AUTOMATED COLLOCATION OF SIMULATION MODULES IN FMI-BASED BUILDING ENERGY CO-SIMULATION

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ABSTRACT

The modularity offered by the Functional Mock-up Interface (FMI) allows straightforward model generation for single simulation modules. However, additional effort is required to organize the Functional Mock-up Units (FMUs) in a whole system simulation. The present article describes a strategy to solve this issue by means of an automated initialization of FMUs in Building Energy Simulation (BES). The introduction of an FMU network, where every unit can be classified within a scheme corresponding to its purpose, further allows exchanging components of alike scope in a seamless way. This enables fast evaluation of design options by making use of precompiled library models. A case study illustrates the procedure.

Die eröffnete Modularität durch das Functional Mock-up Interface (FMI) ermöglicht es einzelne Simulationsmodule individuell zu erstellen. Es ist jedoch notwendig die entstehenden Functional Mock-up Units im Rahmen einer Gesamtsimulation zu organisieren. Die vorliegende Arbeit beschreibt ein Verfahren um dieses Problem im Sinne einer automatisierten Initialisierung von FMUs in einer energetischen Gebäudesimulation zu lösen. Die Definition eines FMU Netzwerks, indem jede Einheit gemäß einem vorgegebenen Schema nach ihrem Zweck klassifiziert werden kann, erlaubt zudem einen reibungslosen Austausch von Komponenten gleichen Typs. Dies ermöglicht schnelle Evaluierungen von Planungsalternativen durch die Nutzung von vorkompilierten Bibliotheksmodellen. Eine Beispielstudie dient zur Demonstration des Verfahrens.

INTRODUCTION

The FMI is a tool-independent standard that allows simulation models to be exported or imported from or to an increasing number of tools and frameworks for the purpose of co-simulation or model exchange (Blochwitz 2008). Examples have shown the applicability for single use cases in BES. Nouidui et al. (Nouidui et al. 2013) applied the co-simulation process to an HVAC model exported as FMU in Modelica and a room model in Energy Plus. A further case study involved a shading device in Energy Plus controlled by an external algorithm wrapped in an FMU. Both studies applied Energy Plus as the master Platform. Plessis et al. (Plessis et al. 2014) coupled a room model FMU from Dymola to the SMACH occupant simulator using the latter as the master. In (Pazold et al. 2012), Pazold et al. coupled several HVAC models from Modelica to the building energy simulation tool WUFI®Plus deploying it as the orchestrating component. Further examples including community energy systems are mentioned in (Widl et al. 2014). All authors accredited the FMI with considering potential to become a useful component in BES, although further testing and validation is needed. This work aims at a more general approach for using FMI in BES in order to fully exploit the advantages arising from a modular simulation design approach.

Future BES application will likely be accomplished by integrated design teams working on individual tasks, generating domain specific simulation models (Wetter 2011). The HVAC engineer is able to drag one of numerous catalogue models, developed by manufacturers during the product design and construction phase, into the simulation to test the products performance within the planned building system. The building physicist changes window properties influencing dynamic simulation models to quantify the effect on key performance indicators (KPIs) of the whole building, including the resulting effects on other modules like occupant behaviour, HVAC performance etc. The FMI and associated master algorithms for co-simulation are keys to realize such kind of interdisciplinary workflow.
Today's BES is still cumbersome, time-consuming and error-prone. Predictions often show considerable discrepancy when compared to measured data (Zhao, Magoulès 2012). The centralized generation of a simulation model within an integrated design team requires frequent information exchange further increasing the time-effort and leading to out-dated input or lost details. In this context, a multidisciplinary approach rather presents an obstacle than the opportunity to benefit from several planners' expertise to create an optimized overall system. A modular approach, allowing every expert to

contribute to the simulation with a model built on his specific knowledge, can increase the speed and quality of modelling as well as avoiding errors from information exchange. Furthermore, catalogue models from manufacturers undergoing testing and calibration can increase accuracy considerably. Different model types like statistical, physical or empirical models can be combined according to the most suitable approach depending on project requirements. The simulation components can additionally vary in their level of detail, thus supporting early phase simulation and progress offset between planning disciplines.

The modularization of BES provides several advantages, however, an additional effort must be considered. The single components need to be organized and orchestrated to perform a simulation of the whole system. In order to eliminate the necessary time effort, a method is suggested that allows for automated instantiation and co-simulation of an arbitrary number of FMUs in a single zone BES. Therefore, a general concept for the BES was developed, categorizing FMUs to avoid incompatible components. Interactions are automatically determined based on the provided or needed variables of each FMU to extract the simulation topology. A demonstration shows the resulting flexibility allowing for evaluation of several system design options in a short time by making use of precompiled models and their seamless exchange in the simulation.

SIMULATION

In order to benefit from catalogue models in a modularized BES, module categories being able to be represented by a range of possible simulation models must be defined. The majority of buildings can be seen as unique due to individual shapes, materials, requirements to meet etc., however, it is possible to decompose the problem definition into a set of subsystems, e.g. HVAC, building envelope, occupancy etc. A building envelope usually underlies the architect's creativity or a building owners specific wishes resulting in an infinite number of design opportunites. Building simulation models are therefore unique in most cases. In contrary to that, e.g. HVAC systems are based on a finite number of basic components that can be combined to execute a joint task. This allows the generation of a customizable FMU library simulating different behaviour to fulfill the same purpose. In such way it will be possible to build and assemble model libraries of main system classes or categories. Besides this aspect, the separation of responsibilities amongst planners was the main criteria for the subdivision of a BES into the modular structure shown in Figure 1. For each category of FMU within this structure, a variety of library models can be developed and supplied to the simulation. This is alike for occupancy models simulating various behaviours influencing the same variables, as well as simple weather models based on table data and HVAC systems of entirely different nature but finally resulting in a heating or cooling rate. It must be noted that the input variables of FMUs in one category may differ. Depending on the system in use, different information may be needed to compute the performance that is realized while fulfilling the system's purpose.

Due to the uniqueness of the building envelope itself, this model represents an exception and can not be taken from a list of catalogue models. Instead, changes in the building geometry often require a regeneration of the FMU. However, model generation from geometry has advanced in recent years. Examples like OpenStudio and EnergyPlus proof the effortless transition from CAD to energy simulation (Guglielmetti et al. 2011).

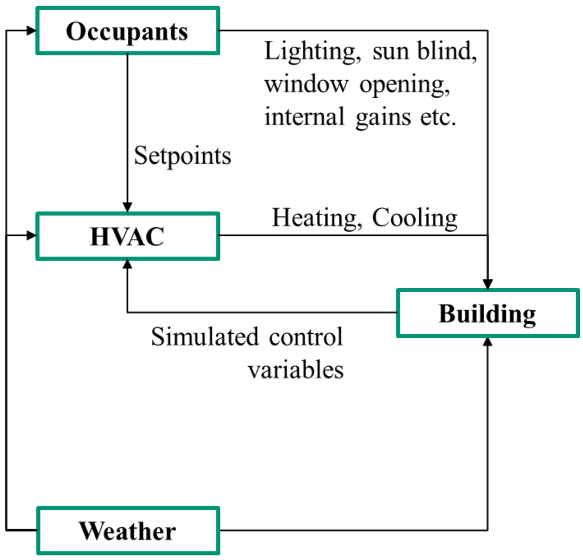

Figure 1: General structure for FMI simulation in BES with main FMU categories framed. Possible exchange variables are noted.

The master algorithm for performing the co-simulation was developed in Python using the pyfmi package. The implementation starts with loading a selection of FMUs into an IPython notebook. In the following, the variables of the FMUs are analyzed and according to the simulation structure and naming conventions, connections between output and input variables are found. A connectivity matrix as shown in Table 1 is derived. Connections between FMUs are indicated by a "1". Corresponding to the matrix, variable values are exchanged during each simulation time step using the loose coupling method (Trcka 2008). Thereby, the FMUs are simulated in parallel with the feedback between them lagging one time step. The numerical accuracy of this method is lower compared to others. However, since the coupling algorithm only served as remedy to show the feasibility of the presented concept, the advantage of

Table 1: Example for a connectivity matrix within the Python simulation framework.

	FMU Models	Occupant	HVAC				Building		
FMU Models	**Output/Input Variables**	**T_Air**	**T_AirSet**	**T_amb**	**Irr_Dir**	**Irr_Dif**	**Q_Int**	**SIG_Window**	**Q_Room**
Occupant	**SIG_Window**	0	0	0	0	0	0	1	0
	Q_Int	0	0	0	0	0	1	0	0
	T_AirSet	0	1	0	0	0	0	0	0
HVAC	**T_Storage**	0	0	0	0	0	0	0	0
	Q_LossStorage	0	0	0	0	0	0	0	0
	Q_Room	0	0	0	0	0	0	0	1
	Q_RoomEnergy	0	0	0	0	0	0	0	0
	Q_LossStorageEnergy	0	0	0	0	0	0	0	0
Building	**T_Air**	1	0	0	0	0	0	0	0
	Illum	0	0	0	0	0	0	0	0
	Irr_Dir	0	0	0	1	0	0	0	0
	Irr_Dif	0	0	0	0	1	0	0	0
	T_Amb	0	0	1	0	0	0	0	0

fast simulation run time was decisive for the selection. Ongoing research for solving the numerical issues during co-simulation with suggestions on an extension of the FMI standard can be found in (Broman et al. 2013). Besides that, several platforms, such as described in (Brooks et al. 2015) provide the capabilities to carry out appropriate coupling algorithms themselves. Only contributing FMUs and their connections need to be defined.

The automatic detection of the simulation topology enables seamless exchange of FMUs with the advantage to extend optimization algorithms from parametric variations to structural modification of the entire system composition. The following paragraph gives a short overview of the used simulation models in this case. Without going into further detail on the physics of the models, their relevancy within the depicted simulation structure as well as input and output variables are briefly explained. Since EnergyPlus is used to generate the building FMU, the weather data is inherited in this module.

- Building_GR: Building as single zone model
- Building_FR: Same as above with flat roof instead of gabled roof
- EmployeesProfile: Defines attendance of employees and provides internal gains (CO_2 and heat) as well as required tap water rate using a customized profile
- HeatPumpGH_Rad: HVAC model containing a ground heat pump, a storage unit and radiators providing heat flow
- HeatPumpGH_SolCol_Rad: Same as above including a solar collector to support the heat pump
- L_Reinhart: Statistical model to simulate electrical lighting based on different propabilities for arrival and on-going attendance (Reinhart, Voss 2003)
- W_Yun_09: Statistical model to determine window opening based on propabilities depending on room temperature, arrival time and on-going attendance (Yun et al. 2009)
- B_Haldi_13: Statistical model applying a Markov chain to derive manual blind control depending on indoor illuminance and arrival or attendance status (Haldi 2013)

In a first simulation the system composition is chosen as shown in Table 2. The connectivity matrix is generated automatically and the simulation topology as depicted in Figure 2 can be derived. Every FMU receives and sends its variables as illustrated within the loose coupling algorithm.

A postprocessing of the first simulation run yields in the degree hours under the temperature setpoint provided by the employees' profile. To improve the resulting degree hours under the setpoint temperature as depicted in Figure 3, the number of radiators is increased for simulation run 2. This is done by a simple parameter change of the already used catalogue FMU simulating the heat supply. The change improves the situation, however, storage tank temperature can not be held constantly at a high level.

Table 2: FMU composition of simulation runs with "x" marking the contributing FMUs.

FMU Models/ Simulation Run	Building_GR	Building_FR	EmployeesProfile	L_Reinhart	W_Yun_09	B_Haldi_13	HeatPumpGH_Rad	HeatPumpGH_ SolCol_Rad
1	x	o	x	x	x	o	x	o
2	x	o	x	x	x	o	x	o
3	o	x	x	x	x	o	o	x
4	o	x	x	x	x	x	o	x

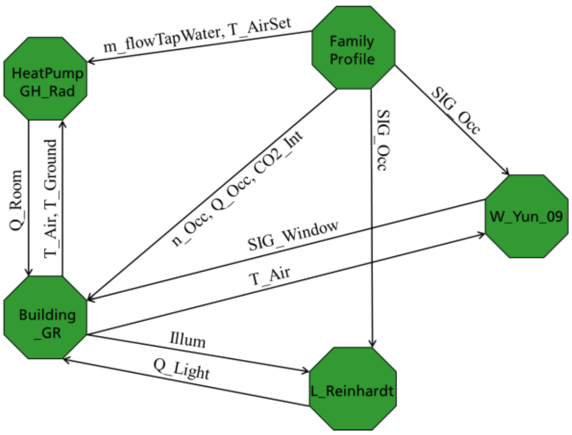

Figure 2: Topology of contributing FMUs in simulation run 1.

For simulation run 3 another design option is therefore being evaluated. In order to gain space for the installation of supporting solar collector panels, the gabled roof construction of the building is changed to a flat roof. The structural change of the building geometry requires a re-generation of the building FMU whereas the new HVAC FMU can be taken from a library and instantiated with the planned collector area. In contrary to the former HVAC model, further input variables, such as solar irradition, solar position etc. are now required. The master algorithm automatically finds the relevant connections and reorganizes the FMUs by coupling the corresponding sources to the new HVAC model with the simulation result proofing the improvement of the design. In continuation of the study, an increase of the number of radiators could now be a promising change to realize further optimizations.

Figure 5 illustrates the degree hours over a temperature of degree hours of 26 °C. Both building FMUs originally contain blinds on the windows. The occupant models in the previous examples, however, have no shading control implemented which leaves the blinds deactivated for the entire simulation. To include manual blind control, a statistical model, based on experimental data, is added to run 4. The resulting simulation topology can be seen in Figure 4.

When compared to Figure 2 it is noteworthy that not only seamless exchange but also prompt integration of additional models providing missing variable values is feasible when the physical purpose is compliant with the present FMUs. Figure 5 illustrates that the addition produces a reduction of degree hours over a temperature of 26 °C. Simultaneously, degree hours under the setpoint temperature grow due to decreased solar gains.

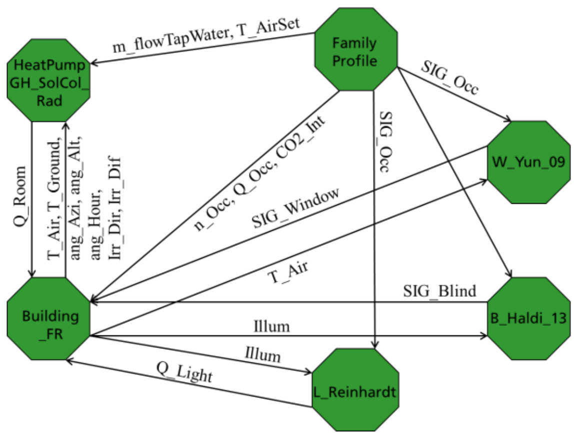

Figure 4: Topology of contributing FMUs in simulation run 4.

DISCUSSION

The illustrated procedure offers considerable potential for improving the quality and status of BES in the building planning process. Especially decisions in early design phases can be supported in profound studies at low time-effort. The simulation benefits from the use of precompiled modules, generated and eventually validated by experts in either planning discipline. Instantiation with project specific parameters allows the planners to effectively make use of the library models and run tests for varying system compositions. At this stage of the research, the connection to a building information model has not been realized yet. However, coupling input data to a central data repository can eliminate the need for manual parameter instantiation of the library modules. Furthermore, additional relational

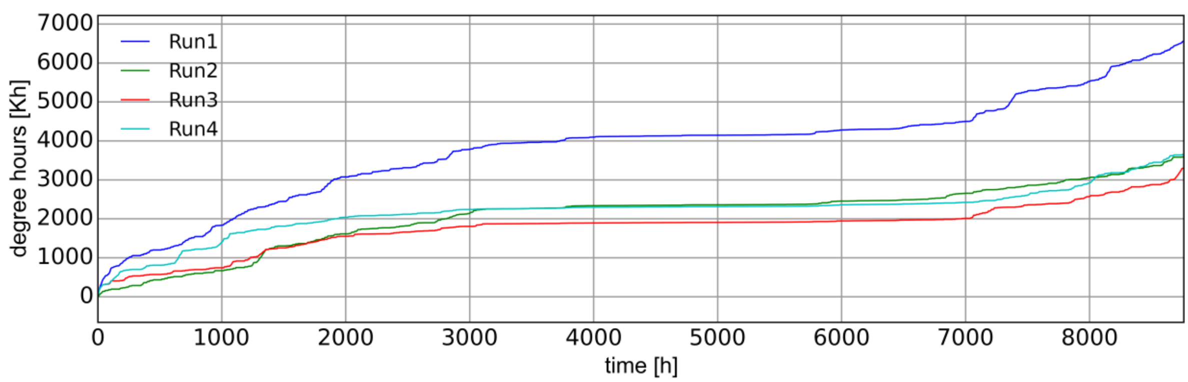

Figure 3: Accumulated degree hours below the temperature setpoint for each simulation run.

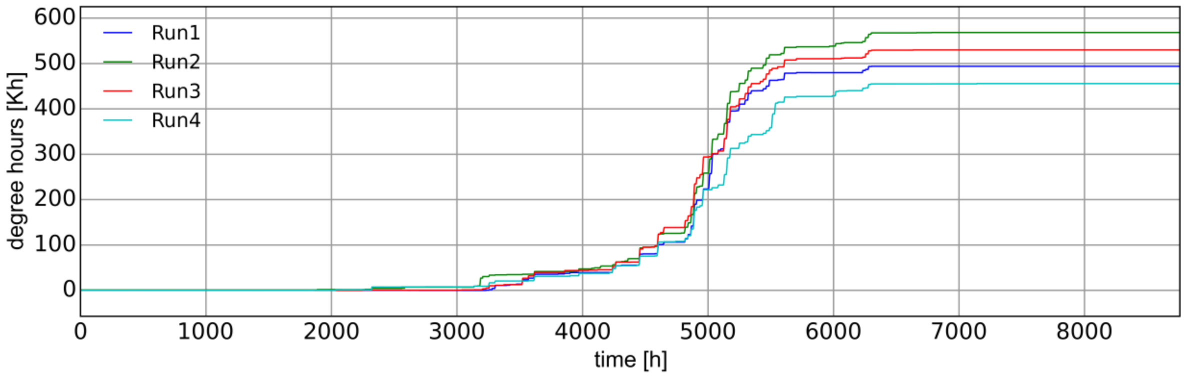

Figure 5: Accumulated degree hours above 26 °C for each simulation run.

information can be required to explicitly define connections between FMUs and their exchange variables. In the presented example, the naming convention was sufficient to generate the simulation topology. However, e.g. in the case of multizone models, the present procedure requires additional information to explicitly assign heat flows from e.g. a number of radiators to the corresponding thermal zones. Relations between the single radiators and their supply zones need to be derived from the Building Information Model (BIM). A further example is the occupant's control of only single blinds. Mapping of blind control signals to several blinds must be ensured. For the automized coupling of FMUs within the simulation network, a BIM needs to provide the necessary relational information in order to derive these many to many cardinalities.

The chosen FMU categories may lead to further difficulties. The decomposition of a BES into smaller modules can be realized properly when unique exchange variables representing the behaviour of the sending module as well as the quantified consequence for the receiving module can be defined. In cases when the behaviour of the sending module is also part of the behaviour of the receiving module, this exchanged value might not be enough to correctly simulate the system. As an example of a highly integrated component in the building sector, floor heating is a fixed part of the HVAC system as well as the building envelope. A simple transfer of heating rate to the thermal zone does not allow for proper computation of surface temperatures in the building model. Providing solely a supply fluid temperature to the building requires modelling of the floor heating within the building domain. This results in a change of the assigned capabilities within categories and therefore difficulties when exchanging simulation modules.

Future research also needs to be conducted regarding the level of the building system subdivision. Especially further partitioning of the HVAC module can lead to more detailed simulations and the exploitation of remaining optimization potential. Later planning phases as well as the building operation can benefit from the growing level of detail. Additionally, single HVAC components, such as pumps, pipes, storage tanks etc. can be exchanged in the same seamless manner as shown above. This extends the model library concept to varying detail categories offering the possibility for manufacturers of such smaller parts to be directly accessible for testing. The trade-off with longer simulation runtime, however, must be taken into consideration when increasing the number of contributing FMUs as already mentioned in (Wetter et al. 2015).

SUMMARY

In this work, a method was proposed to effectively benefit from the opportunity to modularize multidisciplinary simulation models by the use of FMI. The concept implied the partitioning of a BES into classes of components. Validated catalogue models within defined categories can be instantiated corresponding to the specific planning project and exchanged seamlessly to evaluate different system configurations. Especially during early planning stages this procedure offers more possibilities to reach quantitatively supported decisions. In order to extend the concept to multizonal BES, coupling to a BIM containing the relevant relational and parametric information is promising. Furthermore, challenges concerning the scope of the module subdivision, especially for highly integrated system components like floor heating were identified. Due to the demonstrated potential of FMI in BES, future work will concentrate on the above mentioned issues.

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REFERENCES

Blochwitz, Torsten (2008): Functional Mock-up Interface. Edited by Modelica Association. Available online at https://www.fmi-standard.org/start, checked on 3/23/2016.

Broman, David; Brooks, Christopher; Greenberg, Lev; Lee, Edward A.; Masin, Michael; Tripakis, Stavros; Wetter, Michael (2013): Determinate Composition of FMUs for Co-Simulation. In Rolf Ernst, Oleg Sokolsky (Eds.): Proceedings of the International Conference on Embedded Software (EMSOFT). Montreal, Canada, 29.09.-04.10. EMSOFT; Embedded Systems Week; ESWeek. Piscataway, NJ: IEEE.

Brooks, Christopher; Lee, Edward A.; Lorenzetti, David; Nouidui, Thierry S.; Wetter, Michael (2015): CyPhySim. In Antoine Girard, Sriram Sankaranarayanan (Eds.): Proceedings of the 18th International Conference on Hybrid Systems: Computation and Control. Seattle, Washington, USA, pp. 301–302.

Guglielmetti, Rob; Dan Macumber; Nicholas Long (2011): OpenStudio: an open source integrated analysis platform. In V. Soebarto (Ed.): Proceedings of the 12th conference of International Building Performance Simulation Association. Sidney, Australia. International Building Performance Simulation Association. 12th ed.

Haldi, Frédéric (2013): A Probabilistic Model to Predict Building Occupants' Diversity Towards Their Interactions with the Building Envelope. In Etienne Wurtz (Ed.): Proceedings of the 13th Conference of International Building Performance Simulation Association. Chambéry, France, 26.-28.08. International Building Performance Simulation Association. 13th ed., pp. 1475–1482.

Nouidui, Thierry; Wetter, Michael; Zuo, Wangda (2013): Functional mock-up unit for co-simulation import in EnergyPlus. In Journal of Building Performance Simulation 7 (3), pp. 192–202.

Pazold, Matthias; Burhenne, Sebastian; Radon, Jan; Herkel, Sebastian; Antretter, Florian (2012): Integration of Modelica models into an exisiting simulation software using FMI for Co-Simulation. In Martin Otter, Dirk Zimmer (Eds.): 9th International Modelica Conference. September 3 - 5, 2012, Munich, Germany. Linköping: Linköping Electronic Conference Proceedings, pp. 949–954.

Plessis, Gilles; Amouroux, Édouard; Haradji, Yvon (2014): Coupling occupant behaviour with a building energy model - A FMI application. In Hubertus Tummescheit, Karl-Erik Arzén (Eds.): Proceedings of the 10th International Modelica Conference. Lund, Sweden. Modelica Association. 10th ed., pp. 321–326.

Reinhart, C. F.; Voss, K. (2003): Monitoring manual control of electric lighting and blinds. In light res technol 35 (3), pp. 243–260. DOI: 10.1191/1365782803li064oa.

Trcka, Marija (2008): Co-simulation for Performance Prediction of Innovative Integrated Mechanical Energy Systems in Buildings. Dissertation. Eindhoven University of Technology, Eindhoven.

Wetter, Michael (2011): A View on Future Building System Modeling and Simulation. In Jan Hensen, Roberto Lamberts (Eds.): Building performance simulation for design and operation. London, New York, NY: Spon Press.

Wetter, Michael; Fuchs, Marcus; Nouidui, Thierry (2015): Design Choices for Thermofluid Flow Components and Systems that are Exported as Functional Mockup Units. In Peter Fritzson, Hilding Elmqvist (Eds.): Proceedings of the 11th International Modelica Conference. Versailles, France, 21.09.-23.09. Modelica Association; Dassault Systèmes. Linköping, Sweden: Linköping Electronic Conference Proceedings (11).

Widl, Edmund; Delinchant, Benoit; Kubler, Svea; Dan Li; Muller, Wolfgang; Norrefeldt, Victor et al. (2014): Novel simulation concepts for buildings and community energy systems based on the Functional Mock-up Interface specification. In Edmund Widl (Ed.): Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES). Berlin, Germany. Industrial Electronics Society; Austrian Institute of Technology, pp. 1–6.

Yun, Geun Young; Tuohy, Paul; Steemers, Koen (2009): Thermal performance of a naturally ventilated building using a combined algorithm of probabilistic occupant behaviour and deterministic heat and mass balance models. In Energy and Buildings 41 (5), pp. 489–499. DOI: 10.1016/j.enbuild.2008.11.013.

Zhao, Hai-xiang; Magoulès, Frédéric (2012): A review on the prediction of building energy consumption. In Renewable and Sustainable Energy Reviews 16 (6), pp. 3586–3592. DOI: 10.1016/j.rser.2012.02.049.