FMI-Based Co-Simulation of Multi-Agent Occupants Models, with Modelica Building and HVAC System Models

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Abstract

The conversion of the energy supply from fossil to renewable energy sources represents an immense challenge for technicians and engineers as well as the energy industry. The power supply with its short response times, low storage capacities and a largely liberalized electricity market is of particular importance in this respect.

In regards to this, the consideration of the occupant related influence on daily and seasonal energy demand is gaining in importance, in many building domains such as heating and cooling. Due to increasing energy efficiency of buildings, exclusively weather dependent, static energy demands are being replaced by occupancy related demands (e.g. water heating). The importance of other domains of building energy consumption, such as cooling, are also increasing proportionately due to ever changing comfort requirements.

Due to the volatile availability of renewable energy resources, the mere consideration of cumulative energy quantities is no longer possible. The evaluation of new solutions can thus no longer be based on existing standard load profiles or annual and monthly energy balances, respectively. A higher time and local resolution of the energy supply is necessary. This major requirement of building performance simulation is important for both building design and control during the planning and the later-on operation phase.

Multi-agent simulation systems enable the consideration of individual and group behavior as well as machines and machine groups automatically and individually, in the planning of a future energy supply. The world of the interdisciplinary modelling language Modelica offers a variety of suitable simulation libraries for the evaluation of renewable energy production and storage, sector coupling for heat and cold supply, electric mobility and other energy systems. This paper describes the possibility of coupling both simulation worlds with the help of the Functional Mockup Interface Standard implemented, using a suitable application example.

Introduction

Building engineering requires extensive work effort as it combines a wide range of different engineering perspectives such as heating and cooling, air treatment and comfort, power supply, controller design and automation as well as connected tasks like mobility demand management. Heating power consumption highly decreases due to improved insulation and more efficient heat supply systems, smart control and renewable integration. Furthermore, energy supply is progressively changing from fossil fuels to local renewables and grid sources, like district heating and cooling.

In the design of heating and cooling systems, building planners focus more on a temporally, high-resolution evaluation of occupant behavior. The high storage capacities of a building result in a significant time offset between occupant (re)action and energy demand. This reaction-time offset increases complexity however, often has major influence on the development of innovative, smart control systems. The coupling of energy generation in the domains of heat, cold and electricity and the different considered, local storage capacities also influence this development.

Furthermore, building engineers of today increasingly consider the buildings' power consumption, own-production and storage as a main part of their energy supply system. One major task is to design power supply systems by evaluating different variants of local renewable power production, including local energy storage and smart control algorithms. This includes a high-level analyzes of occupants' behavior as they are often responsible for 80% plus of overall power consumption.

In addition, renewable power supply and storage address important topics such as availability and security of supply. Due to the increasing complexity and the dynamic nature of consumption, former analyzing methods regarding only average and overall consumption or monthly intervals, are not suitable for an advanced system layout. New methods are needed to compare future energy availability and consumption dynamically.

Figure 1: Comparison of measured power consumption profile in different buildings and corresponding standard load profile of the utility companies (Eckhardt, 2017)

Figure 1 shows the comparison of the measured power consumption profile in different residential buildings with the utility company's standard load profile of the same energy amount. The figure shows that the single resultant power peaks are much higher than any standard load profile maximum and that measured basic loads are much lower. The combination of all consumption profiles of a city district however, still result in the standard load profile. The previous approach of energy supply planning is therefore, still correct. However, by applying these average profiles an accurate definition of suitable PV systems, decentralized battery sizes and the implementation and test of a suitable battery control are not possible.

Scientific Overview

The integration of multi-agent-simulation models, in building performance simulation has been a major aim of many researchers and engineers, during recent years. Thus, a wide range of about 100 different multi-agent-simulation platforms (c.f. Sangi et.al., 2017) have been developed and tested in different domains. A brief overview of recent scientific papers shall describe the background as well as the scientific foundation of the following presented co-simulation approach.

This analysis summarizes the evaluated references into the four different topics, which are explained within the next paragraphs. A number of relevant studies and papers mainly describe copious evaluations of existing measurement data of occupancy behavior with the aim to develop suitable occupancy models.

Adolph et. al., 2015 presents the development of occupants' presence profiles of different room types, in residential buildings based on preset probability matrices. They use Markov Chains. Itagaki et. al., 2015

provide extensive analysis of available measurement data representing power consumption in residential buildings, to define different agent types regarding electrical energy demand. Mahdavi et. al., 2015 evaluate available occupancy data, in offices, to define corresponding multi-agent-models, for building performance simulation purposes. Dimitrov et. al., 2016 focus on private households. They establish a holistic approach to describe the buildings' energetic behavior, including an agent-based description of the complex occupants' behavior (i.e. with domestic water consumption, window opening, comfort set points, presence and activity).

Other papers mainly use or extend existing multi-agent-simulation systems and frameworks to conduct case studies regarding different application scenarios.

Schaumann et. al., 2017 propose a narrative approach to represent occupants' behavior and test it in a case study of a hospital ward. In Nikolopoulou et. al., 2015, multi-agent-models were used to optimize the energy consumption in regards to thermal comfort, in a small campus with three different building types. Stefanioiu et. al., 2015 analyze a net zero energy residential building regarding influences of different types of inhabitants. This study shows in particular, the actual influence of occupants' behavior on total energy consumption in modern, energy efficient buildings.

A third share of scientific work with multi-agent simulation systems focuses on agent-based system control. Both evaluated papers focus on thermal simulation models of buildings. Bauer et. al., 2016 uses software agents to process sensor and actuator data, to sufficiently control passive building construction parts as additional thermal storages. In Sangi et. al., 2017, a new

Figure 2: Basic software structure of SimulationBus framework

Modelica library is presented which provides interfaces between Modelica HVAC system models and connected multi-agent-simulation models via UDP/IP standard. These agents are closely related to the physical HVAC system models and therefore serve as control units.

The last category of analyzed papers mainly addresses approaches of simulator coupling between multi-agent-simulation and physical building and HVAC system simulation models, with the aim to establish a co-simulation. Chapman et. al., 2017 provides a framework (i.e. No-MASS) which co-simulates Energy Plus building models with the corresponding multi-agent model via an FMI connection. These models focus on occupants' presence, activity, location as well as blind, light and window control.

The second relevant paper in this category presents a real-time co-simulation between Modelica's energy system models and JADE as a multi-agent simulation platform. Constantin et. al., 2017 establish this connection via a TCP/IP interface to the technical equipment of office spaces.

This short excerpt of already conducted scientific work in the field of multi-agent simulation and simulator coupling shows a wide variety of applications and existing solutions. The following paragraphs will show a corresponding approach of a performant FMI-based simulator coupling between the Modelica-based simulation environments SimulationX as well the Netlogo multi-agent simulation tool set. The conducted case studies focus mainly on the influences of electric

system design including renewables integration as well as storage dimensioning and control.

Simulation Framework

Dynamic simulation environments like SimulationX with suitable application-specific libraries (e.g. Green City for HVAC and power supply system simulation) can extensively help engineers to meet the introduced challenges. Green City is a simulation package, which provides a wide range of system components for holistic modeling of heating, cooling and power supply, storage and consumption in the scope of a city quarter. It enables the user to simulate sophisticated HVAC systems including renewables, storage, control strategies and eMobility.

SimulationX is however, mainly focused on multi-domain simulation of deterministic physical systems and not designed to simulate human or corresponding stochastic behavior. Therefore, a number of highly-performant multi-agent-simulation tools, like JADE or AnyLogic, etc. are available. These tools offer engineers a simulation framework to describe this stochastic behavior.

This contribution describes a coupling to the multi-agent simulation framework NetLogo [1]. This is a standalone scripting language and framework based on JAVA. It is accessible via superordinate software and can establish a co-simulation. The visual representation is limited and methods must be scripted independently. This tool is very popular in both teaching and research. Netlogo has a large library of ready-made sample models that can be used and extended.

Figure 3: Integration concept of variable multi-agent models in a co-simulation with Modelica-based building and HVAC system model

Coupling both powerful tool sets via the Functional Mockup Interface standard (FMI) enables the engineers to benefit from several advantages, like domain-specific solvers, etc. To exploiting these, a coupling FMU is automatically created via the SimulationBus framework, which establishes a variable step size communication via TCP/IP, protocol between the SimulationX model and the NetLogo multi-agent system.

This software framework includes a number of different modules that automatically create FMUs of standard 1.0 and 2.0 and thus enables the communication between different simulation (e.g. SimulationX) and controller platforms and languages (e.g. Python, Java, etc.), via native communication or web services. Figure 2, briefly describes this set of modules which are mainly all derived from the SimulationBus Core software.

This basic software environment has been implemented in Java and provides suitable clients for any desired platform, e.g. Python, Java, C/C++, etc. It additionally integrates a Netlogo Client. This client automatically runs any modelled multi-agent-model and exchanges required simulation data between a coupling FMU in a Modelica building and HVAC system model, and the Netlogo model during a co-simulation.

Co-Simulation Approach

The occupants' behavior has a major impact on the total energy consumption of a building, especially when regarding an increase in building energy efficiency due

to better insulation and heat recovery. Occupants are responsible for the energy consumption in different building domains and thus influence the corresponding behavior of HVAC and power supply systems as well as building controllers.

To define occupants' behavior and at least occupants' type in a multi-agent model, a detailed definition of the considered building type is required in advance. When considering industrial applications, like production halls, with highly specific energy consumption profiles and individual machinery, an extensive but individual set of dependencies between occupancy, building control and energy supply infrastructure, need to be defined.

The present approach thus focuses on common applications of building performance simulation, like residential or office buildings. Complex industrial applications are feasible. However, this requires a sophisticated definition of individual agents and types of agents.

Figure 3 shows an overview of the developed co-simulation approach, including a variable multi-agent model as well as a Modelica-based building and HVAC system model. Both are connected via a Functional Mockup Unit (FMU), which establishes a suitable co-simulation interface between both simulation platforms.

The multi-agent-model (Eckhardt, 2017) in Netlogo includes two different types of agents, persons or groups of persons in the building as well as technical

Figure 4: In-the-loop control of blinds and lighting

equipment, like electrical consumers or building and HVAC system components. Each person's agent can make its own decisions depending on a pre-defined set of characteristics (e.g. perception of light and temperature comfort). Several persons can also react dependent on each other's behavior. Agents that represent technical equipment (e.g. washing machine as a simple consumer or window blinds as interactive part of a building control system) also include specific characteristics (e.g. maximum minimum shading; power consumption profile). However, these equipment-agents can only be switched-on by person-agents and have no further interaction with other agents in the multi-agent model. If there is a correlation with the connected building and HVAC system model, they can still affect the persons' behavior via the implemented co-simulation

link (e.g. activate window shading – daylight intensity decreases – occupant activates lighting – power consumption increases – etc.).

This variable approach adds many degrees of freedom to the required multi-agent model. To avoid extensive engineering work the presented toolchain includes a Python-based framework (c.f. Figure 5), which represents a new approach of automated multi-agent model generation depending on a specific set of input parameters. Three types of lists define these inputs:

- Occupants list
- Activity list
- Equipment list

The occupants list defines a number of different categories of persons. Regarding residential buildings,

Figure 5: Automated approach of multi-agent model generation with Python and Netlogo templates

Figure 6: Co-simulation of Green City building model and NetLogo multi-agent model via FMI

these can be children, students, working, unemployed and retired persons. Each of these categories results in different daily routines, which are individually defined in the activity list (e.g. wake up, shower, cooking, entertainment, etc.). The equipment list furthermore characterizes specific properties (e.g. power consumption of consumers) of relevant system components in the multi-agent model. Additionally, this list defines each component's individual operation type (e.g. base load, time-controlled, weather-dependent and controlled by agents). The Python generator finally takes the implemented building structure and the pre-defined usage scenario to assemble a suitable multi-agent model with the information of the above-described lists and a pre-defined NetLogo template (c.f. Figure 7).

Figure 7: Structure of Netlogo template model

The opponent part of the co-simulation is a multi-domain Modelica-based building and HVAC system model. This model calculates the total heat, cooling energy and power consumption of the building based on external weather conditions as well as the operation of the implemented technical equipment (e.g. lighting, heat pumps, CHP, renewables, storages, etc.).

To improve the model accuracy the presented co-simulation approach adds a multi-agent-simulation model, accurately defining the probability-based occupants' behavior. This is especially necessary to implement the closed-loop control of the building control system, like shading or lighting, which have major influence on total energy consumption. This also paves the way for additional applications of building performance simulation models, i.e. in-the-loop tests of control algorithms.

Figure 4 shows a comparatively simple example; the control cycle of lighting and window blind control dependent on available daylight in a room. The multi-physical simulation model thus calculates the natural light intensity in a room. This input signal is used by the multi-agent simulation model to calculate the person's response. This can be the adjustment of the existing blind (e.g. upwards if the room is too dark or downwards if the room is too light) or the usage of artificial lighting. These reaction results are returned to the building model in the co-simulation loop to calculate the adjusted power

consumption due to lighting as well as reduced or increased solar heat gains depending on shading.

The actual co-simulation interface between the multi-domain building and HVAC system model as well as the multi-agent simulation model is an FMU with several inputs and outputs. Figure 3, shows a consistent set of required input and output variables of this co-simulation interface for residential and office building applications.

From the HVAC system's perspective, inputs are categorized as input data and reference values. Input data mainly defines additional building loads, like power and warm water consumption, which have only minor retroactive effects on occupant behavior. Reference values additionally characterize set points of specific building and HVAC system model components (e.g. reference shading of blinds), which are defined by the multi-agent model depending on its agents' decision-making.

The outputs are also divided into two categories. Measurement values describe the delayed reaction, of different parts of the building and HVAC system model, on the changed system or control set points. They directly affect the behavior of the implemented agents. Evaluation results (e.g. energy prices) might also influence the agents' behavior in a higher-order decision-making process. However, an implementation of long-term decision-making processes, in the multi-agent simulation model, have not yet been developed.

Application Example

This paper already motivated the necessity of coupled simulation frameworks, which combine building performance simulation and an accurate multi-agent-model-based description of occupancy behavior. The following paragraph shows a simple application example of such a framework in the building planning process.

This example represents a typical task of building engineers, the design of a coupled renewable power supply system with connected storages in residential buildings. Thus, usual study cases in East Germany are 10-storey prefabricated buildings with 40 flats per each entrance. This application example analyzes the size of a suitable photovoltaic system depending on different numbers of power-supplied flats as well as battery storage capacity.

The implemented framework automatically generates different Netlogo models depending on occupants' type and number described with the help of the activity, occupants and equipment list. The co-simulation framework then calculates PV power production as well as corresponding battery behavior. A multi-criteria variants analysis provides relevant data to find an optimal solution regarding system costs, renewable footprint and benefits for the occupants.

The design of a renewable power supply system, including sufficient storage capacities for grid balancing, is dependent on a number of different influencing characteristics. Residential buildings in Germany, with a high share of tenants, represent a major challenge in

particular. Each individual tenant can sign an individual power supply contract with a local or even international energy supplier. Due to this the produced renewable energy from the building's roof (e.g. by photovoltaic) has to be sold individually to each tenant. There is however no obligation for tenants to purchase the amount of produced renewable energy. The size of the photovoltaic and battery system therefore highly depends on the number of tenants supplied and their individual consumption profiles.

Figure 6 shows a simple Green City building model of a residential building that describes the thermal and electrical behavior of different apartments and floors. It is supplemented by a coupling-FMU, which links a NetLogo model that describes the residents' behavior, to the simulation. Both models run in a co-simulation. In this case, the multi-agent model only provides detailed data about the residents' presence and power consumption (e.g. via household appliances). These are used as variable input data in the SimulationX model to accurately model inner building loads. This model additionally adds an accurate photovoltaic system and variable stationary battery model to the considered building model. The implemented battery control strategy aims to balance grid consumption and grid feed in to zero. An extensive parameter study varied battery size as well as number and type of inhabitants, which are partly supplied with power from the photovoltaic system on the roof or the building internal battery storage.

Figure 8 shows some exemplary results of the conducted case study for a share of 50% of participating tenants and a variable battery storage size (in 10 kWh steps).

Figure 8: Case study results of different battery sizes and corresponding autarky degrees for a share of 50% participating tenants

An increasing battery size provides an increased autarky degree, i.e. the bigger the battery size, the higher the amount of renewable energy, which is supplied to the participating tenants. However, additional battery capacity above 60 kWh does not significantly improve the autarky degree. Thus, the conclusion can be drawn that additional capacity in this saturation region is not cost-effective. With these results, it is easily possible to

identify the optimum battery size for any share of tenants' participation.

Summary and Conclusion

This paper describes an approach to establish a co-simulation between multi-agent simulation models (here: NetLogo) together with Modelica-based building, HVAC and power supply system models (here: ESI ITI's SimulationX / Green City). The paper focusses on a consistent workflow for extensive planning projects regarding an automated model generation as well as the definition of a holistic set of exchange variables of the co-simulation interface based on the SimulationBus framework.

Another focus is on the integration of accurate multi-agent models, which are able to replace existing static approaches of occupancy behavior description (e.g. standard load profiles defining power consumption characteristics) with more accurate solutions. This includes a suitable result validation with available measurement data.

Figure 9: Measured consumption profiles in different buildings (Tjaden, 2015)

Figure 9 shows measured power consumption profiles in different small residential buildings in Germany based on an extensive monitoring study of HTW Berlin (c.f. Tjaden, 2015). These are measurement values for one week with a high time resolution. Furthermore, average power consumption and average peak-power level represent characteristic, probabilistic behavior.

Figure 10: Corresponding output of the implemented multi-agent models of similar building structures

Figure 10 shows the corresponding power consumption output of the implemented multi-agent simulation models of similar building structures regarding the measured example buildings in Figure 9. The depiction shows that the simulated maximum peak power and the corresponding average are at the same level when compared to the measurement values (c.f. Figure 9). The

high peaks result from the high temporal resolution (60 seconds) of both the simulation models and the measurement values as well as the accurate description of the consumer system setup. The resultant total energy consumption of these profiles is also equal to those of the measured values. These indicators suggest that the implemented multi-agent approach fits the defined accuracy requirements. Thus, the multi-agent model approach can ultimately be implemented as a powerful tool in building engineering and planning.

The implemented approach provides several advantages. On the one hand, an automated multi-agent model generation helps engineers to run a high number of occupancy scenarios for a consistent system evaluation with suitable building and HVAC system models. On the other hand, the co-simulation enables the evaluation of occupants' reaction on the simulated system behavior within one simulation loop (c.f. shading vs. lighting in Figure 4).

However, a co-simulation framework is mostly not as performant as single simulation models with external offline input data sets (e.g. txt-files defining occupants' behavior). A brief comparison of both approaches showed that the co-simulation master including all communication increases simulation time about ten times; e.g. from 6 to 60 seconds per simulated day for the chosen application example with a temporal resolution of 1 minute. This is not always feasible for complex engineering tasks and whole-year simulation runs. But, it is always suitable for controller evaluation with input data of different reference days or weeks.

Acknowledgements

The presented work is partly funded by subsidies from the German Federal Ministry for Economic Affairs and Energy.

Supported by:

on the basis of a decision
by the German Bundestag

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