Monitoring Smart Building Performance Using Simulation and Visualisation

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Abstract
Building energy certification standards require that modern buildings meet strict energy consumption targets. However, energy managers do not currently have the necessary tools to monitor building performance. In this paper we introduce a tool-set that supports simulation and visualisation for energy performance monitoring. The Performance Framework Tool (PFT) enables an energy manager to specify specific scenarios e.g. monitor zone temperature, and can produce energy performance indicator metrics for a building model. The Pudecas simulation and visualisation platform has been integrated with the PFT to provide monitoring of buildings with embedded sensors (Smart Buildings) at the design stage. Underpinning these tools is the Industry Foundation Classes (IFC) building information model (BIM). The discussion in this paper will specifically focus on the relationship between the performance simulation and visualisation models, and the building information model.

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ACM Classification Keywords
Prototyping, User-centred design, Evaluation/methodology, Modelling.

Introduction
In March 2007, the European Council set clear goals to reduce total energy consumption by 20%. The building sector is responsible for 40% of total EU energy consumption[1] and so will need to set ambitious

[1] http://ec.europa.eu/research/industrial_technologies/lists/energy-efficient-buildings_en.html

objectives in terms of energy reduction. Performance based assessment of building operation during the design process for accountable energy usage will play a significant role in meeting this objective[1]. Monitoring building energy performance requires embedded technologies which measure aspects of the building environment relevant to energy consumption, like the effect of user behaviour on heating, ventilation and air conditioning (HVAC) systems [2]. We refer to buildings with embedded technologies for monitoring the internal environment as Smart Buildings (SBs).

To analyse SBs at the design stage requires SB simulation. A large number of building energy simulation programs have been developed to date, more recently becoming more sophisticated and focussing on whole-building simulations. These provide users with key building performance indicators such as energy use and demand, temperature, humidity, and costs [3]. However, significant gaps still remain in current knowledge and tools. For example, there is a lack of tools which monitor energy usage into the operational phase of the Building Life Cycle (BLC), which makes it difficult to determine if the building is meeting its original performance requirements. Also, the impact of user behaviour on building energy consumption at design stage is difficult to monitor [2].

Drawing on the experience of the ubicomp community, Virtual Reality (VR) has been employed to conduct evaluations of applications which require contextual data from sensors, e.g. location [4], [5]. In this paper we look at the integration of the Performance Framework Tool (PFT), a civil engineering tool for defining building performance objectives, with a VR based ubicomp simulation and visualisation platform (Pudecas) [6], [7]. Central to our approach is a shared Building Information Model (BIM) called the Industry Foundation Classes (IFC).

Background and State of the Art

Building Information Modelling

The Building Information Model (BIM) is a well established idea within the building industry. It describes a model for storing all the information relevant to the BLC (which defines the life of a building from design, through occupancy and on to demolition) [8]. The BIM extends through the entire life cycle, and therefore performance metrics defined during the design stage, can be used to conduct further monitoring during operation. In order to realise the acceptance of BIMs, the International Alliance for Interoperability (IAI) is developing the Industry Foundation Classes (IFC) standard. IFC has the potential of enabling service engineers to collaborate between heterogeneous disciplines, improving interoperability, reducing costs and overall design quality. Currently, IFC is also the only BIM that is an accepted ISO standard.

Smart Building Simulation

The use of intuitive visualisation of monitoring results from performance simulation and assessment has been identified as an enabler to easy and quick interpretation of results [1]. Research efforts within the ubicomp community have looked into developing user centric simulated smart environments [4], [5] and these have demonstrated their usefulness when developing and evaluating applications which make use of sensed data. As yet, these approaches have not looked specifically at the use of an industry accepted standard like IFC to model their simulations or applications across the BLC.

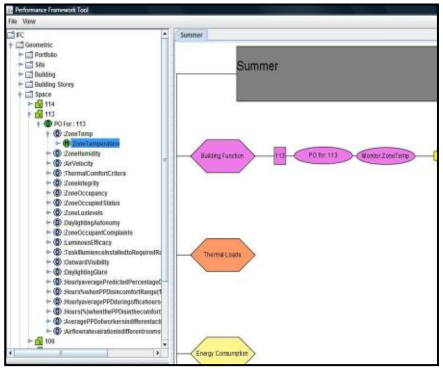

Figure 1 Performance Framework Tool

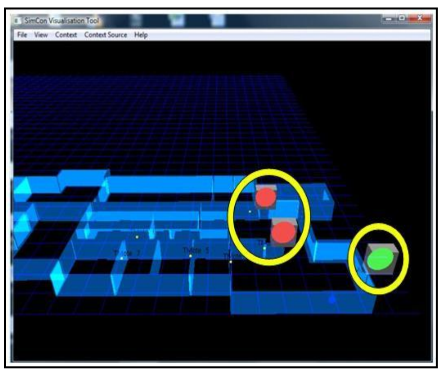

Figure 2 SimConViz Building Monitoring

Within the building performance analysis community, simulation models can be divided into two groups [1]. Those based upon physical (or deterministic) simulation models which use building geometry to build calculation models and those which use statistical (or empirical) calculation models. Physical simulation requires an expert who understands the tools and the process of importing the necessary BIM data to configure the simulation.

Statistical calculation models are derived from measured data which drive simulations that can then be applied to a range of buildings under certain assumptions (e.g. that building systems behave in a similar manner under similar conditions). For example sensor data, like location, can be simulated [9] which in turn can provide contextual data to applications [10]. The benefit of statistical models over physical models is that once the initial models are created they can be applied quickly to other buildings without the need of detailed building geometry at an early stage of design. When more fine grained analysis is required additional parameters can be added.

Monitoring Tool for Building Assessment

In this section we introduce the simulation and visualisation based monitoring tool for SB assessment (Figure 3). Firstly we discuss the Performance Framework Tool (PFT) which enables an energy manager to specify building operation scenarios. Following this we discuss the Pudecas platform which has been integrated with PFT and which includes the Virtual Reality Smart Building (VR SB), the SimCon Generator, the SimConViz monitoring tool and underlying statistical models. Finally we discuss how IFC supports the combined toolset.

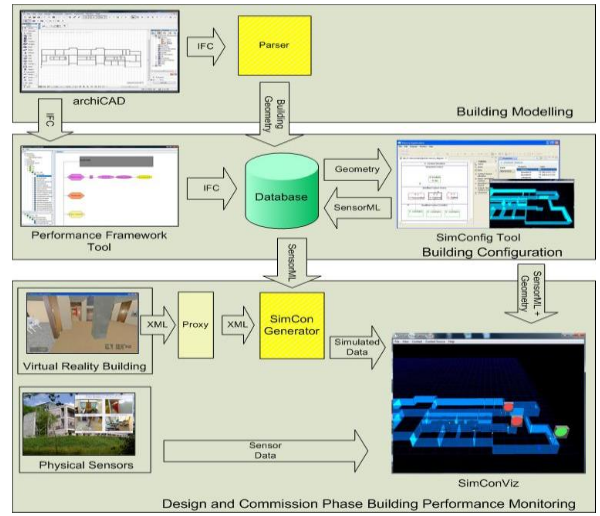

Figure 3 Monitoring Building Performance

Performance Framework Tool

There is significant loss in information throughout the building lifecycle [11], particularly around the client's brief and initial design information. As a project moves through the BLC, information used during the construction phase is lost as the building becomes operational. Information is passed between professionals in a minimalist manner, resulting in information loss and degradation in quality. This is particularly true for HVAC design intent, which is rarely carried through to the operational phase. The Performance Framework Tool (PFT) seeks to provide a framework for the capture of the building energy performance within the context of the BIM. By capturing design intent and operational characteristics, comparisons can be made with actual performance data, gathered during the operational phase, or simulated performance data.

This task requires a formalised, structured approach to the definition of energy performance within buildings and a means of appending this definition to a standardised BIM, using Industry Foundation Classes (IFC). A formal data transformation method has been defined by O'Donnell [12]. This method builds on previous work by Hitchcock, [13] defining the performance aspect concept, aimed at informing building operators about their decisions. Performance aspects are linked to performance objectives, which qualitatively describe a particular aspect of building performance. Objectives are in turn quantified using performance metrics which provide benchmark values for this performance. When taken together, a scenario can be described as a collection of performance objectives, grouped by performance aspect and evaluated using performance metrics. By linking these performance metrics to gathered sensor or simulated data, it is possible to evaluate the qualitative objectives and gain an understanding of how a particular scenario is performing.

In this way, a structured overview of building operation, throughout the BLC, can be established, based on the original design intent. The next stage of the process is to accurately define the scenario methodology within the BIM. Design intent requires that the building operates within certain parameters. For instance an overall Energy Usage Intensity (EUI), in kWh/m^2/yr will give a certain picture of the potential performance levels of the building. Several factors contribute to this figure. By considering these factors in detail and identifying operational parameters for these components, a far greater understanding can be gained about the building operation. For instance, is a boiler or Air Handling Unit operating within defined parameters?

By capturing design intent within a structured framework, an ongoing analysis can be carried out using building operational data. Building optimisation and fault detection are two significant benefits from this type of analysis. Building management systems tend to gather large amounts of data from various sources. Typically this data is discarded on a 24/48hr basis. By capturing this data and comparing it against design intent, a greater understanding of building performance can be gained. The Performance Framework Tool allows the energy manager to break down the building operation to its constituent parts, benchmarking the performance of each. It serves to provide a framework capable of creating, storing and accessing this context sensitive formally transformed data across the entire building life cycle. By formally capturing design intent, using a structured framework, within the context of a standardised building information model, the operational phase of a building becomes as much a part of the building as the roof or the foundation. By aligning this framework with relevant data streams, building performance can be monitored and optimised.

Pudecas Smart Building Simulation and Visualisation

Interactive Virtual Reality Smart Building

During the design phase of an SB, i.e. pre-construction, real data outputs cannot be generated; therefore, simulation of the building environment is necessary. The Pudecas VR SB provides first person interactive environments for conducting user centric building performance monitoring early in the design phase. It provides dual functionality to the Pudecas platform. Firstly, it maintains the global state of the world including information about the precise location of simulated users (avatars). Secondly, it generates XML encoded messages to the other components and monitoring tools which make up the Pudecas platform. This VR simulator is a modification of the popular Half-Life 2 games engine [14]. Multiplayer simulations allow up to 32 users to interact simultaneously in the context of the virtual world.

SimCon Generator

The SimCon Generator provides dynamic, interactive, simulated sensed data on the state of a simulated SB (e.g. temperature, location). The simulated data streams are modelled as SimCon Sources through a usable interface called the SimConfig tool [10]. The dynamicity of the generated data is the result of configurable response curves and error distributions. Response curves define outputs over a given set of conditions, for example, simulated temperature data which changes depending on the time. Error distributions can be used to model expected deviations in the output to mimic the uncertainty inherent in sensed data.

Simulating Sensed Data

The simulation models are based upon readings taken from the Environmental Research Institute (ERI) building over a one year period[2]. The ERI is equipped with more than two hundred sensors and the simulated temperature data is based upon measurements taken by three sensors every fifteen minutes for the year of 2008. The SimCon Generator reads in xml data sets of these readings to create simulated data streams. A mean value is used to provide a more accurate representation of the temperature over a given span of time (e.g. from 12:00 to 13:00 hours over the month of June). This value is used as the simulated output and the standard deviation is used to introduce a variance in the output using a Gaussian distribution. This data has been sufficient for early proof of concept testing of the SimConViz building performance monitoring (detailed in the next section), but as yet has not been integrated with the data taken on the state of the VR SB, which is necessary to provide the interactive element required for user centric evaluations.

[2] http://www.ucc.ie/en/eri/

SimConViz

SimConViz provides visualisation of building geometry and provides a systems view of different aspects of building state, e.g. temperature and occupancy [10]. SimConViz has been integrated with the PFT tool. PFT performance metrics are compared against simulated data streamed from the SimCon Generator. A traffic light system (highlighted by rings in Figure 2) displays red when a performance metric is falling outside the required range and green when it is within the expected range. This type of visualisation highlights building performance in an intuitive manner and as such should be accessible to the range of expected users who are involved in building monitoring (e.g. energy managers). SimConViz can monitor both simulated data at the design phase and also data produced by real sensors at the operational phase.

BIM Support

The IFC approach which supports this tool-set offers significant benefits in terms of interoperability and shared data support. This has meant that the toolset is based on a standardised data model and enables interoperability with IFC compliant 3-D CAD tools. IFC is still limited in terms of sensor definitions and other devices of interest to the ubicomp domain. However, extensions are being developed within the NEMBES project[3] to extend the IFC model enabling the toolset presented here to monitor a wider set of considerations more relevant to SBs and the concerns of smart energy management. The NEMBES project has a niche position in that it has brought together professionals from a diverse set of disciplines including Civil Engineering, Architecture, Ubiquitous Computing, Networking, and Sensor Motes and Hardware.

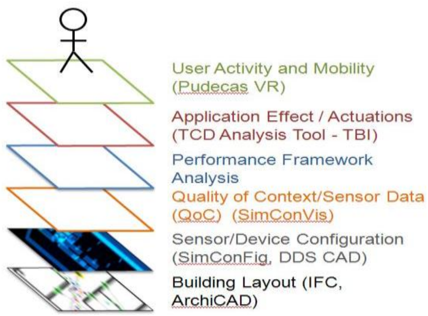

Figure 4 Environment Information Layers for holistic monitoring.

From this experience, we have identified a number of layers within our view of the information model as shown in Figure 4**.** Each of these information layers represents an aspect of the environment and as such has the potential to impact on the effectiveness of a SB's performance. Starting with the Building Layout, this layer defines the physical configuration of a building and its spatial relations. Often this is a constant factor within a design process since many SB installations involve retrofitting sensor technology. The next layer describes the sensors, their location, positioning and other attributes. The third layer, which is the least mature in this work, looks at supporting investigation of building performance in response to changing quality of sensor data (context). Finally the top two layers look at performance from an occupant-centric point of view. As such these layers include models to support activity and mobility simulations.

Future Directions and Next Steps

A number of directions have been identified to progress this work. Firstly, we intend to extend the analysis capabilities to include low level sensor concerns including the impact of the quality of context (sensor data inputs) and system behaviour in response to imperfect context. This will support and account for a fuller profile of analysis for SB systems; potentially going further to address more of the building lifecycle. Secondly, we intend to make more extensive use of the Pudecas VR SB simulator to investigate the impact of occupancy levels on building performance. The new work undertaken as part of this research will draw on the occupancy and mobility simulation in Pudecas to drive multi-occupant test scenarios for building performance analysis.

Conclusion

In summary, in this paper we presented a tool-set and framework for monitoring SB performance using simulation and visualisation. Initial integration of the PFT and Pudecas Simulation Platform has been completed. In this work we are providing a tool which can analyse the large data-sets gathered by building management systems to produce meaningful assessment of the building's performance. Simulation enables designers of these buildings to perform

[3] http://www.nembes.org/

assessments prior to the construction stage with a view to delivering accurate predictions about the buildings efficiency. Finally, visualisation enables us to provide an intuitive view of the environment in which the designer can use their own mental model and spatial understanding of the building to more easily relate to the PFT output.

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