BuildingSystems_VR – A new approach for immersive and interactive building energy simulation

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Abstract

The contribution describes a new modelling and simulation approach, which enables the simulation analyst to have an immersive interactive experience of a building energy simulation (BES) in the role as the user of the building. For this purpose, a geometrical building model, a thermal building model based on Modelica (Modelica Association, 2012) and a Head Mounted Display (HMD) are integrated to a virtual reality (VR) simulation environment. In this manner the interaction of the user (e.g. switching on a light) in the VR world is directly coupled to the physical building model, whereby the room energy balance is modified. Important state variables of the room model as the air temperature or the illumination level can be observed by the HMD.

Introduction

Usually BES is an analytical process, in which the person, who performs the simulation experiment, is working with a building model, but he or she is not directly embedded in the simulation experiment. This is valid for the majority of the BES problems, especially if the energy analysis, the optimal design or the optimal operation of the building are in the focus of the simulation experiment. During the last years the impact of the user behaviour in BES became more important and is often integrated in simulation models as time dependent boundary conditions and sometimes also as more complex behaviour models (Hoes et al., 2009; Burak Gunaya et al. 2014; Annex 66, 2016). Nevertheless, a direct 3D experience of the indoor climate in thermal simulation tools by the analyst itself is not realised up to now. This could become an interesting new simulation approach, which can serve as a flexible "close to the reality playground" using the manifold interaction possibilities within a VR world.

The computer games industry has made huge progress in the last decade in the field of realistic interactive 3D physical and technical simulations, based on game engines such Unity (Unity, 2016) or Unreal Engine (Unreal, 2016). For example, a first interactive 3D simulation scenario in the automotive industry for a physical car simulator was prototypically realised through a real time co-simulation between Unity and a physical car model, based on Modelica/Dymola (Yamaura et al., 2016).

Recently, two interesting interactive VR projects have started: first, the "The Void" (The Void, 2016) combines spaces and rooms with interactive behaviour and physical (mechanical and thermal) experience. Second, the Birdly VR device from Somniac (Somniac, 2016) integrates a human flying machine with a HMD and gives the test person the feeling of the flight of birds.

Also in the building sector, an increasing number of VR applications are realised. Commercial companies such as Arch Virtual are developing virtual interactive models for building designs or building projects including a light and simplified acoustic simulation (Arch Virtual, 2016). On the city level, the VR implementation of Google Earth (Google, 2016) enables the user to fly over or to walk through an increasing number of 3D district models of numerous large cities all over the world.

The following sections of this paper describe a software architecture for an interactive VR building energy simulation environment, in which a test person can show a user behaviour and interact with the thermal building model in real-time. Different technologies (a game engine, a HMD, software libraries for data exchange and VR interaction) are used, which are also core technologies of the mentioned VR projects.

Method

Figure 1 illustrates the new VR based modelling and simulation approach, in which different existent hardware and software technologies are integrated to an immersive real-time simulation environment. Starting from one common architectural building model, modelled in Archicad, Revit or Sketchup, two different building models are generated: A geometrical building model, exported in the FBX[1] model format that can be imported into the game engine Unity (Unity, 2016) and a Modelica thermal building model, generated with the information from an exported IFC[2] model. The geometrical building model has to be enriched within the Unity editor with some dynamic features, such as movable building elements (e.g. doors, windows or shading devices), colliders (collision detection for geometrical objects), sensors for the user interaction (e.g. opening switches for doors and windows or switches for lights) and an ambient

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[1] proprietary file format from Autodesk
[2] Industry Foundation Classes from the IAI

model (a terrain model, an optional model with adjacent buildings and a dynamic sky and weather model).
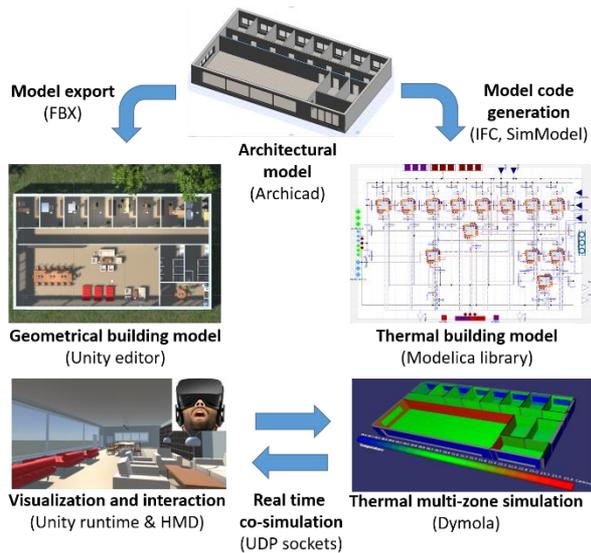
Figure 1: VR modelling and simulation approach for immersive and interactive building simulation.

During the simulation experiment the physical Modelica building model runs in real time with Dymola (Daussalt Systems, 2016) and sends the relevant data (e.g. the air temperature und surface temperatures of a thermal zone) via UDP sockets to the Unity runtime and can be visualised there in the geometrical building model (e.g. as surface temperatures or air flows). The Unity runtime itself is coupled with the HMD and enables the navigation and interaction of the user within the VR scenario. User triggered interaction events within Unity are sent also by UDP to the Dymola simulation environment. Unity and Dymola run together in a real time co-simulation.

Architectural model

The architectural model defines the building shape and the inner structure based on a BIM approach. The construction type and geometry of each building component (walls, ceilings, roofs, windows, doors etc.) and their relations to the different thermal zones is structured and stored in an object-oriented data model.
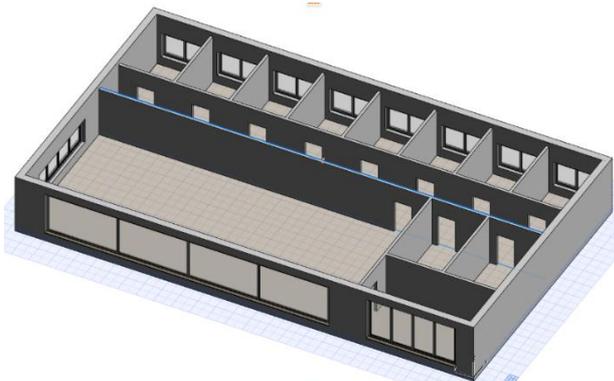
Figure 2: Architectural model, modelled in Archicad.

For the present research Archicad 19 (Archicad, 2016) is used. Figure 2 shows the Archicad model of a storey of a generic office building, which is described more in detail in the case study section below.

Starting from the architectural model in Archicad, two different data models are exported: First, a model in the FBX format as an input for the 3D visualisation model in Unity. Because Archicad does not support a direct FBX support, Cinema4D is used for an intermediate step (Archicad export to Cinema4D and Cinema4D export to FBX). In principle also other data formats could be used, but the FBX formats supports a data transfer from CAD to Unity with the smallest information loss (Boeykens, 2013). Second, a model in the IFC2x3 format as in input for the thermal building model based on Modelica.

Unity building model

The VR visualisation and user interaction takes place in a 3D building model realized in Unity. Unity is a cross-platform game engine, which is being developed by Unity Technologies (Unity, 2016). This platform was selected for the VR building simulation approach, because its supports following needed basic features:

- import of structured geometrical building models as FBX-files, modelled in CAD-program (e.g. Archicad, Revit or Sketchup),

- transformation of fixed geometrical model parts into dynamic model elements (e.g. openable doors and windows),

- software integration for Head Mounted Displays (e.g. Oculus Rift or HTC Vive),

- User integration within the VR scene realized by a first person controller with possibilities to navigate through and interact with the elements of the building model and

- a C# scripting interface, which supports the access to the entire data model of the VR scene and enables the data exchange by network protocols such as TCP/IP or UDP.

Figure 3 illustrates the Unity building model, based on the imported FBX model from Cinema4D/Archicad.

Figure 3: Unity model, enriched with furniture and dynamical building elements (windows, doors, switches).

Within Unity the building model was extended with furniture, lights and technical devices, which are

characteristic for the different room types (office rooms, rest rooms, conference rooms etc.). Further, building elements for user interaction, which are still static in the FBX model, were dynamized (e.g. a window can be tilted or totally opened). All physical objected are equipped with a collider element. This modelling step avoids the unrealistic situation that a person in the VR environment can navigate through material objects such as walls or furniture. Finally, the unity building model is embedded in a 3D ambient model, which includes a ground and optional surrounding objects, e.g. trees or adjacent buildings (compare Figure 3).

Modelica building model

The modelling and simulation language Modelica (Modelica Association, 2012) in combination with the simulation tool Dymola 2017 (Daussalt Systems, 2017) is used to describe the thermal behaviour of the building model in real-time. For this purpose, one of the Annex60 Modelica libraries for building energy simulation (Wetter et al., 2015), the Modelica BuildingSystems library is used as a general base for modelling the thermal behaviour of multi-zone buildings. This library is being developed since several years at the Institute of Architecture and Urban Development at UdK Berlin (Nytsch-Geusen et al., 2012, Nytsch-Geusen et al., 2016).
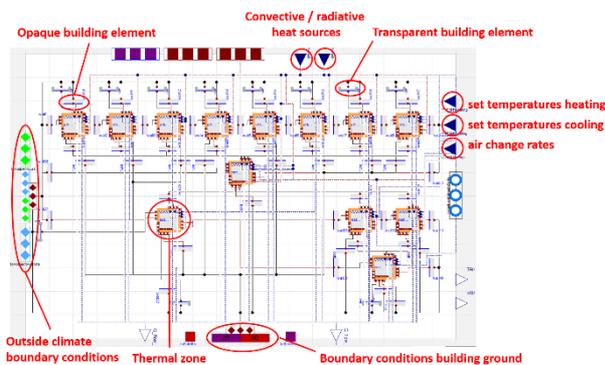
Figure 4: Structure of a Modelica building model with 13 thermal zones based of the BuildingSystems library

The library includes predefined models for thermal zones and building standard elements such as walls, windows, ceilings, doors etc. and also some specialized models e.g. for air paths, which can be configured a parameterized to a multi-zone building model (compare with Figure 4).

For small multi-zone building models with only two or three thermal zones, the configuration and parameterization of the simulation model can be manually realised. More complex building models need large Modelica files, e.g. the 13 thermal zone model in Figure 4 is described with approximately 1,500 lines of code. Because for these complex building models a manually configuration would be highly error-prone, a tool chain for automatic Modelica code generation is used, which was developed in the EnEff BIM project (Remmen et. al, 2016). The input of this tool chain is an IFC file exported from Archicad and the output automatically generated Modelica file based on the Mako templates for python (http://www.makotemplates.org) adapted to multi-zone

building model of the BuildingSystems library. The fact that the generated visualisation model for Unity and the generated physical Modelica are based on the same CAD model is the pre-condition for an efficient data exchange for the entire VR simulation environment.

Real time data exchange

During the whole VR experiment, Unity and Dymola exchange information in real time. Unity is sending information regarding e.g. user behaviour and is receiving simulation results from Dymola, which can then be visualized in VR. The communication is sent over UDP. Information has to be serialized or packaged before it is sent, received packages have to be de-serialized. On Modelica side, the existing library Modelica_DeviceDrivers (Thiele et al., 2017) is used for these tasks. Modelica_DeviceDrivers is organized in several layers; a low-level C-code layer that contains operating system specific code and multiple high-level layers written in Modelica that interface the C-code.

To provide a compatible serializer/de-serializer and UDP socket on Unity side, a C# wrapper and interface for selected functions of the C-code delivered with Modelica_DeviceDrivers was generated using SWIG (Simplified Wrapper and Interface Generator). The generated C# scripts can be called from any Unity model. A Python wrapper was also generated for testing purposes.
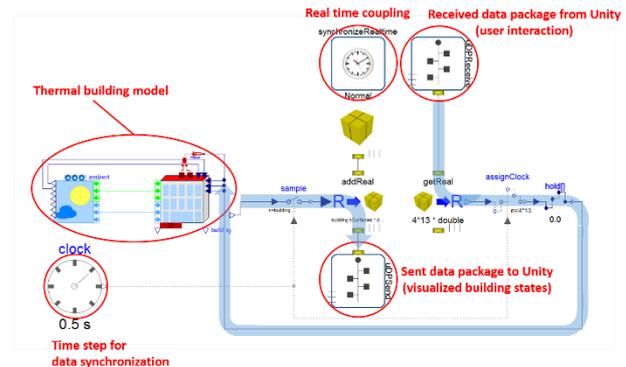
Figure 5: Modelica system model, which enables the bi-directional data exchange of the thermal building model with Unity model based on the UDP data protocol

Figure 5 shows the Modelica system model and illustrates the data exchange between Modelica/Dymola and Unity. The thermal building model includes the multi-zone building model of Figure 4 and an ambient model, which calculates its climate boundary conditions (ambient unad sky temperature, beam and diffuse radiation, wind speed and direction, moisture). Calculated simulation results as the air and surface temperatures of the individual thermal zones are sent as serialized data packages via UDP to Unity (components sample, addReal, uDPSend) with a synchronisation time step of 0.5 seconds (component clock). Signals, triggered by the user behaviour and user interaction in the Unity VR environment are received as data packages and de-serialized and are sent as inputs to the thermal building model (components uDPReceive, getReal, assignClock, hold) with the same

synchronisation time step. The component synchronizeRealtime guarantees, that the entire simulation runs with real-time.

Visualisation and interaction with a HMD

In the present version of the BuildingSystems_VR environment the HMD Vive from HTC is used (Vive, 2016). These HMD comes together with two hand controllers, which are used to navigate through and interact with the building model. The general software integration of the HMD in Unity 5 is realised with the SteamVR plugin from the Unity Asset Store (https://www.assetstore.unity3d.com). For the more specialized interaction functionalities the SteamVR Unity toolkit(https://github.com/immersionate/SteamVR_Unity _Toolkit) is used and was extended. Figure 6 shows a user, who navigates with a HTC Vive and its controllers through a building model and opens a window.

Figure 6: Navigation and interaction with the HTC Vive within the BuildingSystems_VR simulation environment

The following Figures 7 to 10 demonstrate different implemented possibilities for navigation and interactions.

Figure 7: Walking outside or inside of the building with the trackpad of the hand controller

Figure 8: Opening of a door with the dual-stage trigger of the hand controller

Figure 9: Adaption of the set point temperatures for heating and cooling or switching on/off lights with the dual-stage trigger of the hand controller

Figure 10: Opening of a window with the dual-stage trigger of the hand controller

Case study

The case study demonstrates the application and the present state of the development of the BuildingSystems_VR simulation environment. For the simulation scenario one story of an office building with 13 thermal zones is considered. First, it includes eight single office rooms, each of them has the same floor space (3.0 m x 4.0 m) and a window with the same size (3,75 m^2), oriented to the North. Second, it has a bullpen (8.00 m x 19.35 m) with a large south oriented window (40.0 m2) and a smaller west oriented window (7.5 m^2). Beside the bullpen, a conference room (3.00 m x 6.27 m) is attached, which has also a south oriented window (7.5 m^2). Further, the story includes two sanitary rooms (each of them 3.00 m x 5.00 m) without windows and a corridor, which divides the north oriented by the south oriented rooms as a thermal buffer zone. All rooms have a unique clear height of 3.0 m.

The building construction consists in a massive facade (concrete) with an outside insulation (U-value about 0.25 W/(m^{2}K)) and includes double-glazing windows (U-value about 1.4 W/(m^{2}K), g-Wert of 0.52). The inner walls between the thermal zones are made from calcium silicate bricks. The ceilings and bottoms are also made from concrete with impact sound insulation and a wooden floor covering. Four different user interactions are possible:

- **Set temperature for heating and cooling**: The user can adapt with a thermostat in each room the heating set temperature between 10 °C and 30°C and the cooling set temperature between 15 °C and 40 °C. The heating rate can be controlled between 0 W and 1,000 W in the small office rooms and in the

restrooms, between 0 W and 2,000 W in the conference room and between 0 W and 10,000 W in the bullpen.

- **Switching on/off the lights and electrical devices:** The body of the user itself generates a base level of 70 W thermal energy, which is a heat source in the room, where the user is present. In addition, the user can switch on electrical lights and devices (computer, screens etc.) up to 230 W thermal energy (compare with Figure 11).
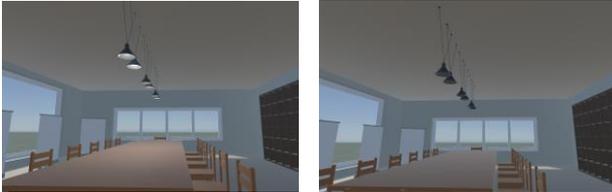
Figure 11: Activated and deactivated lights

- **Opening and closing process of the doors:** All rooms of the building are connected by doors, which can be opened and closed by the user. Dependent on the opening angle of the door more or less air is exchanged between two thermal zones (inner doors) or between a thermal zone and the building ambient (the two doors of the thermal buffer zone), compare with Figure 12.

Figure 12: door between thermal zones and to the building ambient

- **Opening and closing process of the windows:** The windows of the eight small office rooms can be opened in two different manners: tilted and totally opened. The tilted window leads to air change rates about 2 and 5 per hour and the totally opened window up to 10 per hour (compare with Figure 13).

Figure 13: Tilted and totally opened window

The diagram in Figure 14 illustrates the interaction of the user with the thermal building model for a simulation real-time experiment about 900 seconds. The scenario takes place during in January and the weather location is Berlin with an outside temperature about 5 °C. The entire building model – the building elements and the enclosed air - is initialized with 20 °C. From the beginning the user is present in one of the small office rooms (office1) and his or her body works as a heat source of 70 W, the heating system is switched of (heating set temperature of 10 °C). After 20 seconds the user totally opens the window, this leads to an air change rate about 10 per hour (1). Consequently, the air temperature is dropping down. At time 140 seconds the user closes the window and changes heating set temperature with some intermediate stages finally to 20 °C (2). As a result, the heating systems works with its maximum power of 1,000 W and the room air temperature is increasing after a while up to the wished 20 °C. At time 310 seconds the user is switching on the lights and some electrical equipment, why the heating system reacts and decreases its power (3). At time 430 seconds the user switches the internal heat sources off and
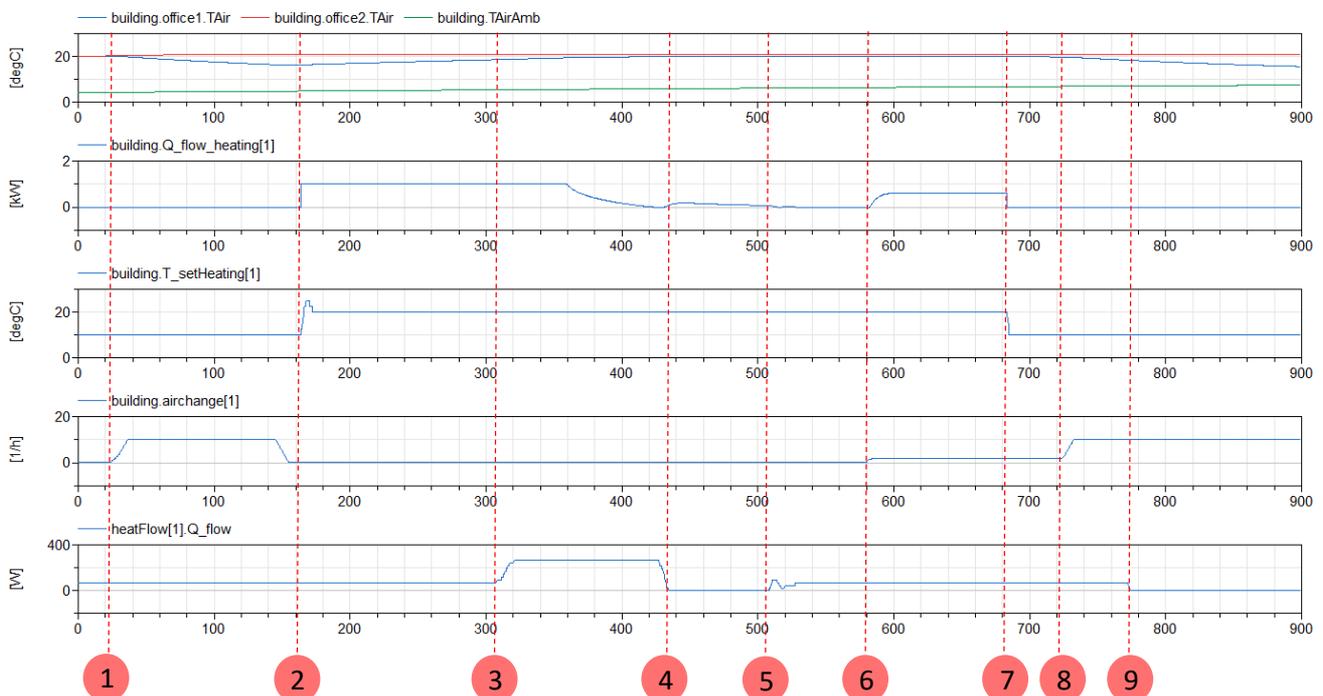
Figure 14: Real time simulation experiment with 8 different user interactions (zone office 1)

leaves the room (4). As a result, the power of the heating system is slightly increasing. At time 505 the user reenters the room (5) and move after a while (at time 560 seconds) the window in a tilted position, which induces an air change rate about 2 per hour and the heating rate is increasing again (6). After 680 seconds, the user reduces the heating set temperature to 10 °C and the power of the heating system suddenly changes to zero (7). At time 720 seconds, the window is totally opened again (8) and at time 775 seconds the user leaves the office (9). As a result, the room temperature is decreasing once more and reaches at the end an uncomfortable state.
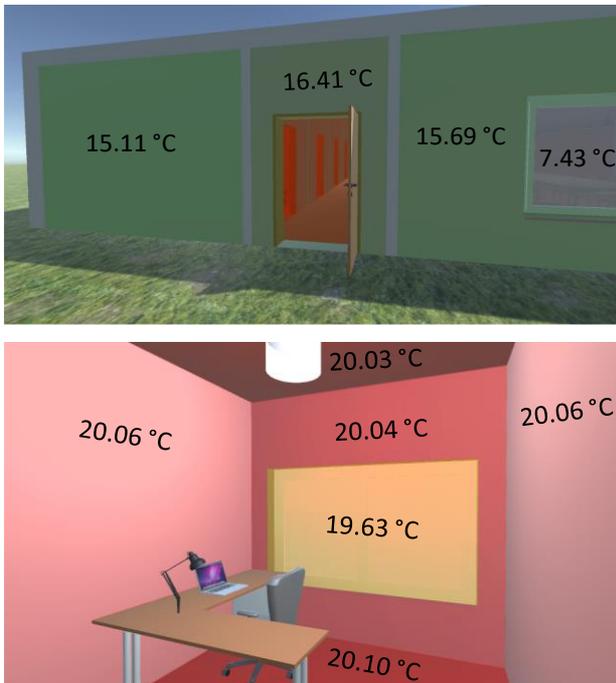
Figure 15: Visualisation of simulation results: Outside surface temperatures of the west façade and inside surface temperatures of office1 at time 505 seconds

Figure 15 demonstrate the visualisation of simulation results within the VR environment at time 505 seconds (event 5 in Figure 14). Based on the data exchange between Unity and Dymola selected physical states of the building model such as the surface and air temperatures, the air moisture or the carbon dioxide level can be optionally displayed within the VR environment by colours and optional as numerical values. At this, the colour scale reaches from blue (small values) over green to red (large values).

This displayed information and the light/shadowing model of Unity can be employed by the user for decisions for his or her user behaviour, e.g.:

1. Open a window in a winter situation in order to reduce the content of carbon dioxide of the indoor air.

2. Close the window and heat up the fresh room air by setting the thermostat to 21 °C.

3. Switch on the light if the daylight level is too low.

Results

The new approach makes an analysis of the impact of a direct user interaction on the thermal energy balance and the indoor climate of a building model possible. This interaction takes place within a VR simulation environment based on a HMD, the game engine Unity and a Modelica thermal building model and opens the simulation analyst a wide field of immersive simulation experiments.

For the realization of this VR simulation environment a bi-directional data exchange between Unity and Modelica/Dymola was implemented, based on the Modelia Device Drivers Library.

A case study with a multi-zone building model with 13 thermal zones illustrates the complex pre-processing steps from the CAD model to the Unity model and the Modelica building model and demonstrates the different possible interactions (thermostats for heating and cooling, light switches, opening and closing processes of windows and doors etc.).

Some of the pre-processing steps can be automatized and supported by a Mako based code generator, e.g. the Modelica system model and the correspondent visualization model for the model states (compare with Figure 15). Other steps are still work-intensive and up to now hard to automatize: An example is the necessary dynamization of the static model parts (windows, doors) of the CAD model within the modelling editor of the game engine Unity.

The interactive simulation scenario takes place in one of the small office rooms of the multi-zone building model about 900 seconds real-time and includes 9 successive user interactions. Together they constitute a complex pattern of a user behaviour with a strong impact on the indoor climate and the related building energy demand.

Conclusion and outlook

The new approach of an interactive VR building energy simulation environment enables an iterative and flexible understanding of the impact of different user behaviours on the energy balance and indoor climate of buildings. In this way complex scenarios can be analysed and discussed in small groups (e.g. the architect, the client and the climate analyst) during the early stage of the building design process: How comfortable is the indoor climate for a room with a new designed adaptive building façade for a given weather location during the different seasons of the year? Who easy and efficient works the control system for the shading devices of this façade for the user?

The next steps of the development will be a further automation and simplification of the pre-processing steps for the building model. More complex case studies, based on real buildings or building designs will be specified and implemented. Further, controllable HVAC technology components, such as cooling ceilings, radiators, movable shutters etc. will be integrated in the interactive building models.

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