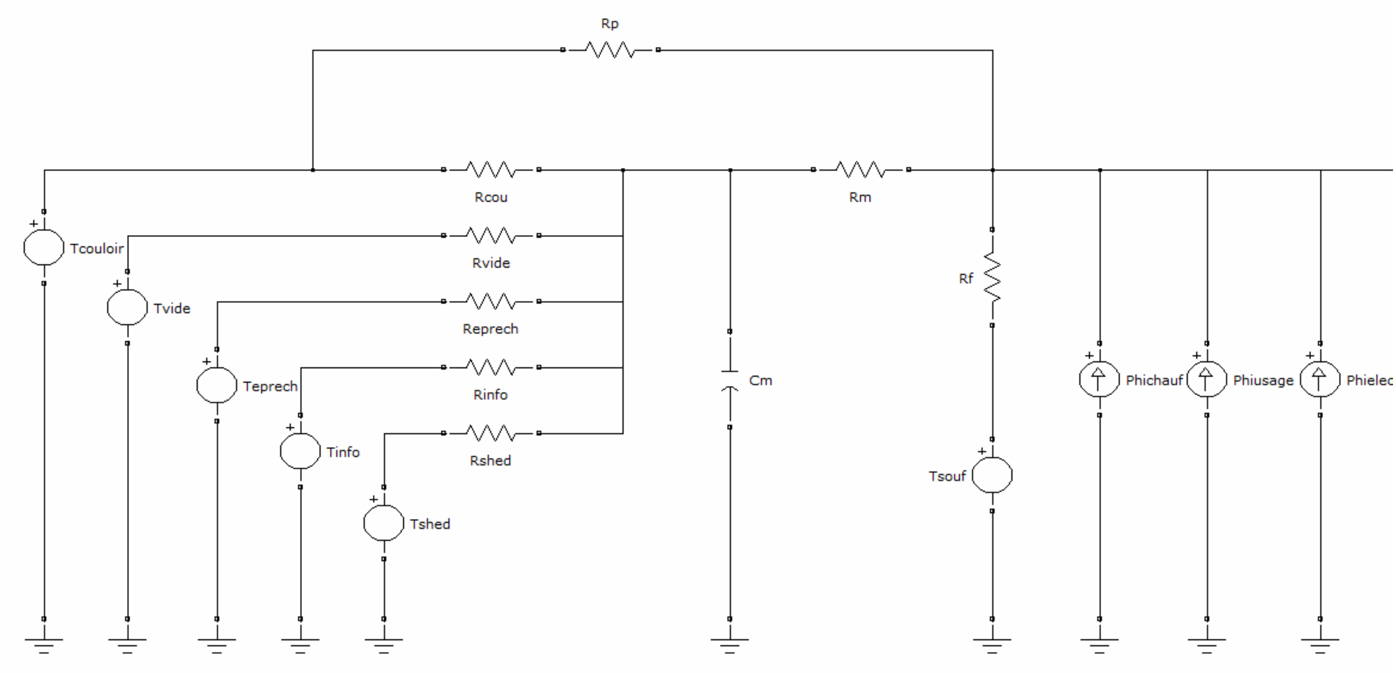

Figure 11: PREDIS Research space thermal model