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A new method for optimizing operation of large neighborhoods of buildings using thermal simulation

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ABSTRACT

Energy consumption in buildings is a key factor when accomplishing national and global CO_2 emission goals. The economic savings per building are limited and are difficult to argue. However, the efforts can be aggregated on district or city level: the approach described in this paper is a large scale co-simulation environment that helps to leverage efficiency by providing quantitative information about the efficiency impact on large scale, while minimizing the efforts in modeling single buildings. It addresses the challenge of modeling thermal behavior of a large neighborhood of buildings in order to calculate energy demands, regarding weather conditions, shading and room temperature settings with a time resolution below one hour. A proof of concept applies the method to a demonstration site of residential buildings and shows the heating demand and CO_2 footprint of the neighborhood.

1. Introduction

The European Union has declared reduction of energy consumption as one of its main goals and manifested it, amongst others, in the Energy Performance of Buildings Directive (EPBD) [1]. The building sector, including both residential and non-residential building stock, has significant impact on the European energy policies: buildings are responsible for 40% of the overall energy consumption in the European Union as well as 36% of all greenhouse gases (GHG) [2]. Measures to reduce GHG in planning and operation of buildings thus have strong leverage, especially when applicable to large building stock and not only to single buildings. Such measures include refurbishment measures in the façade and in the building's energy systems, but also refer to changes in operation of the building. As 80% of the energy is used during operation the energy management of buildings (and neighbourhoods of buildings) provides a way to increase efficiency while keeping investments cost low.

A quantitative assessment of the impact of measures like adapting control strategies in building management supports the decision process, but requires detailed analysis of the impact. For single buildings the impact of building automation on energy efficiency is described in the standard EN 15232 [3]. Neighborhoods of buildings that are energetically coupled e. g. by a common heat distribution grid, can also exploit the optimization potential each building for itself, but have additionally the possibility of coupling optimization efforts. This allows for multiplying the effect of a measure.

The method described in this paper exploits this multiplication effect by addressing the energy provisioning side of a neighborhood of building. Through better coordination of buildings' operation it is possible to reduce the overall CO_2 emissions of a central heating system that supplies the neighborhood through a heating grid. In order to exploit the efficiency potential it is necessary to have detailed understanding of the energy flows in the system. A mere energy balance analysis of heat provisioning and building heat demand does not suffice; instead, a dynamic production and consumption profile with a time resolution well below one hour is needed, otherwise it is not possible to assess, for example, peaks in the energy profiles. The system boundary is therefore drawn around energy provisioning, grid and building neighborhood and requires modeling of the components in sufficient level of detail.

In order to constrain modeling effort for creating the building energy profiles a method has been developed that allows to rapidly create building models for a large neighborhood while still regarding effects like characteristic heat losses, solar irradiation, orientation, shading and indoor temperature. This is achieved by employing a fully-fledged, dynamic thermal simulation tool, while at the same time significantly reducing the modeling effort through simplification and automation. The method is built upon the inte-

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gration of thermal simulation into a co-simulation platform. The workflow to apply this method includes three steps:

1) Geographic information system (GIS) based geometry creation
2) Automated building model including building physics, floors, glazing, thermal zoning and controls
3) Co-simulation and analysis

As proof of concept a demonstration site in Germany has been selected, which consists of 72 residential buildings that are connected to a local district heating plant. This heating plant produces heat for the buildings using three energy sources:

1) Renewable biomass source of wood chips (RES)
2) Combined heat and power plant (CHP)
3) Backup gas boiler

A simulation scenario has been created where the operation of the neighborhood is influenced towards the global goal of minimizing CO_2 emissions of the different components in the heating plant. This optimization requires thermal simulations of all 72 buildings regarding outside weather conditions, solar irradiation, orientation, and also shading effects between buildings.

The rest of the paper is organized as follows: Section 2 gives an overview of this paper's framework and the existing work, Section 3 explains the process of GIS data extraction, while Section 4 focuses on creating detailed thermal models. Section 5 gives an insight into the workflow within the co-simulation environment, Section 6 shows the results and the proof of concept of the introduced method and Section 7 concludes the paper.

2. State of the art

Residential and non-residential building stock has the potential to support decarbonizing economy, if CO_2 emissions are reduced significantly: the European commission aims at 50% energy consumption by 2050. Especially residential building stock is a major challenge, but is also a good opportunity for implementing sustainable business growth. Aside of decision support on European level, also tools for specific objects are required that are capable of assessing the planned and actual consumption of buildings. CitySim, for example, is an urban energy use simulator and it can calculate the energy needed for heating, cooling and lighting [4]. It uses information about the building physics as well as local information e.g. shading trough surrounding buildings. Each building model is represented using an equivalent electric circuit (RC-model) to describe the dynamics of the building. This is a coarse model sufficient for city simulation but not reflecting, for example, temperature distributions within the building. Due to its capability to calculate the energy demand of a large number of buildings, all information needs to be available in XML-format. This requires on the one hand a database to handle all information, on the other hand the mandatory information of each individual building needs to be known and available, which can be a tedious task. Other available simulation tools for district or city level energy systems are compared in [5]; however, the level of detail does not include the capability of deep influence of building energy systems (e. g. implementing room control).

The nationally varying energy certificates assess the expected energy demand of buildings during planning phase and give a coarse estimate. For detailed analysis of building performance tools for thermal building simulation are required. These tools rely on building models including information about the building geometry, spatial relationships, geographic information and building properties [6]. Developing building models is a resource intensive task due to its complexity in the modeling process and the preparation of the necessary building information. The market provides several building simulation tools, which differ in complexity and user-interface. State-of-the-art building simulation environment is EnergyPlus [7] and TRNSYS [8]. Both focus on building energy performance simulation and are widely used in the research community and in engineering practice. With both tools it is possible to create a building geometry model and its internal heating, ventilation and air conditioning (HVAC) components. EnergyPlus is an open source tool and offers a wide range of interfaces like DesignBuilder [9] or OpenStudio [10]. EnergyPlus has been the tool of choice in this research work due to its capability of parameterization using text configuration files.

The coupling of tools for co-simulation has been realized a number of times within the context of building and district energy simulation. Maybe the most well-known and successful example in this regard is the *Building Controls Virtual Test Bed* (BCVTB) [11], which provides dedicated interfaces to link a specific set of simulation tools and hardware devices. This and other approaches successfully combined different simulation tools in order to exploit their individual features. However, due to the lack of a generally accepted specification for application programming interfaces (API) for co-simulation, all these approaches come up with solutions that were mostly incompatible with each other. Thus, the API implementations for the various tools usually had to be maintained by the developers of these approaches themselves. Among other things, this led to an increased effort generally associated with co-simulation approaches.

This situation started changing with the introduction of the *Functional Mock-up Interface* (FMI) [12] standard. FMI is a non-proprietary, industrial-strength specification developed by both academia and industry, which provides a simple and generic specification for APIs for co-simulation. To be more precise, the *FMI for Co-simulation* (CS) specification defines stand-alone black-box simulation components that can be directly linked within a co-simulation environment. The exchange of data with these simulation components is limited to discrete communication points, between those the encapsulated system model is solved by the component's internal solver. Simulation components that are FMI-compliant are referred to as *Functional Mock-up Unit* (FMU). Such an FMU comprises a ZIP file containing an XML-based model description together with a shared library and/or source code implementing the API. This shared library may be either a self-contained simulation component or call another simulation tool at execution time (tool coupling).

Currently, there are several projects ongoing within the context of building and district energy simulation that use the concept of FMI-based co-simulation as a means to different ends [13]. While some emphasize the vertical integration of domain-specific simulation tools (such as the FMI support for EnergyPlus), others put their focus on the development of generic simulation environments that enable a system-level view. However, they all demonstrate the benefits of FMI-based developments, since they enable collaboration across individual projects on a technical basis, advancing interoperability and reuse of existing implementations.

3. GIS block model extraction

Moving from a single building approach to a district- or city-wide view, while having the buildings as the smallest reference unit in mind, is a challenge and shall be addressed in this step. Obtaining the required information is often difficult due to insufficiently integrated building data. The most common way to create such data sets – if they are not provided by a city council – is through the use of a Geographic information system (GIS). A GIS is a system designed to