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A NOVEL CONCEPT FOR VIRTUAL REALITY ENHANCED BUILDING ENERGY MODELLING

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Abstract

Energy services are central components for reducing the energy consumption of buildings. In the context of a long-term transformation towards sustainable energy systems, it is crucial that the building occupiers remain at the centre of such services. This paper presents a new technological conceptual framework for "Next Generation Energy Services" which involves a combination of the following technologies: Virtual Reality (VR), physical simulation and Internet of Things (IoT) platforms. The paper demonstrates the concept of this framework on the use case “Human Aspects in Buildings”, where variations in material properties can also show an educational value in conveying the principles of building physics, using building performance simulation.

Introduction and concept

Whilst the EU aims to be climate-neutral by 2050, the Austrian government has committed itself to accelerate the transition of its energy systems to achieve this target by 2040. To achieve this goal, Austria needs to significantly step up its efforts to decarbonise all parts of its energy sector. Building and service sectors account for about one-third of the total final consumption (International Energy Agency, 2020). In this context, the optimisation of the energy efficiency of buildings and energy services (including measures such as predictive maintenance, demand-side management and model predictive control) are central tenets for reducing the energy consumption of buildings and transforming them into, intelligent actors in higher-level energy systems.

With the growing interest in reducing energy demand in buildings, proper interoperability between Building Information Modelling (BIM) and Building Energy Model (BEM) (Cemesova et al., 2015; Gupta et al., 2014) is paramount for integrating the digital world into the construction sector and, therefore, increasing competitiveness by saving costs. BIM is the first step towards the implementation of the industrial revolution 4.0, in which digital twins and Virtual Reality (VR) are key elements (Porsani et al., 2021). VR offers many different potential applications in building simulation and it has become an enabling technology in a variety of building performance applications due to its ability to present three-dimensional, complex data and information intuitively and interactively (Bahar, 2014). Furthermore, VR offers several advantages as a visualisation tool, by providing its users with a much better understanding of the space that they are designing, both in quantitative and qualitative terms (Pilgrim, 2003).

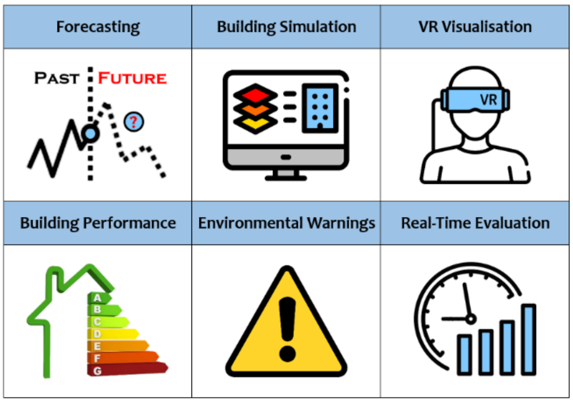

Figure 1: Use case “human aspects in buildings” – overview of its different components and technologies

The BEYOND project at TU Graz has the ambition to develop the technological foundation for Next Generation Energy Services by integrating various technologies in the design of buildings: (1) VR, to enable the real-time visualisation and interaction with the building; (2) building performance simulation, to show the impact of the selected interventions and decisions; (3) Internet of Things (IoT) platforms, to enable bidirectional real-time communication between the building and its users. This paper proposes a new conceptual framework and focuses on one of the use cases that will be addressed by the project, i.e. “Human Aspects in Buildings” (Figure 1). This will be presented here in the context of evaluating different window and wall components.

Background

The use case presented here aims to enhance the understanding and impact of user decisions on the energy performance of buildings by allowing the users to evaluate different building envelope materials and components (i.e. walls and windows) and also change the shading levels within a single room. For this purpose, the Virtual Environment (VE) of a physical office was designed such that the user can interact with the room via a VR headset.

Figure 2: example VR setup, glasses and navigation handset

The user can access and visualise historical and real-time climate (from the local weather station), and room energy and environmental data (i.e. indoor air temperature, relative humidity, air pressure, CO_2, illuminance, occupancy, window/door openings, and electricity consumption) directly from the virtual environment. In addition to that, the BEM was derived from an existing BIM model of the entire office building. The VR system allows the user to modify the envelope materials and shading levels, and subsequently visualise and compare the thermal energy simulations directly from the VE. The integration of the thermal energy simulations with the VR technology enables the users to enhance their senses through visual (e.g. heat loss, heat output etc.), acoustic (e.g. acoustic warnings when temperatures or CO_2 levels are exceeded etc.) and haptic (e.g. to feel temperature changes etc.) information, whilst providing a real-time evaluation of the users' decisions.

Methods

The case study and different methods (VR, BEM, and IOT) are described in the following section.

Case study room and monitored data

To test the conceptual framework, a modern newly-built office building at the Inffeldgasse Campus of TU Graz was selected. The EBS Centre (completed in 2020) contains an Innovation Cluster in the field of Electronic Based Systems and various R&D activities, which aims to support technology transfer between Academia and Industry. The case study focuses on a single corner office (with internal dimensions 3,9 x 5,2 x 3,0 m), which is located on the first floor, on the South corner of the building. This office was specifically selected because it is South-facing and therefore receives higher solar gains in winter time relative to the other orientations. Moreover, since it is occupied by TU Graz staff this facilitated the installation of the necessary monitoring equipment.

Figure 3: South-West view of the EBS Centre and of the office (marked in red)

The building uses a floor heating and cooling system, and it is equipped with two air handling units to circulate, filter and supply fresh air to the offices. The selected office was equipped with a number of different WiFi/LoraWAN sensors to monitor the environmental conditions and energy use: a WiFi environmental multi-sensor device and datalogger was installed to measure the air temperature, relative humidity, CO_2 levels, air pressure and illuminance (using an external photometric probe with a0-200,000 lux range) equipped with a cosine correction diffuser to provide accurate measurements on flat surfaces from all angles; window/door sensors to monitor their state and statistics on their use; infrared people counting devices to monitor the occupancy of the office; contact temperature probes to monitor the temperatures of all the different surfaces (i.e. walls, floor, ceiling, windows and corners of the external walls as a proxy for thermal bridges); and plug-load electricity monitors to record the power consumption in the office. The Inffeldgasse Campus at TU Graz is equipped with a modern weather station that is continuously gathering the climate data needed to produce climate files for dynamic simulations.

IoT platform

The Internet of Things (IoT) is understood as a ubiquitous, complex network of networkable, heterogeneous entities or ‘things’ (Bertin et al., 1998). It collects environmental data, interacts with the physical world, communicates through internet standards, provides applications, data transfer, and data analysis (Jin et al., 2014) with minimal human interaction (Cruz et al., 2018). Communication between networkable, heterogeneous computational components, i.e. Machine to Machine communication, is a key requirement. However, state-of-the-art devices from different vendors often employ incompatible protocols and data formats, which inhibits interoperability. There are two approaches to mitigate this issue: (i) the introduction of universal standards and (ii) the use of translation layers, so-called middleware platforms, between the components. The introduction and more importantly, the enforcement of standards has proven non-trivial in most instances, however, there are several cases where the standardisation was problematic (e.g. different charger standards for small electronic devices, inhomogeneity of electric socket type across Europe etc.) (Cruz, 2018). Since the cost of retrofitting existing systems with components that adhere to new universal standards can be prohibitive, a backward-compatibly has to be considered and hence the practitioners typically opt for middleware solutions in their IoT systems.

BIM and BEM

In a previous project (Schweiger et al., 2021)a BIM model was made in Revit and it was exported using the green building extensible markup language (gbXML) open schema. Compared to the open schema industry foundation classes (IFC), the gbXML format provides a more flexible and direct approach to energy analysis (Elagiry et al., 2020). While both of schemas transfer the material properties, HVAC systems data and thermal zones, only the gbXML format provides location data (Kamel and Memari, 2019). The translation from a BIM to BEM format is always a challenging and delicate task because numerous problems can arise during the process. The BIM–BEM process consists of three parts with interoperability issues that might occur in any or all of the following parts: the BIM tool, model schema exchange format, and BEM software. This means the encountered problems are not caused exclusively by the limited ability of BEM tools to translate input data from BIM (Akbarieh, 2018). OpenStudio was selected as an appropriate open-source BEM software development kit (SDK) since, it is capable of importing BIM models with the gbXML open schema and it is able to perform energy analyses using the well validated BEM engine EnergyPlus (OpenStudio, 2022). Generally, the BIM to BEM translation does not work well for big and complex buildings (Porsani, 2021). In fact, after importing the gbXML open schema into OpenStudio several errors were detected and some adjustments were required to the imported geometries. Nevertheless, OpenStudio only permits material and thermal zone changes. To make the necessary geometrical adjustments the SketchUp OpenStudio plug-in software was required. The model was reduced to a single zone office space by setting the boundary conditions of the internal walls, floor and ceiling as adiabatic. Heat transfer in the BEM model was therefore limited to the two external walls. After the gbXML geometries were adjusted and the boundary conditions were specified, the followings steps were required in the OpenStudio Graphical User Interface (GUI) in order to perform dynamic EnergyPlus simulations: uploading a local weather (.epw) file for Graz; setting schedules for typical occupancy and activity (i.e. occupant internal heat gains, lighting, equipment and infiltration levels in the office; loading and selecting the construction assembly (i.e. layers and materials for the various building components) from the BIM model; defining the HVAC loads; specifying the output variables; and lastly, specifying the simulation settings. Once these input parameters were defined, it was possible to run the dynamic simulations in OpenStudio for the various design decisions and export the results.

VR and virtual environment

We developed the Office VR environment with the well-known game engine Unreal Engine 4 (Unreal Engine, 2022b), assisted by two plugins DataSmith (industry CAD extensions support) (Unreal Engine, 2022a) and MegaScans (high-quality materials support) (Quixel, 2022). The office furniture was created with the open-source 3D modelling tool Blender (Blender, 2022). We designed the VR Office structure and lighting using the building BMI model and real pictures as reference. We chose the Valve-Index headset as a VR device (Steam, 2022). The VR interactions for the use caseand the data exchange with the server were implemented using two supported Unreal Engine 4 languages: (i) a visual scripting language called Blueprints and (ii) C++.

Integration VE and BPS

The VE under development is integrated with the IoT system and the BEM of the office. Once fully developed, the VR system will enable users to exchange of the construction layers and materials of the building whilst visualising the results immediately via the EnergyPlus simulations which will take place directly within the VE. The user is then able to interact with the outputs using the VR joystick and is able to visualise the results in either a tabular or graphical format. In the example shown in this paper, the user is interacting with the envelope of the building by replacing the insulation of the external walls. Choice #1 represents the current composition of the building (i.e. wall with an Expanded Polystyrene (EPS) insulation with thermal conductivity (λ) of 0,035 W/mK, an insulation thickness (t) of 0.30 m) which provides a total wall transmittance (U-value) of 0,170 W/m^2K. Choice #2 represents the alternative envelope construction assembly that construction #1 is being compared with (which in this case is composed of the same layers, but with a mineral wool board insulation with λ of 0,040 W/mK, an insulation thickness (t) of 0.15 m) and which provides a total wall transmittance (U-value) of 0,245 W/m^2K. Both envelope constructions assemblies were simulated in EnergyPlus using OpenStudio as the GUI. The simulations were performed with the EnergyPlus reference (.epw) weather file for Graz in free-running conditions (i.e. without mechanical heating and cooling) and with natural ventilation equal to 4 air changes per hour.

Results and analysis

IoT platform

Innovative Energy Services build on a bi-directional real-time interaction with real buildings. Innovative solutions are needed to produce and analyse these large amounts of data. Internet of Things (IoT) technologies are the backbone and enabler of these smart systems.

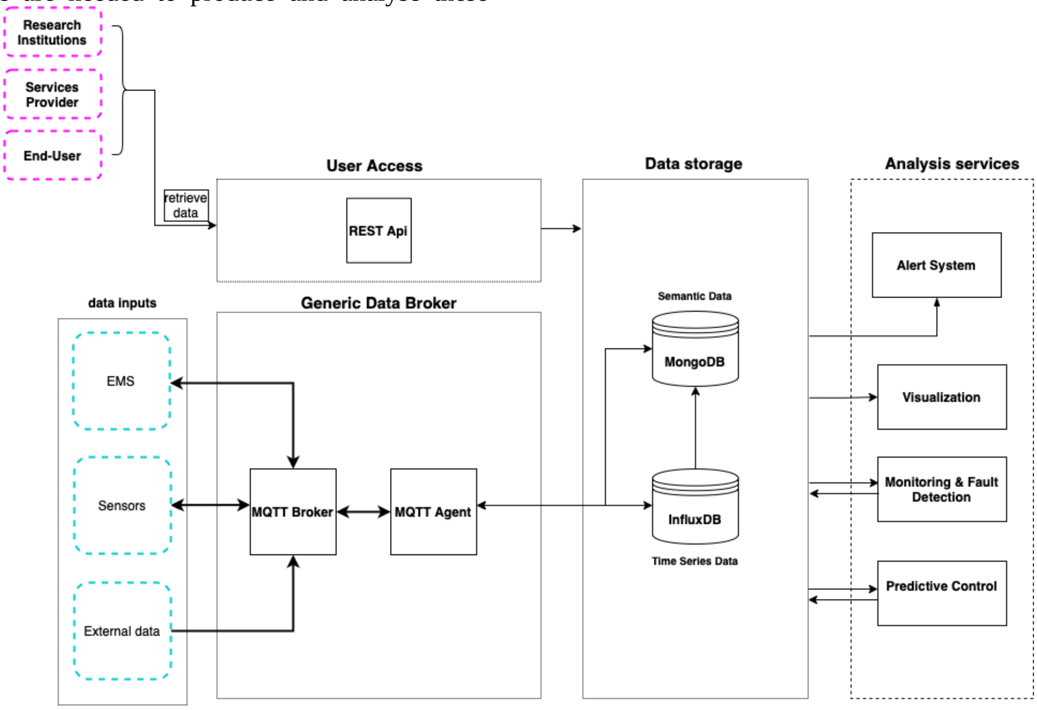

Figure 4: Scheme of the IoT Platform at Innovation District Inffeld

As shown in Figure 4, the data is sent to the integrated MQTT Broker from multiple sources located at the Inffeldgasse campus. An MQTT Agent listening to any changes on the MQTT Broker stores this data in a NoSQL MongoDB instance and is integrated into an NGSI-LD compliant information model. Data is then repeatedlystored in an InfluxDB time series database at a regular, per sensor configurable interval. Semantic models are represented in SAREF which is a reference ontology for IoT applications. Access to historical data as well as to the information model is possible through an OpenAPI specification (OAS) for REST API.

Simulation and experiment

The following images display the initial results of the interaction with the energy services using VR. Figure 5 shows the room simulated using OpenStudio (top) and using the VR environment (bottom). Figure 6 presents the users interaction with the VR environment. Figure 5 bottom illustrates the composition of the wall construction including the thermal conductivities of the individual layers as well as the overall U-value. At this stage the user can change material layers or delete and add new ones and then see the effect this has on the overall heat transfer coefficient. Figure 7 illustrates the VR showing the temperature distribution in the room obtained from the simulation.

Figure 5: BEM model and VR image corner room with wooden window frames and shading

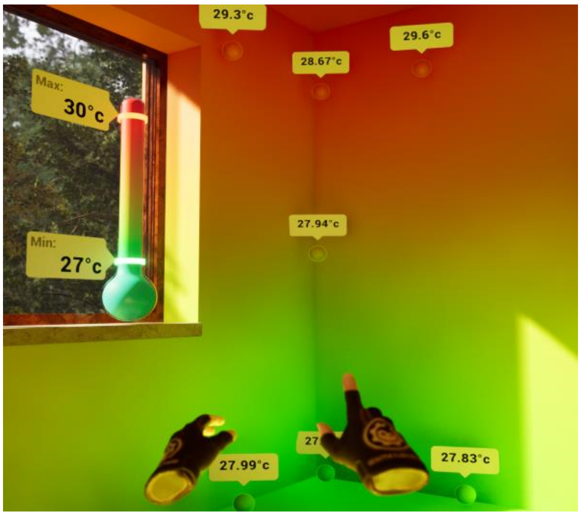

Figure 6: Virtual reality (VR) image showing the interaction with the environment.

Figure 7 shows the outdoor (blue) and operative temperatures of choices #1 (orange –30 cm EPS insulation) and #2 (red 15 cm mineral wool insulation) as created using BPS. Overall the two insulation choices demonstrated mixed results in free-floating conditions during the warmest period of the reference weather file (1-14 August). Despite the higher thermal resistance of the 30 cm EPS insulation layer (choice #1) the office did not overheat significantly more than with the 15 cm mineral wool layer. The reason for the relatively small differences observed between these two options can be attributed to the facts that the office has a large window-to-wall ratio and is well ventilated. Further exploration is possible by modifying the boundary conditions and these results are then communicated to the user when evaluating changes to the building envelope.

Conclusion

VR has multiple applications in different fields: gaming, training, learning, design and operation. VR allows user involvement to be enhanced by the creation of sensory and informatic experiences otherwise impossible in the real world (Cipresso et al., 2018). This study has shown that in the building design process, a VR system incorporating BIM geometry and BEM simulation outputs is able to greatly augment the design and learning process through enhanced user interaction and visualisation of critical design choices. In this use case the benefit of allowing the users to test different materials and layers of the thermal envelope was demonstrated. Similar applications would be possible in relation to understanding the performance characteristics of HVAC systems and other building services. In this way building and services professionals and their clients can evaluate and compare the impact of various design choices in real-time directly from the VE. Similarly, many other design and planning applications would be possible, for example allowing designers and end-users to experience the resilience of their proposed buildings to a warming climate by stress-testing them with the use of future climate files.

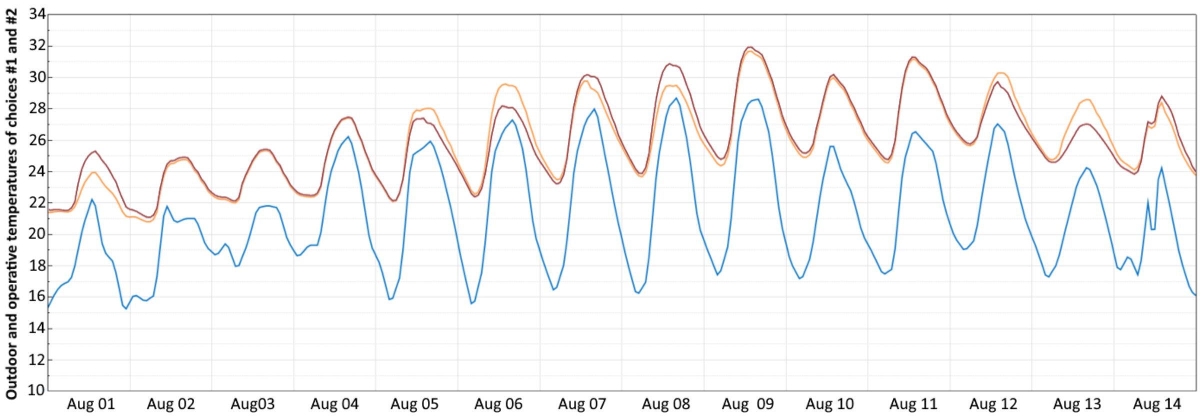

Figure 7: Outdoor (blue) and operative temperatures of choices #1 (orange) and #2 (red)

Last but not least, the VR process shown here can provide a useful learning tool for students and non-experts in the field of building physics. Students can use it to learn, interact and evaluate the immediate impact of various building design decisions. Equally non-experts can use it as an educational tool to understand more about building performance and energy efficiency.

Further work

Short and long term future work is planned as part of the Beyond project. In the very near future, the monitored office will be equipped with an external façade pyranometer, which will help to calibrate the external shading levels in future dynamic models.

In the longer run, the white box models will be further complemented by the use of back box models.

Fast and accurate simulations are critical to providing a satisfactory user experience and smooth workflow. Computationaly expensive simulations from detailed physical or Computational Fluid Dynamics models offer a detailed analysis of the system's dynamics. However, these simulation methods are computationally expensive and cannot generalize to different initial or boundary conditions. There have been many studies on improving or even replacing expensive simulation methods with data-driven models that use universal non-linear approximators developed in the field of Machine Learning (e.g. Neural Networks etc.) (Gustin et al., 2019; Calzolari and Liu, 2021; Kochkov et al., 2021). Machine Learning has the potential to enhance the simulation model's performance and may lead to the development of new state-of-the-art techniques with higher generalizability in the future.

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