Semantics For Assembling Modular Network Topologies in FMI-Based Building Performance Simulation

Matthias Mitterhofer[1], Georg Ferdinand Schneider[2],
Sebastian Stratbücker[1], Simone Steiger[2]
[1]Fraunhofer Institute for Building Physics (IBP), Holzkirchen, Germany
[2]Fraunhofer Institute for Building Physics (IBP), Nürnberg, Germany

Abstract

As current literature states, the transfer of Building Performance Simulation (BPS) tools in terms of holistic assessment capabilities of today's building systems as well as their transfer to the daily design process has stagnated. To antagonize this development, the present work investigates a modular simulation setup based on the recently developed Functional Mock-up Interface (FMI) standard. A procedure for the realization of such an approach is presented and implemented. The main obstacle of the modular simulation is identified to be the collocation of simulation modules, which is addressed using a knowledge-based method enabled through ontology. The procedure allows one to automatically derive a simulation topology based on information about the interfacing variables. A single and a multi-zone BPS serve as examples and illustrate the information requirements as well as the integration of information from building information modeling (BIM) to instantiate a simulation.

Introduction

Over the last decades buildings have developed into increasingly complex technical systems that dynamically interact with their surrounding ecosystems from the single occupant to whole quarters. The high standards on low greenhouse gas emissions, thermal and visual comfort, acoustics and air quality expected to be fulfilled by buildings require a variety of expertise from qualified engineers and architects.

Simulation tools have been developed and deployed to capture this complexity and allow for informed decisions on design alternatives not only prior to construction but also during the commissioning and operation of a building. Tools emerged from different domains yielding a heterogeneous software landscape with a high probability of each stakeholder working with his own tool. However, finding the optimal design or even simply complying with the set requirements in all assessment areas can generally only be achieved by a joint effort involving all design domains. The latter not only refers to the exchange of information among the involved parties but also to the involved design tools.

In order to support the building industry with adequate software capable of meeting today's demand, Clarke and Hensen (2015) identified three main requirements for BPS:

- high-integrity representation of the involved physical processes;
- coupling of different domain models;
- integration into the design process.

Several efforts in the past addressed these requirements. The best opportunity to meet the criteria are multi-domain modelling languages, such as *Modelica*, which allow for the integration of multiple domains into a single simulation environment. The use of the language allows for a numerically efficient solving process of the resulting equation system. However, as Köhler et al. (2016) pointed out, the learning effort of the language and the well-established tools in certain disciplines still limit its broad application in practice.

Another approach emerged with the development of the FMI standard and especially its revision to the most recent version 2.0 (Blochwitz et al., 2012). The standard allows for exporting simulation models for co-simulation or model exchange as a black box entity termed Functional Mock-up Unit (FMU). External master platforms can execute the FMU as a standalone unit or in conjunction with other simulation models independent from the source tool. This allows for the coupling of models from heterogeneous tools and can provide a fully dynamic simulation considering various design disciplines and physical domains.

In the building sector, several case studies have shown the applicability and the accompanied benefits of FMI through extended tool interoperability. Pazold et al. (2012) coupled several HVAC models exported as FMUs from Modelica to WUFI® Plus where the latter served as the master, i.e. the orchestrating component in the co-simulation. The approach allows for the quantification of the thermal response of a building envelope to the dynamic processes of its heat supply system. A similar case is simulated in Nouidui et al. (2014) with EnergyPlus as the master. Furthermore, a second study showed the behavior of a shading controller reacting to the indoor air temperature and solar radiation calculated in an EnergyPlus room model. Another application is demonstrated by Plessis et al. (2014), who coupled an occupant behavior model to a building FMU. The mentioned efforts congruently accredited the FMI with considerable potential for its use in BPS, however, a general methodology for its application is yet to be developed.

In this contribution, an FMI-based method is presented in order to address the three requirements for BPS tools. To comply with the current design process, a higher degree of modularity is applied to the co-simulation than in the mentioned examples. This allows for the consideration of several stakeholders in the simulation and facilitates adaptation in the design process. The co-simulation allows one to couple the contributed design concepts and detect dependencies, synergies or discrepancies. The increased number of simulation units, however, leads to two drawbacks: A growing complexity in coupling the inputs and outputs of each simulation unit as well as increased simulation time and requirements to the solver. The latter is successfully addressed by platforms as presented by Galtier et al. (2015) or Brooks et al. (2015), which incorporate tailored, numerically efficient solvers and multi-core computing. Therefore, on the path to realizing a higher degree of modularity in BPS, the former issue is identified as the key obstacle and is therefore addressed in the proposed solution. The presented procedure allows one to automatically derive a simulation structure of a modular simulation through the formal specification of simulation entities, e.g. FMUs. By using ontology for the annotation, the semantics can be described unambiguously. This information is used to match variables of simulation entities and automatically derive the simulation topology by means of reasoning. Additionally, system or project-specific information models can be integrated when needed.

In the remainder of this paper, we present the methodology and process to realizing the modular BPS. We briefly introduce ontologies and semantic web technologies before we present *FMUont*, an ontology to annotate the exchange variables and parameters of an FMU, and show how to integrate system information from external information repositories, e.g. an information model from BIM, into the approach. Finally, we present results from a pilot implementation for a single and a multi-zone BPS.

Methodology

In order to ensure integration of BPS into the design process, the goal is to "accommodate the different skill levels and conceptual outlooks of those who collaborate in the design process" Clarke and Hensen (2015) within the BPS.

Simulations are often set up by a simulation expert who gathers information from multiple planners from different domains. His responsibility is the consolidation of the information in order to realize a simulation of the current design. The introduction of a central information repository, i.e. BIM, can help to mediate the information transfer between the planners and the simulation specialist. Information discrepancy and time-intensive communication can be avoided in a setup, as shown in Figure 1. However, since the automated generation of a simulation from a widely appreciated BIM format as analyzed in Nasyrov et al. (2014) is not yet realized, a simulation expert is still necessary to integrate information from multiple domains and choose the corresponding modeling approach as well as a general tool capable of considering that information. This consolidation requires a specialist with deep insight into every domain. Furthermore, information is not generated and used by the same person, leading to the possibility of misinterpretation or inconsistency. Referring back to the above-mentioned statement, this approach does not ensure the direct accommodation of planners' skills and concepts in the simulation. Instead, information they provide is interpreted by a single person and modeled in a single tool, which might not be able to accurately reflect every planner's concept.

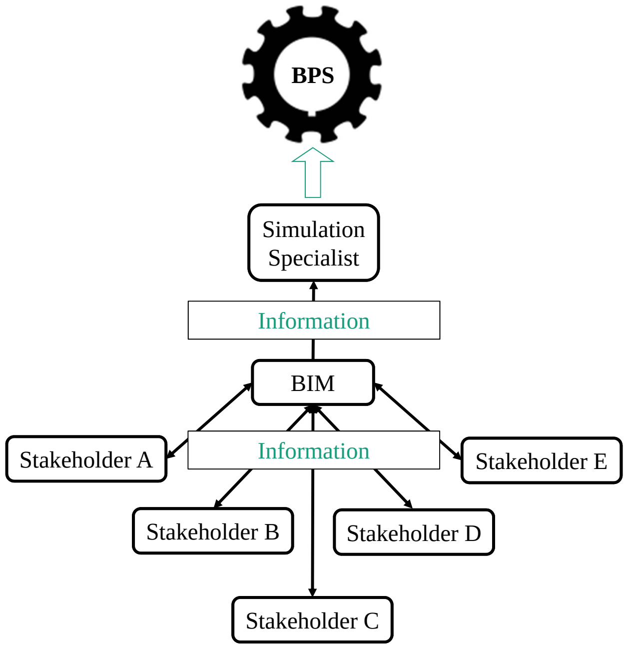

Figure 1: Current process for the realization of a BPS during the design process involving a BIM.

With the fragmentation of a BPS into smaller modules, this process can be restructured as illustrated in Figure 2. Planners can directly contribute to the BPS by delivering a simulation model, generated in their preferred tool, based on their own expertise. A central BIM can serve as a basis to every planner and provides a possibility to set the model in context with the current design project. This approach enables the use of detailed knowledge and specified tools to

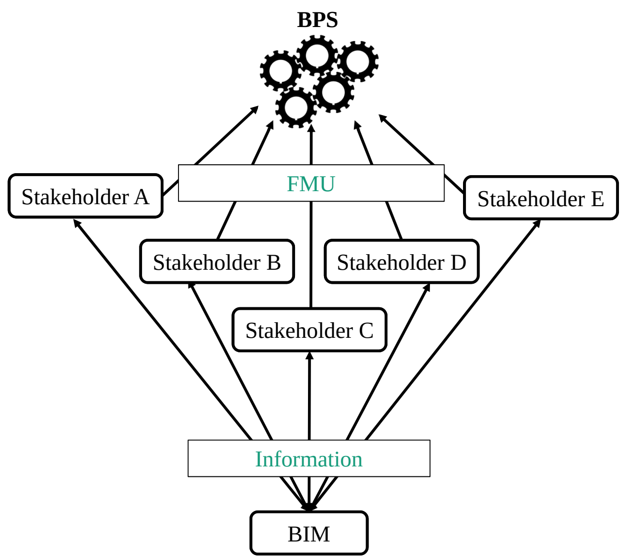

Figure 2: Process for realization of a modular simulation based on distributed FMU generation.

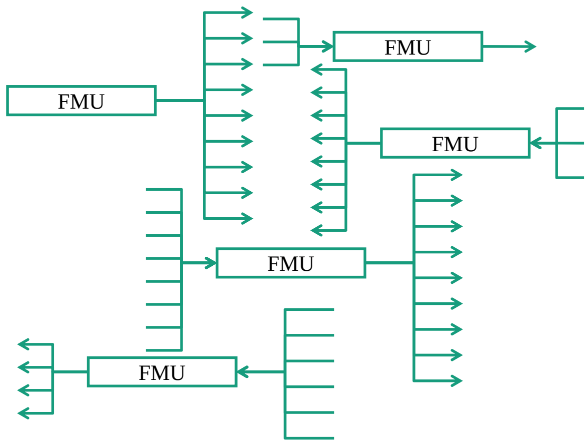

Figure 3: Coupling problem for higher degree of modularity with various FMUs (represented in rectangular box) with varying number of inputs and outputs (represented with arrows).

generate a simulation model and not only prevents a misinterpretation of information and time-intensive information exchange, but may also enhance the accuracy of the model due to the effective placement of expertise and highly specialized tools. In addition to that, different levels and types of simulation models, such as empirical, physical or statistical models, or merely differently detailed models, due to temporal discrepancies between the planning domains' individual progresses, can be combined. Due to their reduction to interfacing variables, interactions can always be quantified.

The restructured procedure based on the modular simulation approach, however, requires an additional effort regarding the simulation. The single simulation modules have to be connected in order to form a whole system simulation. The challenge is to identify the connections between the input and output variables of the contributing FMUs. As Figure 3 illustrates, the complexity rises with the number of FMUs as well as the number of interfacing variables. Deriving the right connections manually can be a cumbersome process as mentioned in Mitterhofer and Stratbücker (2016), constraining the application of modular simulation techniques in practice.

Ontology-based Annotation and Information Integration of FMUs

In the following section, we explain in detail the information model and process for realizing the automated generation of a simulation topology using ontology. Figure 4 provides an overview of the process.

The procedure starts with several stakeholders working in their domain within their preferred tool environment. They generate a model compliant with the FMI standard. In order to provide information about the input and output variables, a simple GUI loads the FMU (Figure 5) and guides the planner through the annotation process (Figure 6). The resulting annotation using the ontology described later is stored (*.owl* file) within the FMU zip-file alongside the originally existing (*.xml* and *.dll*) files.

When setting up the modular simulation consisting of several FMUs, the semantic descriptions of the FMUs within the *.owl* files are extracted and merged. An algorithm based on inference matches the required input and output variables of the FMUs. If necessary, the integration of information from BIM can be realized at this point.

Ontology and Semantic Web Technologies

To annotate the dynamic simulation models with meta-information, we use ontology. When using ontology to specify a domain of interest, it essentially requires one to define the concepts of this domain and the relationships among them. The Web Ontology Language (OWL) (W3C, 2016) may be used to implement ontologies and is based on a first-order logic, which enables specialized algorithms termed *reasoner* to automatically infer implicit information from explicitly stated information.

Examples for the use of ontology for information modelling, exchange and integration in the building domain can be obtained from the literature. An ontology to model and integrate information for energy analysis in residential buildings is the *ThinkHome* ontology as presented by Kofler et al. (2012). It includes concepts to describe, amongst others, the users of a building. A conversion process from the EXPRESS implementation of the Industry Foundation Classes (IFC) to an OWL representation of the data model is presented by Pauwels and Terkaj (2016). For the particular case of BPS, *SimModel*, as first presented in O'Donnell et al. (2011), provides a sound basis of

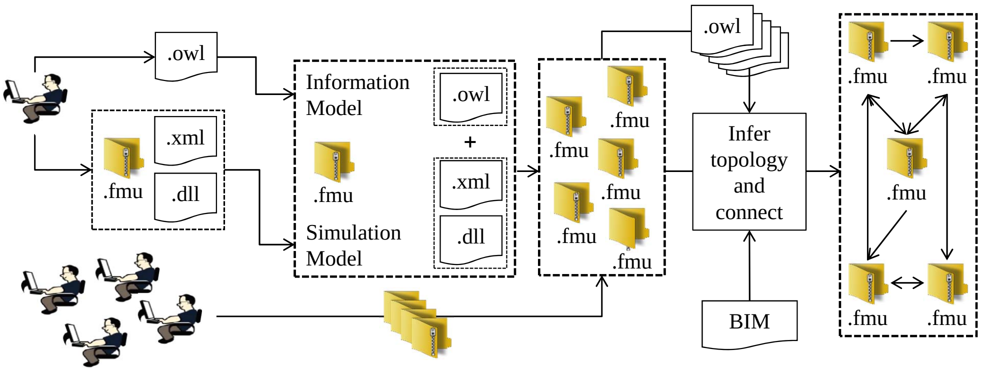

Figure 4: Process overview of the modular BPS from FMU annotation to the automated generation of the simulation topology.

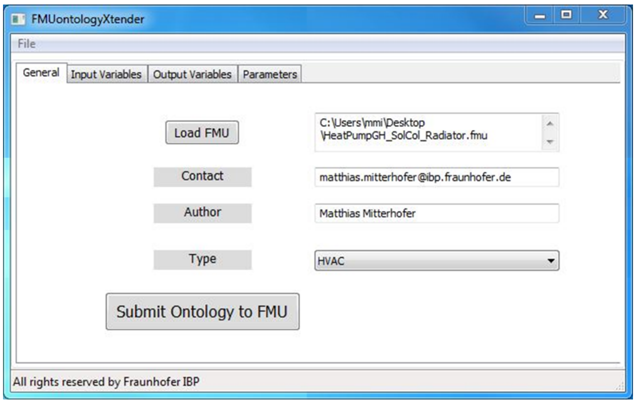

Figure 5: Graphical User Interface (GUI) FMUOntologyExtender for manual annotation of FMUs; loading and definition of general information.

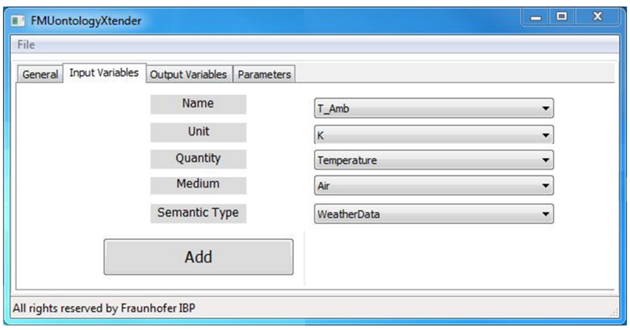

Figure 6: Graphical User Interface (GUI) FMUOntologyExtender for manual annotation of FMUs; annotation of input variables.

information needed for carrying out the simulation of buildings and is also translated to OWL (Pauwels et al., 2014). A framework for annotating simulation entities by means of ontology is presented by Leung et al. (2009). It allows for the consistency checking of manually composed simulations.

In order to retrieve information stored in ontologies as well as performing reasoning on them, the query language SPARQL, as described in W3C (2016), can be used. A concise introduction to the topic may be found in Hitzler et al. (2010).

FMUont - An Ontology for FMUs

In the following chapter, we present *FMUont*, an ontology to annotate simulation entities encapsulated as FMUs. The structure of the ontology is shown in Figure 7. Nomenclature and prefixes are used as depicted.

The central concept is *FMU*, which represents a single FMU in a simulation environment. The object properties *hasInputVariable*, *hasOutputVariable* and *hasParameter* relate each FMU to its respective input variables, output variables and parameters, which are all specializations of *AnnotatedElement*. To differ between variables and match corresponding input and output variables, it is necessary to define the *Medium*, *Quantity*, *Unit* and *SemanticType* of a variable by relating the annotated element via the respective object properties. Established ontologies from their respective domain can be linked here. For example, for the description of different types of media we recommend the use of ontologies like dbpedia (www.dbpedia.org). For the description of quantities and units we reuse the concepts provided by the OM ontology presented in Rijgersberg et al. (2016). It may be the case that the previously stated annotations are not enough to differ between two variables, e.g. indoor and outdoor air temperature; this information may then be added using a corresponding semantic type, as introduced

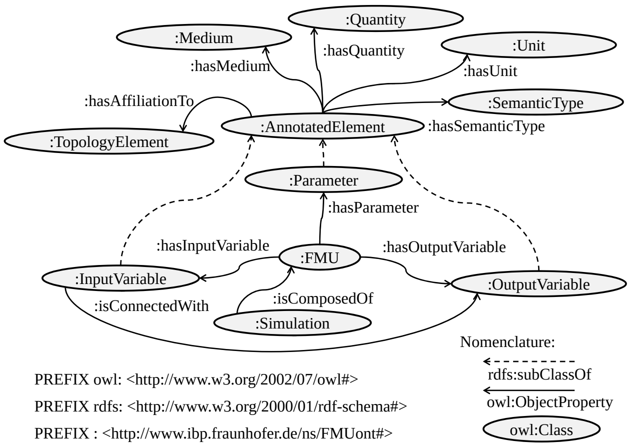

Figure 7: Structure of FMUont, an ontology for annotating FMUs.(Note, prefixes introduced allow for the definition of unique identifiers for abstract resources that may be beyond webpages and therefore cannot be displayed in a web browser.)

by Dibowski et al. (2010). To state a connection between variables of different FMUs, the object property *isConnectedWith* is introduced.
The relationship of an FMU to its corresponding simulation is modeled by defining the concept *Simulation* and an object property *isComposedOf*.
The description of variables through base properties and semantic information might not always be enough for the correct derivation of the connected variables. For example, in a building simulation, linking an FMU containing several separate zones to an FMU containing a radiator model for each zone, additional information is required to assign each radiator to its designated zone. In Figure 7, the object property *hasAffiliationTo* is a place holder to allow variables of FMUs to be related to corresponding objects in a system-level ontology. For the domain of BPS, we used SimModel (O'Donnell et al., 2011) to describe system-level topology, as it provides a profound basis of concepts in the BPS domain. Each variable can be related to an object in SimModel, thus providing access to the topological information within the building system.

Test Case Results

In order to validate and test the feasibility of the presented methodology, an implementation of a single and a multi-zone BPS is realized. The test case is set up with a fictional three-story office building with 360m^2 in total floor area located in Munich, Germany. The envelope consists of a well-insulated, concrete-based construction. Heating energy is provided by a heat pump combined with a solar collector. The entire procedure, as illustrated in Figure 4, is implemented using the Python programming language. The co-simulations are based on the loose-coupling algorithm explained in Trčka et al. (2009). Since

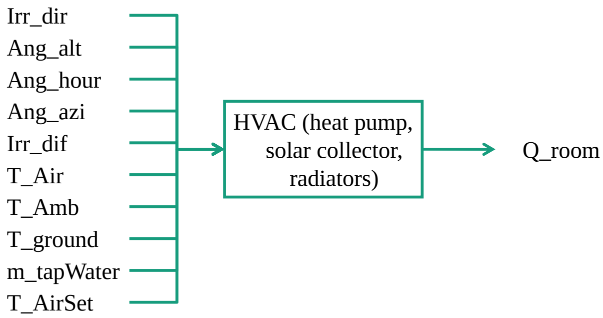

Figure 8: Input and output variables of the HVAC FMU.

the coupling algorithm is not the main objective of this study, the numerical inaccuracy of this coupling method is accepted in order to benefit from faster simulation times.

Single-Zone Test Case

At the beginning of a design project, simple assessments of design options, for example, to determine the influence on heat loads, can serve as valuable information for often far-reaching decisions. A single-zone BPS can lead to quick results at low effort based on little information. In the following example, an FMU representing a single-zone model of the building envelope is created. It has to be noted that the building FMU also includes the weather data model. This is due to the usage of EnergyPlus (Crawley et al., 2001) for the generation of the building model and its tool specific implications for exporting FMUs. The HVAC FMU inherits the heating system including radiators and thermostats to control the room temperature. The model computes the provided heating energy to the building and returns the magnitude of the heat flow as a single variable to the building FMU. The setpoint for the room temperature is provided by the occupancy FMU as well as internal loads. In order to consider the interaction of occupants with the artificial lighting system, a stochastic model based on Reinhart and Voss (2003) is included. To illustrate the FMU annotation process, Figure 8 shows the structure of the HVAC black-box simulation model. Each of the input and output variables is to be connected to inputs or outputs of other FMUs. Therefore, a description following the scheme in *FMUont* has to be provided for each variable. As an example, the description of the variable providing the value of the current air temperature inside the building zone, is provided in Table 1.
After integrating the FMUs into one simulation ontology, the reasoning process is started and derives the connections between the single variables. The resulting simulation topology is shown in Figure 9 with only the output variable names noted to maintain readability. Contrary to the following multi-zone simulation, an association to a BIM is not necessary for this step. Due to the presence of only one thermal

Table 1: Example of an annotated output variable from the building FMU for the single-zone test case.

ObjectProperty	T_air
hasMedium	Air
hasUnit	Celsius
hasQuantity	Temperature
hasSemanticType	ZoneCondition

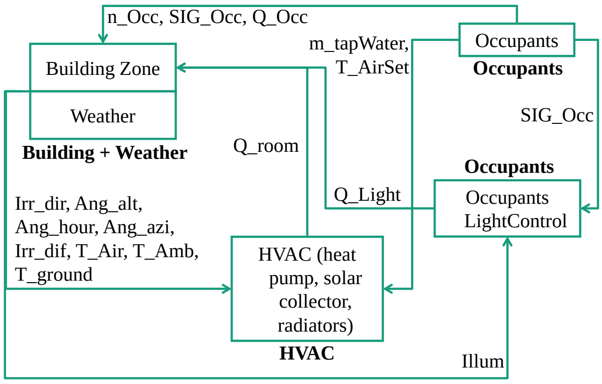

Figure 9: Resulting FMU topology of the single-zone simulation.

zone, the spatial association of variables is unique. The building FMU serves as a thermo-physical response model to the active systems and occupancy influences. The resulting effect, due to the interactions by means of the indoor air temperature, is shown in Figure 11.

Multi-Zone Test Case

For the multi-zone simulation, systems, parameters of the models etc. remain equal. Nevertheless, it is shown that the increased level of detail also leads to new insights and the seamless continuation of the simulation models can provide a valuable contribution to the planning process.

Although the simulated building system remains the same, the increased level of detail leads to changes in the contributing FMUs. The building FMU now incorporates four zones. Three of the four zones are regularly occupied and heated. Correspondingly, input variables for heat flow rates as well as occupancy need to be connected. The former is realized within the HVAC FMU. To comply with the latter, the occupancy FMU from the single-zone simulation is initialized three times with varying parameters corresponding to the people's distribution inside the building. The artificial lighting control is applied to one zone only.

In order to uniquely identify the connections between input and output variables now, an additional property associating the variables with the corresponding zones needs to be included. As Table 2 shows, the mere meta description of the variables without information from a BIM does not allow one to distinguish between the two variables.

Table 2: Example of annotated variables in the multi-zone test case. Zone information in italics.

ObjectProperty	Q_in_Zone1	Q_out_Rad3
hasMedium	Air	Air
hasUnit	Watt	Watt
hasQuantity	RadiativeFlux	RadiativeFlux
hasSemanticType	Heating	Heating
hasAffiliationTo	*Zone1*	*Zone2*

In order to realize the individual assignment to zones, every stakeholder contributing with an FMU is required to associate the interfacing variables with an object in the shared digital data model of the building, which reflects the semantic classification of the variable inside the project. In the present case study, a SimModel representation of the building system is used as the common data repository. Input and output variables of each FMU are associated with objects in the SimModel. Within the SimModel, queries formulated in the SPARQL language allowed for the retrieval of the related thermal zone, which can then be associated with the initial FMU exchange variable via the mentioned additional object property *hasAffiliationTo*. However, not every exchange variable can be affiliated to a thermal zone. Variables such as weather data, for example, do not possess such an affiliation; instead they are of a more global nature. The semantic description provided in the FMUs allows for the detection of these variables. A connection to the *TopologyElement GlobalEnvironment* is automatically created. This step is necessary in order to provide every variable with the later interrogated *hasAffiliationTo* property.

The connection to BIM objects finally enables a unique definition of each coupling path. Reasoning of the simulation ontology, just like in the single-zone example, then yields the *isConnectedWith* statement for each connection. Figure 10 illustrates the resulting simulation topology for the multi-zone test case with the variables requiring an association to a thermal zone in *italics*.

Simulation Results

Figure 11 shows the results of both simulations for a winter week in mid-February. As mentioned above, system composition and the parameters of the models are equal for the single and multi-zone simulation. It is shown that, in this case, the multi-zone simulation leads to an increased information gain. The single-zone simulation is not able to differ between heated and non-heated zones. The provided maximum heating capacity might not be enough to reach the setpoint of 21°C during office hours. When increasing the level of detail, the same heating capacity can be applied to the conditioned zones only and therefore results in an improved situation. Furthermore, during some days, the solar gains in the attic lead to an in-

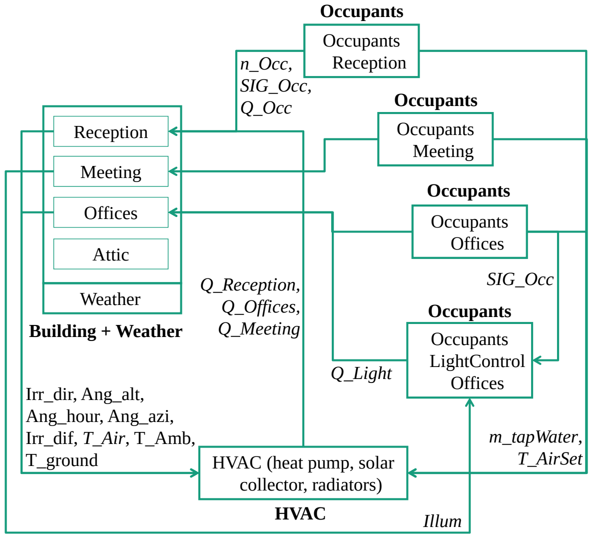

Figure 10: Resulting FMU topology of the multi-zone simulation (output variables of occupants models only stated once).

creased temperature level inside the single-zone level. The zone's thermal encapsulation, however, shows the more realistic behavior and the necessity to also heat the other zones during this time of the day.

Discussion

The implementation of the procedure, as depicted in Figure 4, proves its feasibility and provides valuable experience in order to validate the potential for future application in the planning process. It is shown that the modular approach based on FMI is able to meet the three mentioned requirements for future BPS concepts formulated by Clarke and Hensen (2015).

The modularization allows for the integration of dynamic models based on different physics in a whole system simulation through the consideration of the relevant interactions between the different domains. The same is valid for different planning disciplines. The modular setup allows every stakeholder to work in his own environment within his own area of responsibility, thereby taking advantage of his expertise and problem tailored tools. The specification of the interaction points with other domains allows for the consideration of every single domain in a fully dynamic simulation of the entire building system. This also provides the foundation to integrate the procedure into the design process. Every stakeholder finds his individual contribution and concept directly reflected in the simulation. The increased level of detail during the design process or conceptual changes can immediately be validated in the simulation independently from the progress of others. The performance of one's concept as well as the effects on other domains can directly be quantified.

However, some limitations have been identified. During the generation of the single simulation modules, the demand for a guiding framework by means of FMU categories became apparent. A structured partitioning allows one to avoid overlapping of functionality and ensures compatibility of the simulation units. Furthermore, it allows one to comply with the distribution of expertise and responsibilities in the design process. As an example, the following categories provide a simple basis for such a partitioning scheme:

- Building Envelope
- Environment
- Occupancy
- HVAC
- Building Automation

In order to fully exploit the advantages of modular simulation, the automated collocation procedure is a major requirement. Time-intensive efforts to combine the individual FMUs is an obstacle for possible adaptation by planners.

The deployment of OWL in order to realize the automated coupling provides large opportunities. Efforts, as mentioned by Kofler et al. (2012), Hong et al. (2015) or Pauwels and Terkaj (2016) have developed ontologies for building automation, occupancy behavior or the widely accepted IFC data model. The integration of such concepts can be achieved seamlessly, as shown for the OWL representation of SimModel. This ensures flexibility and a broad application not only in the planning phase but also after the commissioning of a building. However, the potentials and concepts to realize such an extension of the life cycle of a BPS are yet to be explored.

The present study emphasized the description of exchange variables in order to automatically derive the topology of a modular simulation. At this stage, the consideration of FMU parameters in the methodology has not been realized yet. However, the automated retrieval of product data from the web can lead to significant advantages during the design phase since real product data can be applied in a dynamic simulation. The performance of various products within the individual building system can therefore be tested in batch simulations and evaluated instantly.

Conclusion

This work presents a novel methodology to paving the way towards next generation BPS based on modular simulation techniques using the FMI standard. The problem of increased manual effort to collocate simulation modules in a full-system simulation when increasing modularization is solved by annotating FMUs. For this purpose, we introduce *FMUont*, an ontology to describe variables in simulation modules. Based on this self-description, the simulation topology is derived automatically through reasoning.

It is shown that the procedure meets the formulated BPS criteria and for the integration of various stakeholders directly into the process of generating a sim-

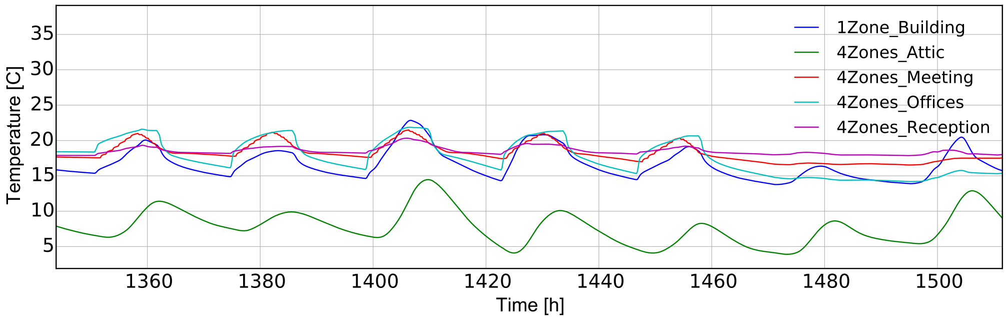

Figure 11: Simulation results for both, single- and multi-zone simulation.

ulation. The ontology is implemented using the established standards from the semantic web. This allows one to easily integrate various information repositories, e.g. information from BIM, in order to instantiate a simulation and connect to other web services. Such a distributed simulation environment potentially leads the way to the vision of a modular, interconnected web of simulation modules, i.e. an 'Internet of Simulation Things'.

The standardized exchange enabled through the FMI-standard combined with the automated collocation of simulation modules using a knowledge-based approach provides the technical foundation to realize prospects such as those described in Wetter (2011) by means of a drag'n'drop BPS. The methodology allows one to integrate every stakeholder's models and expertise into one consistent approach. Considering these aspects, the modular approach is accredited with high potential to mediate the development of next generation BPS tools.

Future work will address the integration of additional information repositories such as product data for parameterization as well as the export of a modular simulation to the cited platforms in order to ensure numerical robustness. The development should be aligned with current advances of the FMI standard, such as the SSP-project (Köhler et al., 2016).

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