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Data visualization and analysis of energy flow on a multi-zone building scale

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A B S T R A C T

Modern commercial buildings' resource consumption is metered at various levels of spatial and temporal resolution to track and reduce energy use and greenhouse gas emissions. However, not all data that could be used to detect faults or identify efficiency improvements are available due to the cost of meters and inaccessibility of the data they produce. In the field of building operation, building performance simulation (BPS) can help in quantifying unmeasured energy flows, for instance solar gains, heat loss from infiltration, etc. Furthermore, integrating building information modeling (BIM) in building operation and maintenance can decrease operation risk and costs, as well as maintain facility management quality. However, in practice there is a lack of efficient utilization of this application by building operators. The aim of this paper is to provide an integrated framework to estimate and visualize energy flows and the associated cost. The framework consists of 1) developing a BIM model, 2) converting the BIM model to a BPS model, 3) calibrating the model, and 4) visualizing energy and cost flows using Sankey diagrams. The study demonstrates this framework on a real-world case study, and hence provides a comprehensive energy use assessment on the building level to facilitate the decision-making by building operators. Finally, the results of a survey that was deployed to a sample user group to assess the usability and effectiveness of the proposed Sankey diagrams are provided.

1. Introduction

Most of modern buildings utilize building management systems (BMS) for monitoring and optimizing building systems during operation. However, the data from metering and logging systems are often inconvenient and difficult to access due to the use of multiple systems and technologies of varying vintages and platforms. BMS end-users (such as building operators and other stakeholders) might look for easily understandable metrics such as electricity cost rather than delivered energy [1]. However, the complex interactions between building systems make it difficult to understand the impact of changing a single component or operational schedule within a system [2]. For instance, the decision-making process for light bulbs/fixtures should incorporate their impact on heating and cooling loads. Moreover, some other variables are impractical and difficult to meter.

Building performance simulation (BPS) tools can be used to help in quantifying unmeasured energy flows, for instance solar gains, heat loss from infiltration, etc. Building performance simulation has emerged as a viable method to emulate reality and improve on traditional manual methods to study and optimize the energy performance of buildings and systems [3,4]. In order to use the building performance simulation models to help in understanding the thermal behavior of an existing building, the model should be calibrated with measured data. Several studies highlighted great discrepancies between simulated building energy performance and measured performance [5,6]. Such discrepancies may be attributed to an incomplete knowledge of the building; the building model may thus not correctly reflect the real behavior of the building intended to be simulated [7]. This discrepancy could be due to lack of information about building's construction quality, occupant behavior (i.e. window openings, set point temperature, and internal gains), actual materials/equipment used, deterioration of building systems, infiltration and ventilation rates, and algorithms uncertainties [8,9]. Thus, adjustment of the model parameters is generally needed when applying a simulation tool to a real case on different levels of analysis (inspection/audit, evaluation of energy conservation opportunities or continuous performance analysis) [10].

In the field of building operations, using building information modeling (BIM) for building performance analysis can facilitate a more accurate and efficient analysis process. Building information modeling is a process involving the generation management of digital representations of physical and functional characteristics of the building [11]. In order to perform a successful BIM-based building performance analysis, it is necessary to improve the interoperability between a BIM based architectural model and analysis programs [12]. Interoperability can occur either, directly between the platforms and tools, or using a data transfer model such as Industry Foundation Class (IFC) or the

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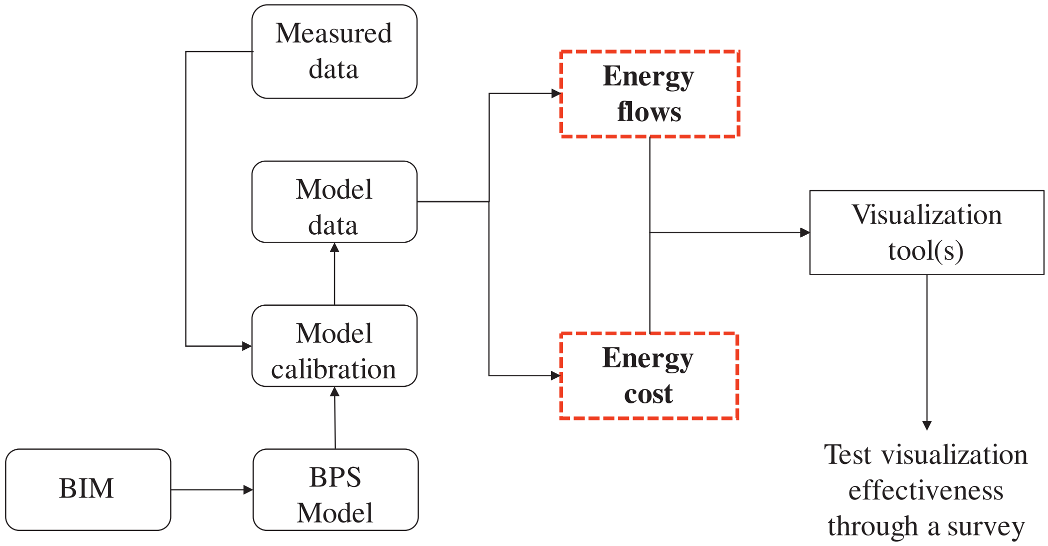

Fig. 1. The proposed framework.

Green Building XML schema (gbXML) [13]. The initial BIM model is an architectural view of a building, and it does not necessarily correspond to a 'thermal' view necessary for performance analysis tools [14,15]. Thus, BIM models should be adjusted first before data can be exchanged between a BIM platform and energy tools [16,17].

Most of the developed visualization tools for building energy management use simple line or bar charts for presenting and comparing metered energy consumption, greenhouse gas (GHG) emissions, and other performance metrics [18]. On the building level, Pulse Energy developed an energy dashboard tool that shows real-time building consumption of energy, natural gas, hot water, chilled water, and steam for campus buildings [19,20]. Other tools such as Building Dashboard and Energy Efficient Education Dashboard were developed to visualize energy consumption of commercial buildings [21]. Yarbrough et al. [18] developed a new visualization tool on the campus level to understand the relationship between individual building peak demand and the campus peak energy use based on data provided by energy meter. Current visualization tools or models typically only provide an end-use breakdown of energy consumption, depending on installed meter resolution. The above-mentioned tools are useful in providing quantitative analysis to inspect trends and patterns over time [22]. However, these tools are difficult to provide a comprehensive energy flow analysis on the building scale (e.g., how energy enters and is consumed in buildings). Furthermore, as building size and complexity increases, it becomes even more challenging to provide useful performance visualization [23].

On the other hand, Sankey diagrams can provide relative flow magnitudes, direction of flows, inputs and outputs of interacting systems, energy recovery, and spatial representation (e.g., the layout systems and components can be approximately laid out in a Sankey diagram). Abdelalim et al. [24] proposed several methods to analyze and visualize building-level water, natural gas, and electricity consumption and the upstream environmental impacts and the associated cost using Sankey diagrams and other graphical techniques. Belzer [25] developed energy flow maps to depict energy flows from source to end-use in the building sector using Sankey diagrams. The end-use consumption was based on estimations from Building Energy Data-book (BED). Phineas [26] used dynamic Sankey diagrams to visualize internal and external flows through building envelopes. The study by Phineas helped in visualizing the amount of energy incident hitting and leaving the façade by radiation and convection. His Sankey diagrams also helped in visualizing the amount of energy required for heating and cooling to maintain an acceptable indoor air temperature. O'Brien [27] addressed major issues involved in creating Sankey diagrams to represent building energy flows of a solar house obtained from a building performance simulation (BPS) model. Schlueter and Thesseling [11] developed a prototype tool integrated into building information modeling (BIM) to enable instantaneous energy and exergy calculations. Moreover, Sankey diagrams were implemented in the proposed tool to visualize the resulting performance indices [11]. A limited number of building design and analysis tools, such as CASAnova [28] and Sefaira [29] use simplified Sankey diagrams for visualizing predicted energy use.

The aim of this paper is to implement an integrated framework to estimate and visualize energy flows and the associated cost on the building level to provide a comprehensive energy use assessment on a real case study (the Canal Building at Carleton University in Ottawa, Canada). The framework consists of 1) developing a BIM model, 2) converting a BIM model to a BPS model, 3) calibrating the BPS model, and 4) visualizing energy and cost flows using Sankey diagrams. Within the scope of this work, by using a combination of measured and modeled data, a comprehensive energy use assessment at the building level can be formed. This information can yield greater insights about opportunities for operational improvements and retrofits that would not be available through measurements alone to facilitate the decision-making by building owners, operators, and other stakeholders. Moreover, this approach will result in estimating and understanding the impact of unmeasured energy flows (for instance, solar gains, heat loss from infiltration, etc.). Finally, the paper summarizes a survey that was deployed to a sample user group (building energy professionals) in order to assess the usability and effectiveness of the proposed Sankey diagrams.

2. Framework

The framework of this study is divided into three main parts. The first part consists of: 1) develop BIM model and convert the BIM-based architecture model to a building performance model, 2) perform model calibration, and 3) modeling approach in energy analysis tool, which are discussed hereunder. The second part of this framework focuses on converting model data into reliable energy flows and costs and producing Sankey diagrams. This is discussed in Section 4 after presenting the case study. The third part tests the usability and effectiveness of the proposed Sankey diagrams through a survey. Fig. 1 shows the proposed framework of this study.

The building management systems (BMS) provide real-time and historical energy consumption data, which are obtained from meters

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