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An FMI-enabled methodology for modular building performance simulation based on Semantic Web Technologies

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ABSTRACT

The concept of modular building performance simulation has been accredited with considerable potential to realize the vision of an integrated building simulation platform for several stakeholders. Current literature identifies missing technological advancement as the key obstacle for its realization. This work presents a methodology that incorporates the Functional Mock-up Interface, Semantic Web Technologies and Building Information Modeling to realize a modular building performance simulation. The approach is based on the specification of Functional Mock-up Units using a formal information model. This allows to set individual simulation modules in context with an overarching data framework in order to identify their role within a building performance simulation. Through the additional association to project-specific information in a digital representation of a building, an algorithm is able to automatically infer the simulation topology of an arbitrary number of contributing simulation modules by means of reasoning. An example demonstrates the feasibility and indicates the technological potential of the approach.

1. Introduction

With the connection of several fields of expertise and a rising number of inter-dependencies, buildings are evolving into highly complex systems. Continuously increasing requirements concerning key performance indicators (KPIs), e.g. energy usage, comfort, day-lighting etc., and the development of numerous innovative technologies in various areas augment the challenges for practitioners. In this regard, Building Performance Simulation (BPS) has been a supporting technology for several decades. Efforts as presented in Refs. [1] and [2] have improved tool functionality in order to provide the required integral view within simulations. However, recent literature identifies limitations of current simulation processes regarding the integration of BPS into the design process [3,4] leading to a stagnation of its application in practice.

In order to overcome this issue, Attia et al. [5] demand a harmonization of tools with the design process in terms of continuing information enrichment and scalability of models. An evolution of the simulation model through the design process from early stage representation to high-resolution is necessary to adapt to the planning process. Struck [6] congruently emphasizes the need for tools being able to dynamically scale the model resolution as the design proceeds and deepens in planning details.

A further deficit is the missing capability to fully support an interdisciplinary design process (IDP). Negendahl [4] states that the "best performance outcomes can be expected to be reached through mixed design teams consisting of engineers and architects". The radical change of buildings towards complex technical systems intensifies the need for such a multidisciplinary design approach. In Ref. [5] the authors therefore call for the possibility of different user types to be able to execute simulations in order to test their anticipated design option and its effects on other domains. Work in different fields must be represented jointly within the simulation at a dynamic level avoiding simplifications in order to detect interdependencies and their significance for the overall performance [7]. However, as elaborated in Ref. [8], the simulation executing person is generally not the same person who generates the need for a simulation. Instead, information about a design

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option is provided by one person and subsequently processed to be included in the simulation by a second person. The resulting time delay in designing and receiving performance feedback presents an unsatisfactory aspect in the decision-making process. Attia et al. [5] term this discrepancy one of the largest problems in early design optimization.

Addressing the issue of missing user integration, Hensen [9] proposed an open simulation environment that allows for feature and model sharing among multiple stakeholders including producers, manufacturers and even building owners. He suggests a modular approach for future environments in which single units communicate in a co-simulation setup to form a holistic simulation. The concept is congruently [3,7,10,11] accredited with considerable potential to meet the mentioned criteria, namely: *integral building view, scalability, integration of multidisciplinary users and openness.*

Mazzarella and Pasini [7] argued that technology-driven research is required on the path to such solutions. This especially involves efforts regarding the possibilities of current information technology. In 2015 Clarke and Hensen [3] indicated that missing efforts and little progress concerning the communication between tools led to low prospects on such an integrated BPS platform that is harmonized with the needs of its users.

In this work, we present an approach to realize a modular simulation that can serve as a mediating concept on the path to an open simulation environment. Simulation modules generated from several tools compliant to the Functional Mock-up Interface (FMI) standard are collocated automatically to cooperatively form a BPS. Recent developments in information technology, namely the Semantic Web Technologies [12] and Building Information Modeling (BIM) are applied to set single Functional Mock-up Units (FMUs) in context with each other through a common information model. The formal specification of FMUs by means of ontology enables a reasoner to ensure the integrity of the simulation through automated inference of the simulation topology. After an elaboration of the state of the art in modular simulation and an overview of supporting technologies, the methodology will be highlighted. A subsequent example study illustrates the feasibility and prospect of the approach, followed by a discussion of its characteristics and ideas for future extensions.

2. State of the art

Modular Simulation. The concept of modular simulation can be described as a process in which numerous entities, called objects or modules, working as stand-alone simulation models communicate in order to simulate a system consisting of these components. It originates from object-oriented simulation processes as formerly described in Refs. [13,14], or [15]. Mazzarella and Pasini [7] substantiated the conceptual idea and established a consistent description allowing for a differentiation of modularity on four levels.

- Functional layout modularity: The possibility to recombine design-functional elements to increase the flexibility and end-user-friendliness for simulation configuration.
- Mathematical models modularity: Mathematical modification of a sub-model does not require changes in the entire system model, i.e. connections between sub-models are restricted to inputs and outputs.
- Standardized mathematical models modularity: Allows new mathematical models, as single units, to be instantly compatible with other simulation modules.
- Code's modularity: Describes the possibility to reuse code following paradigms of object-oriented programming.

An example for modular co-simulation is shown in Ref. [11] with the coupling of a Heating, Ventilation and Air Conditioning (HVAC) and a building model. The author emphasizes the advantages regarding the flexibility of simulations and tool-capability extension. However, it is remarked that a considerable amount of time and expertise is required for the realization of communication protocols between tools, which might differ for varying tool combinations. A step towards the facilitated interoperation of tools was realized with the launch of the FMI.

FMI. The FMI is a tool-independent standard first published in 2010 [16] and in 2014 released in its revised form [17]. It enables the export of simulation models as FMUs, allowing for the exchange of stand-alone models or their usage in co-simulation setups independent from the source tool. The exported black box units encapsulate an *xml* file containing descriptions of the model parameters, inputs and outputs as well as further meta-information. A second file inherits the functionality of the model in the form of a dynamic link library (*dll*). This ensures the protection of the original source code and therefore intellectual property. The mentioned characteristics set limits for the usage of FMUs. Whereas values of parameters can be varied and adapted to individual purposes, the inherited functionality of the model can not be changed.

In the field of BPS, several studies have shown the benefits arising from FMI. Since the focus of this contribution lies on the co-simulation functionality, the following examples are chosen correspondingly. Pazold et al. [18] successfully coupled FMUs representing HVAC systems to the existing simulation tool WUFI® Plus. In this case, the benefits of the Modelica languague were used to extend the software tool with dynamic HVAC system models. Nouidui et al. [19] implemented the interface in the building simulation software EnergyPlus [20]. Two case studies involving the coupling of a ventilation model and a shading controller to a building model in EnergyPlus were conducted. The authors accredited the FMI with considerable potential to contribute to the challenges involved in establishing an integrated building simulation process. In Ref. [21], Plessis et al. coupled a building including its heating system to the occupancy simulator SMACH. The setup allowed for the integration of the dynamic response of a building system with the occupancy simulation.

The examples follow an identical scheme that shows the increased possibilities of a simulation tool when extended with features from a different tool through the FMI standard. The simulation tool serves as the master to the co-simulation, triggering the step-wise execution of the FMU and the simultaneous exchange of data.

Contrary to the scenario above, platform solutions allow for the execution of an FMU co-simulation independent from the modeling tools. Platforms such as described in Refs. [22–25] offer master algorithms to effectively trigger simulation steps of contributing FMUs through the detection of continuous or discrete simulation dynamics, while maintaining numerical correctness of the co-simulation. Besides the orchestration of the simulation process, some platforms provide further functionality, such as outsourcing the simulation to local clusters or other computational resources through cloud technology.

Current Issues. At present, two main issues are encountered when working with FMI co-simulation. The first aspect is the disadvantage of increased simulation time due to frequent data exchange among simulation modules and drawbacks for solver algorithms resulting from the partitioning. The mentioned platforms present a remedy to this issue by ensuring a nearly unlimited source of computational power and optimized co-simulation solvers. Concrete performance comparisons, however, are still missing.

A second issue imposed by the modularization is the collocation