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ENERGY BUILDING CO-SIMULATION BASED ON THE WRM ALGORITHM FOR EFFICIENT SIMULATION OVER FMU COMPONENTS OF WEB SERVICE

Abbass Raad¹, Vincent Reinbold¹, Benoit Delinchant¹, Frédéric Wurtz¹

¹Univ. Grenoble Alpes, G2Elab, F-38000 Grenoble, France

CNRS, G2Elab, F-38000 Grenoble, France

Email: firstname.name@g2elab.grenoble-inp.fr

ABSTRACT

Interoperability between languages, components or web services has some drawbacks, the most important one being the overhead time. This paper proposes a non-classical co-simulation method (or master algorithm) that allows reducing the number of calls of the different sub-models and thus, the computation time. This method, the so-called waveform relaxation method (WRM), will be explored and it will be shown that it is especially performant when the simulation time is long. In the end of this paper, some limitations of this method will be underlined. The present study was performed on a real case, in a smart building environment: the PREDIS building.

INTRODUCTION

Building envelopes with energy systems associated to their control strategies, and with occupants, are an example of complex systems. This kind of system can benefit from holistic approaches in order to take into account emerging effects and to optimize the design of a project. Emerging effect is the case when the global behaviour of the system is greater than the sum of the behaviours of the components of this system, and it strongly depends on the interactions between these agents.

An interesting approach for the present study is simulation. This allows studying the dynamic aspects of the system, while highlighting on these behaviours and interactions.

Nowadays, it is common to use different models to simulate the behaviour of complex systems, especially in the energy buildings sector (heating, lighting, acoustics, energy ...). These models are rarely interoperable with each other, and do not operate in an "aggregate" environment that would allow multi-physics simulation of the entire system.

The standard FMI¹ (Functional Mock-up Interface) (e.g. Blochwitz T., 2012) allows modelling tools (energy+, Amesim, Dymola...) to generate C or binary code, which represents a model for dynamic system fully interoperable with other environmental

modelling and simulation tools. This is a standard "black box" representation of dynamic models, regardless of the tools or languages allowing their description, and after that their re-use as a black box.

The web service is a unit of managed code that can be remotely invoked using HTTP. It can be activated using HTTP requests. A web service allows the user to expose the functionality of existing code over the network. Once it is exposed on the network, another application can use the functionality of the program. It allows various applications to communicate between them and share data and services among themselves.

Recently, several tools (FMU, MUSE², Web Service ...) have been created and are still being developed to respond to the need of interoperability and ensure a multi-physics simulation of a complex system as a whole.

These tools require a considerable computation time, which varies according to the integration and master algorithms used, and all the co-simulated sub-models. In addition, the need of interoperability and coupling systems around the world is increasing, making the co-simulation computation time proportional to the number of remote calls.

In this context, two co-simulation algorithms are presented:

- Coupling based on scalar value exchanges: in this case, models are loosely or strongly coupled when they are simulated separately, with same or a different temporal discretization.
- Coupling based on waveform exchanges, named the Waveform Relaxation Method (WRM) (e.g. Lelarsmee E., 1982): in this case, each subsystem is solved for the whole time domain and its solution (the entire waveform) will serve as an input for other subsystems.

¹ <https://www.fmi-standard.org/>

² A component of proposed standard proposed outcome of the ANR project Plume, <http://muse-component.org/>

In order to highlight the differences between these methods and their results, a comparative analysis is done.

As a proof of concept, simulations are performed on a real case study: the demonstrator building “PREDIS” lab - on G2ELAB (e.g. Dang H-A., 2013).

After a quick description of the chaining algorithm for the co-simulation, the paper presents the WRM method (e.g. Lelarsmee E., 1982). Then, the model of the PREDIS building, composed of a building envelope, a HVAC system and a simple heating system is described.

Thirdly, the paper presents a comparison of simulation times in a context where sub-models are interoperable and are computed through FMUs and Web Services. Indeed, in this context, the communication time is not negligible, and the key point is to compare co-simulation methods that allow reducing the number of request. In what follows it will be demonstrated that the WRM algorithm can be the most performant method for co-simulation when taking into account the importance of the communication time.

Finally, the paper presents a case study in which the WRM shows some limitations.

COSIMULATION ALGORITHMS

Chaining algorithm for co-simulation (loosely coupled) (e.g. RAAD A., 2015).

Chaining algorithm ensures low coupling between two subsystems, the entry of a model at a given time being the output of another model at the previous time (e.g. Wetter, M., 2011 and Sicklinger S., 2014). Thus, the consistency of the coupling is then never verified, but convergence is generally obtained with small enough steps. Figure 1 shows the steps of a weak coupling chaining with two subsystems (SS).

At the first time step, the initial solution of the sub-system 2 is exchanged with the sub-system 1 in order to simulate the first sub-system (step 2). The solution of the sub-system 1 is then exchanged with the sub-system 2 (step 3) for the simulation of the sub-system 2 (step 4). In this case, it simulates the subsystem 2 for 4 time-steps.

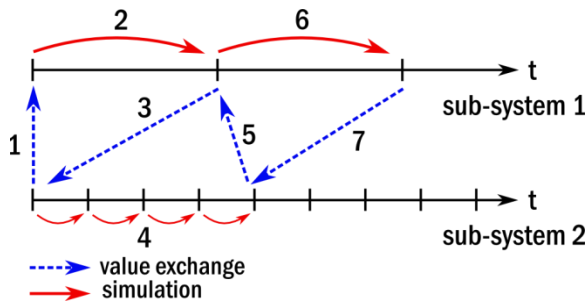


Figure 1: Chaining Algorithm

Waveform Relaxation Method – WRM (e.g. Lelarsmee E., 1982).

The idea is to combine several heterogeneous systems (different dynamics), the coupling being performed by an iterative method on the waveforms (see Figure 2). Each system is solved in time throughout the considered time domain, and its solution (the entire waveform) is used as an input for other systems. The procedure can be done for the whole time domain, or for a sequence of sub-domains. This approach is like a strong coupling, and instead of exchanging simple value at a given time, it is exchanging the final waveform.

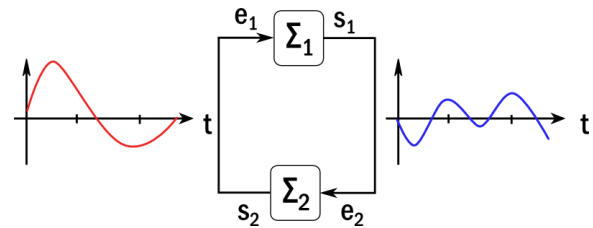


Figure 2: Wave Form Relaxation Method

Table 1: Comparison between the two types of algorithm

	Chaining	WRM
Coupling type	Low coupling	Strong coupling
Data exchanged	Scalars	Waves
Discretization time	Same or different	Same or different
Principle method	Ping Pong	Convergence with iterations

APPLICATION TO THE BUILDING SIMULATION

Description of the PREDIS SB platform³

The platform PREDIS / MHI is dedicated to teaching, research and industrial innovation in the field of intelligent energy management of buildings. Established on 2500 m² of premises INPG school ENSE3 France (School of energy, water and environment), the platform fits within PREDIS technological and scientific platform. Its vocation is to make available to all players in the energy, a training and research tool based on technology demonstrators developed through a strategy of alliances and partnerships with industrial and local authorities. This platform aims to support work on the subject of energy efficiency at the scale of a building or territory, efficiency and safety of power distribution networks, taking into account the

³<http://predis.grenoble-inp.fr/smartbuilding>

diversity of sources and the ability of users to sell their electricity production.

PREDIS SB was constructed inside another building (**Erreur ! Source du renvoi introuvable.**). The “building inside a building” concept could reduce direct external factors (wind and solar) impact to the building.

In fact, PREDIS SB has been renovated from an old building by walls insulation improvement and HVAC dual flow. The main thermal insulation is cellulose wadding (14 cm), which was installed on a wooden cladding that surrounds both interior and exterior walls of the platform. However, the intermediate floor composition was unchanged as part of the original foundation.

Materials and HVAC system have been chosen so that the building’s maximal energy consumption decreases, in order to respect low energy buildings restrictions.

A heating ventilation and air conditioning (HVAC) system is essential for PREDIS SB to maintain comfort temperature since no zone heating device is installed. Its role is to ensure fresh air inside the platform and save power heating/cooling energy by heating exchange between incoming and outgoing airflow.



Figure 3: PREDIS Smart Building Platform

Models used for the co-simulation

- PREDIS Building

It models the thermal parts of the PREDIS envelope. It calculates the internal temperature using the values of the external temperature, the solar flux and the internal gain taking into consideration the envelope’s insulation. (see Figure 4 the proposed model in modelica):

Inputs: external temperature (T_{ext}), solar contributions (P_{sun}), and internal gains ($P_{heating}$).

Outputs: internal temperature ($T_{internal}$).

Note that the internal gain is only represented by the heating power for simplicity.

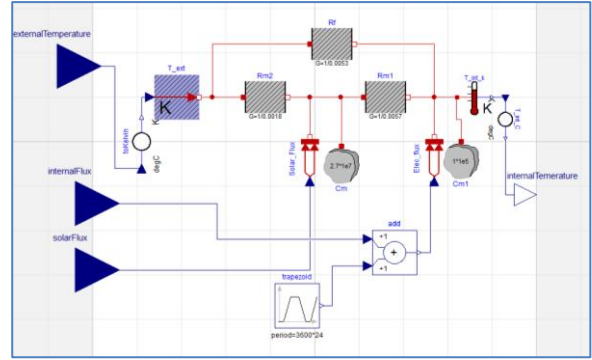


Figure 4: PREDIS Building model in Modelica

- HVAC

It models the heating ventilation and air conditioning of the platform. This is an HVAC system where main **inputs** are: the temperature of injected fresh air & return air, the airflows and the heat exchanger rotation speed.

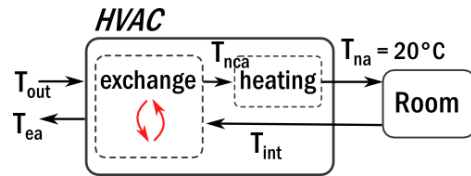


Figure 5 : Description of the HVAC system

The **outputs** are: the heating power ($P_{heating}$) & the temperature of the exhausted air (T_{ea}) not used in our co-simulation. The heat exchanger is modelled as follow:

$$\begin{aligned} T_{nca} &= T_{out} + \eta \cdot (T_{int} - T_{out}) \\ T_{ea} &= T_{out} - \eta \cdot (T_{int} - T_{out}) \end{aligned} \quad (1)$$

Where η is the efficiency of the exchanger. For simplicity, the temperature of the new air (T_{na}) is fixed to a value of 20°C. The heating power injected in the room, is thus deduced knowing the new air temperature, T_{na} , by respecting equation (1).

$$P_{heating} = C \cdot (T_{na} - T_{int}) \quad (2)$$

Where C is a constant, which depends on the flow and the heat capacity of the air.

In what follows, only the $P_{heating}$ output (which represents the total output power from the HVAC) is used. Figure 6 shows the HVAC System model that is used.



Figure 6: HVAC model

- Heating System with hysteresis

This model represents a type of hysteresis heating to regulate the temperature around 20°C at the time of

work (08:00 to 18:00) and around 17°C in the time left. The nominal power is fixed at 4500W and the constant time is around 50s (see Figure 7).

Inputs: internal temperature ($T_{internal}$).

Outputs: heating power ($P_{heating}$).

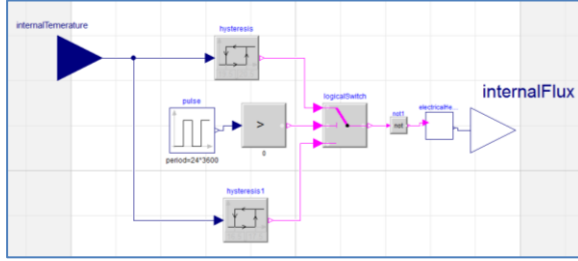


Figure 7: Heating System with hysteresis model in Modelica

Co-Simulation of the building and the heating system

All models are exported as FMUs for co-simulation components to overcome the interoperability problems. These simulations were done using Python code - package PyFMI.

The applications of co-simulation algorithms (chaining and WRM) are applied on the FMUs models “PREDIS Building” with either “HVAC” or “Heating System” (see **Erreur ! Source du renvoi introuvable.**).

The values of inputs “ T_{out} ” and “ P_{sun} ” are measured by G2elab’s equipments and sensors in the period of January 2014. The values of the variables “ T_{int} ” and “ $P_{heating}$ ” are calculated by the solver of “FMU PREDIS Building” and “FMU HVAC/FMU Heating System” respectively and exchanged to one another according to the requested algorithm (Chaining or WRM).

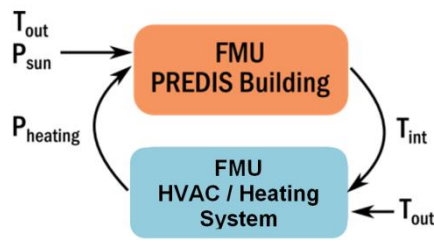


Figure 8 : Co-simulation of FMUs PREDIS Building and HVAC

This will highlight the additional cost of the computation time of interoperability solutions.

RESULTS AND ANALYSE

As a first step, a co-simulation for the FMUs models “PREDIS Building”, “HVAC” is executed using two algorithms, the chaining and the WRM methods, for

two simulations time periods, a single day and a month.

Note that the complete system model was simulated in Dymola to obtain the reference values (see Figure 9)

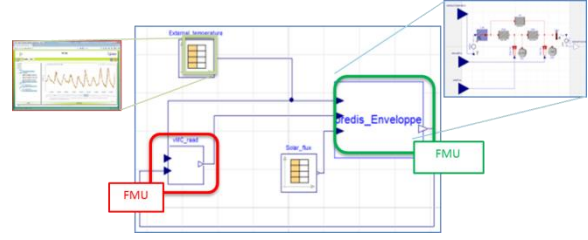


Figure 9: Complete system, “PREDIS Building” and “HVAC” coupled in Dymola model

Co-Simulation: PREDIS Building and HVAC

• Chaining method

Firstly, a co-simulation, using the chaining method, of the building and the HVAC system is presented over a single day, using a one minute time step. In the following, the physical values are compared to a **reference given by the Euler algorithm in Dymola**, which uses a variable time step.

The Figure 10, Figure 11 and Figure 12 illustrate the inputs and the outputs, represented by the main temperatures and heating flux over a day and a month. One can see the good agreement between the computed internal temperature ($T_{internal}$) and the reference internal temperature ($T_{internal_ref}$).

Co-simulation for 1 Day:

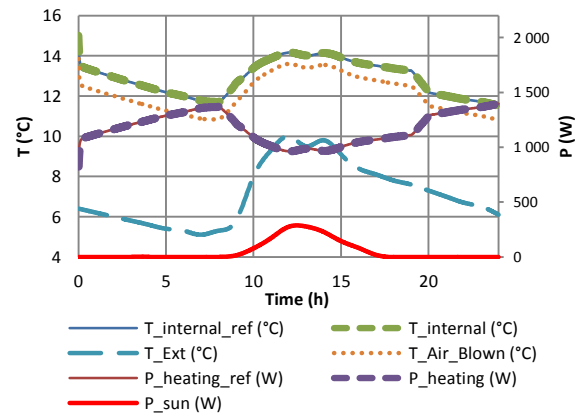


Figure 10: Result of FMUs PREDIS Building and HVAC using chaining co-simulation (1 Day)

Note that the internal temperature of the room is quite low corresponding to a day without presence. This is mainly due to the external temperature, corresponding to winter, and to the fact that it was considered only an extra heating in the HVAC, without taking into account the heating system of the room.

Co-simulation for 1 Month:

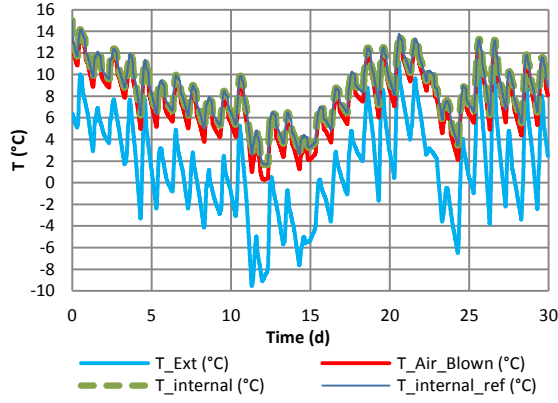


Figure 11: Temperature results of FMUs PREDIS Building and HVAC using chaining co-simulation (1 Month)

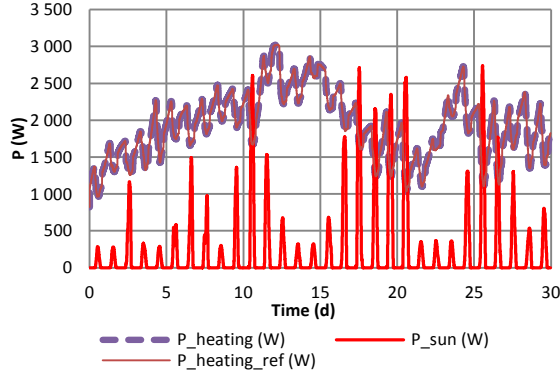


Figure 12: Power results of FMUs PREDIS Building and HVAC using chaining co-simulation (1 Month)

• WRM

Secondly, a co-simulation is presented over a single day with WRM. This co-simulation uses the same model (PREDIS building and the HVAC system) and inputs as the previous algorithm.

Co-simulation for 1 Day:

The external temperature and the solar flux over a winter day are presented on Figure 13. Figure 14 illustrates the simulated outputs of the model and several iterations of the WRM. As it can be seen, when considering a day as time domain, the algorithm converges after 10 iterations.

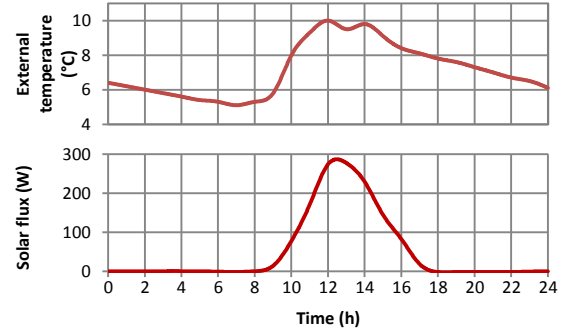


Figure 13: Inputs for "PREDIS Building" and "HVAC" co-simulation (1 Day)

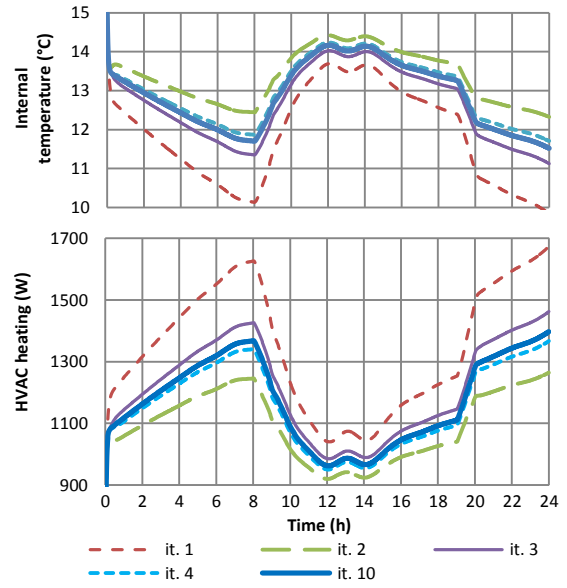


Figure 14: Results for "PREDIS Building" and "HVAC" co-simulation (1 Day)

Co-simulation for 1 Month:

Similar with the previous co-simulation, Figure 15 illustrates the evolution of the external temperature and the solar flux over a month. The results obtained after running the co-simulation are shown in Figure 16. As illustrated, even if the time domain is significantly bigger than for the previous co-simulation, the algorithm converges after only three more iterations (thirteen iterations in total).

As can be seen from the figure at iteration 1 the curve is far from the reference; however, as number of iterations increase, the error difference decreases (curve become nearer to the reference) to be stable at iteration 13.

In order to compare the accuracy of both algorithms, Table 2 presents the Mean Absolute Percentage Error (MAPE) for 1 day and 1 month with respect to the reference value given by the Euler algorithm in Dymola. One can see the good agreement of the

results, the chaining algorithm and the WRM present acceptable results.

Regarding the WRM algorithm, the stopping criteria are defined by the user. This permits to obtain even a higher accuracy. In the present case study, the algorithm stops if the difference between two consequently iterations is below 0.001.

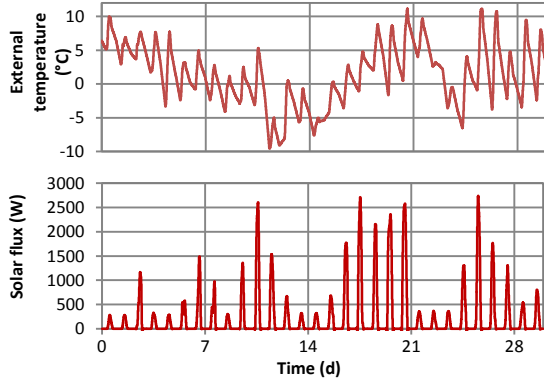


Figure 15: Inputs for “PREDIS Building” and “HVAC” co-simulation (1 Month)

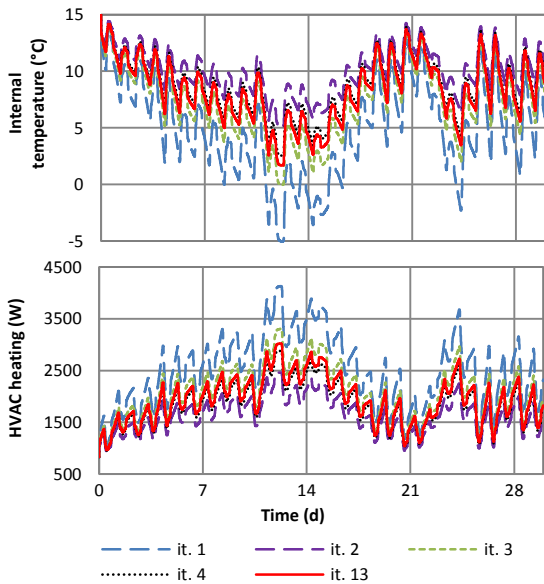


Figure 16: Results for “PREDIS Building” and “HVAC” co-simulation (1 Month)

Table 2: Evaluation of the mean absolute percentage error

ERROR MAPE	1 DAY		1 MONTH	
	T _{internal}	P _{heating}	T _{internal}	P _{heating}
Chaining	0.02%	0.07%	0.07%	0.02%
WRM	0.02%	0.06%	0,1%	0.03%

Simulation time analysis

Both algorithms provided good accuracy with close MAPEs. However, the performance of the algorithms is compared in terms of time consumption.

Table 3 presents communication and computation time for only one iteration. Note that the communication time is highly dependent on the network performance and the web service technology. Thus, the values which correspond to communication time, given in

Table 3, are estimated. Regarding the chaining algorithm, the communication through web service exchanges a single scalar data, whereas the WRM exchanges the whole vector for each iteration of the algorithm.

As a result, communication times through the web service (WS) are different for the tree columns. In addition, the computation time for one iteration of the WRM algorithm is higher than the computation time for the chaining algorithm.

Table 3: Communication and computation time for 1 iteration

	WRM		Chaining (Exchange scalar data)
	1 Day	1 Month	
Communication time on WS	3s	11s	1s
Computation time	42.4s	1m20s	$1.7 \cdot 10^{-4}$ s

Table 4: Simulation time for chaining and waveform relaxation methods with web service

		1Day		1 Month	
		WRM	Chaining	WRM	Chaining
Number of iteration		10	1440	13	43145
Local	Simulation Time	7m 04s	2s	17m18 s	0m 15s
	Time per iteration	45.4s	1s	1m31s	1s
Web service	Simulation time	7m 34s	24m 0s	19m43 s	11h 59m 05s

Table 4 compares the simulation time for 1 day and 1 month in local and web services between WRM and Chaining methods.

In fact, the local network is solved in internal company server; the web service uses protocols (e.g. HTTP) to make a connection with external servers and solvers in other company or country.

The main difference between the two methods is that the WRM algorithm costs less in terms of iterations, which may become an important advantage for a longer simulation time. Indeed, 10 iterations are

sufficient for a 1 day co-simulation, and only 13 are needed for a 1 month simulation. This leads to a real gain in terms of number of communications and thus, in terms of total simulation time. Unlike the WRM, computation time of the chaining algorithm is linear to the time range of the simulation. In the context of co-simulation through web service, the 1 month co-simulation time for the WRM is thus faster than the chaining algorithm.

Models “PREDIS Building”, “Heating System”

If the model contains a test of hysteresis, the WRM does not work so well.

Figure 17 shows the results of the co-simulation model "PREDIS Building" and "Heating System" model-based hysteresis. The hysteresis test unsettles the relaxation waveform of the considered inputs throughout the simulation time. Therefore, for each hysteresis test an iteration is executed. Thus, at each iteration, the WRM converges sequentially, from left to right, obtaining the expected results after 67 iterations.

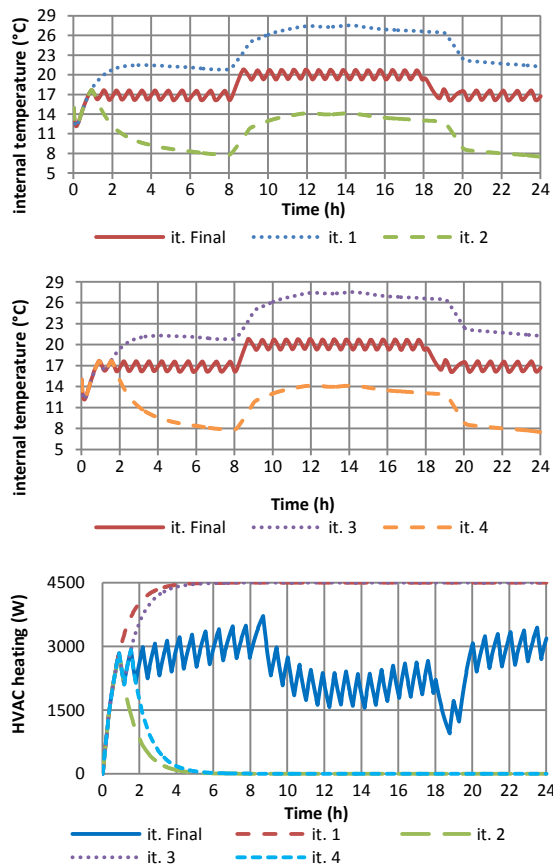


Figure 17 : Results for “PREDIS Building” and “Heating System” co-simulation (1 Day)

CONCLUSION AND PERSPECTIVE

Conclusion

Classical coupling methods (e.g. chaining) ensure interoperability between heterogeneous components. However, using these classical methods through web service may create issues regarding the exchange data time.

The waveform relaxation method (WRM) allows reducing the number of calls of the different sub-models and thus, the computation time. As the simulation time is longer, the efficiency of the waveform relaxation method increases.

Perspective

As the WRM method does not have a high efficiency when applying it on a model that contains a hysteresis, a process analysis in order to identify the problem is ongoing.

In order to fix this dysfunction of the WRM algorithm, several assumptions are to be made. This will allow improving the WRM method and applying it efficiently on hysteresis models.

NOMENCLATURE

<i>FMI</i>	= Standard Functional Mock-Up Interface.
<i>FMU</i>	= Functional Mock-Up Unit.
<i>WRM</i>	= Wave form Relaxation Method.
<i>PREDIS</i>	= Platform Smart Building in G2elab.
<i>HVAC</i>	= Heating, Ventilation, and Air Conditioning.
<i>MAPE</i>	= Mean Absolute Percentage Error.
T_{ea}	= Exhausted air temperature (°C).
T_{out}	= External air temperature (°C).
T_{int}	= Internal air temperature (°C).
T_{nca}	= New cold air temperature (°C).
T_{na}	= New air temperature (°C).
η	= Efficiency of the exchanger.
C	= Constant that depends on the air flow and the heat capacity of the air (W/°C).
$it.i$	= Iteration number i .
$P_{heating}$	= Heating Power (W).
P_{sun}	= Solar Contributions (W).

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