Development of a virtual metering visualization tool to characterize energy flows in variable air volume air handling unit systems

Darwish Darwazeh[1,*], Burak Gunay[1], and Jean Duquette[2]

[1] Carleton University, Department of Civil and Environmental Engineering, Ottawa, Ontario, Canada
[2]Carleton University, Department of Mechanical and Aerospace Engineering, Ottawa, Ontario, Canada
* Corresponding author e-mail address: darwish.darwazeh@carleton.ca

Abstract

This paper introduces a novel visualization tool that uses visual analytics to present energy data estimated by equipment-level virtual meters and allows end-users to interact with the visualization to gain insights that can be used to improve building energy performance. The features of the visualization tool are demonstrated through a case study that utilizes data collected from an air handling unit and variable air volume zones located in a commercial building in Ottawa, Canada. The data are used to train inverse greybox models, and model parameters are fed into the visualization tool to create virtual meters that estimate the heat added or extracted by the air handling unit and the heat added by zone-level radiant heaters. End-users can interact with the visualization via interactive processes that enable them to select, filter, and/or explore the virtual metered energy to assist in building operational decisions. The potential of the visualization tool for improving building energy performance and assisting decision-making processes is discussed through illustrative examples.

Introduction

Efficient visualization of energy data is essential to understand energy use dynamics, support operational decisions, and improve building operations. Data collected from sensing and metering networks can be utilized to visualize energy flows across critical heating, ventilation, and air conditioning (HVAC) components of a commercial building. These visualizations allow key building stakeholders to interact with the graphical representation and gain valuable insights that would facilitate the decision-making processes and improve building energy performance. However, most existing building automation systems (BASs) do not use the available data to their full potential due to a lack of visualization techniques that can potentially turn energy data into a meaningful visualization. A visualization tool that utilizes available data from the BAS to create meaningful visualizations and allows end-users to interact with these visualizations would help building stakeholders better understand how energy flows in a building and enable insights that would improve operational decisions.

Visualization of energy data provides a tool that allows end-users to identify anomalous values, malfunctioning or poorly commissioned systems, and energy consumption patterns (Meyers et al., 1996). Real-time interactive feedback between an end-user and a visualization tool adds another layer to the visualization that creates a dialog between the user and the system and enables the user to derive insights based on processes such as comparing patterns of energy consumption of similar HVAC components (Yi et al., 2007). Visual analytics is an emerging field of research that combines automated analysis techniques and interactive visualizations to improve the understanding of large datasets for decision-making (Keim et al., 2008; Lu et al., 2017). As shown in Fig.1, the process of applying visual analytics involves the following interdisciplinary domains: a) data analysis which includes data collection and processing and model training using an analysis algorithm, b) visualization which presents the modelling results through graphical representations that allow end-users to notice correlations between variables and identify energy patterns and trends, and c) human interaction which utilizes human knowledge to interact with

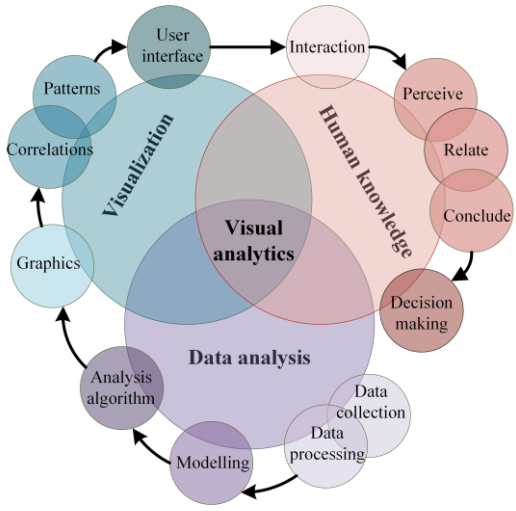

Figure 1: A schematic illustrating the concept of visual analytics which combines data analysis, visualization, and human knowledge.

the visualizations and provide feedback that would refine the visualization to include the target information.

Visual analytics can be applied to utilize energy data collected from physical meters; however, critical thermal energy flows are not typically measured in commercial buildings, such as the heat added or extracted by an air handling unit (AHU) and the heat added by heating devices in variable air volume (VAV) zones. Measuring these quantities using physical meters is uncommon due to cost and practical issues such as space limitations and installation difficulties. Virtual meters (VMs) can be employed to estimate these unmetered energy flows to understand their impact on the total energy consumption of a building. The process of developing a VM includes data collection and processing, model selection and training, and VM implementation and validation (Li et al., 2011). Data from available sensors, meters, and actuators are collected from the BAS and processed to fit models representing the equipment-level heat transfer mechanisms. An optimization algorithm is applied to estimate model parameters that are used to create VMs that predict the heating or cooling energy of HVAC equipment. Visualization allows presenting the knowledge gained from VMs to evaluate the findings and identify energy consumption patterns. Finally, user interaction allows users to interact with the visualization using their expert knowledge to derive insights that would improve their operational decisions.

Visualization tools developed in the reviewed literature can be classified as a) Visualization tools that use historical data (Hsieh & Lu, 2012; Yang & Ergan, 2014; Mcnamara et al., 2016; Azaza et al., 2019). These tools focus on monitoring sensing and metering data through visualizations that apply scientific or information visualization techniques to present data obtained from sensing or metering networks, and b) Visualization tools that use modelled data (Abdelalim et al., 2017; Raftery & Keane, 2011; Bush et al., 2018; Dutta, 2013; Ruiz et al., 2020). These tools employ modelling techniques to quantify unmeasured values or predict future values. However, a visualization tool that applies visual analytics to present energy data estimated by virtual metering algorithms has not been developed.

This paper presents a novel virtual metering visualization tool that can improve building energy performance and allow end-users to interact with the visualizations to gain insights into operational decisions. The visualization tool's use is demonstrated through illustrative examples using data collected from a commercial building. To this end, inverse greybox models are trained using operational data from an office building in Ottawa, Canada. Model parameters are used to create virtual meters that estimate the heat added or extracted by an AHU and the heat added by zone-level perimeter radiant heaters. Virtual metering results are presented through a novel visualization tool that allows end-users to interact with the virtual metered energy and gain insights that would facilitate the decision-making process.

Methodology

The process of developing a virtual metered energy (VME) visualization tool consists of the following stages: a) data collection and processing, b) modelling and parameter estimation, c) virtual metering, and d) developing a visualization tool, as illustrated in Fig. 2. These stages are described in the following subsections.

Data collection and processing

Data from a multiple zone VAV AHU system serving a commercial building in Ottawa, Canada, are collected from January 2019 to December 2019 at 1-hour intervals. As illustrated in Fig. 3, the AHU is equipped with outdoor and return air dampers that control the amount of fresh air intake, and heating and cooling coils that condition the supply air. The supply air is ducted to 41 VAV boxes (VBs) distributed across the first and second floors of the commercial building. The VAV zones are provided with

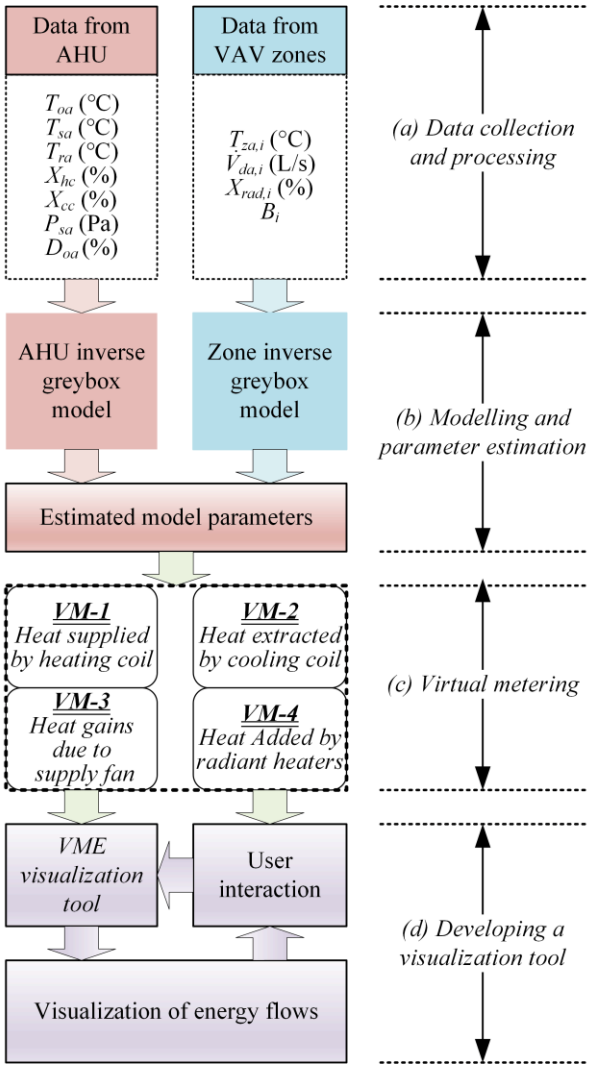

Figure 2: Schematic illustrating the process of developing a virtual metered energy visualization tool

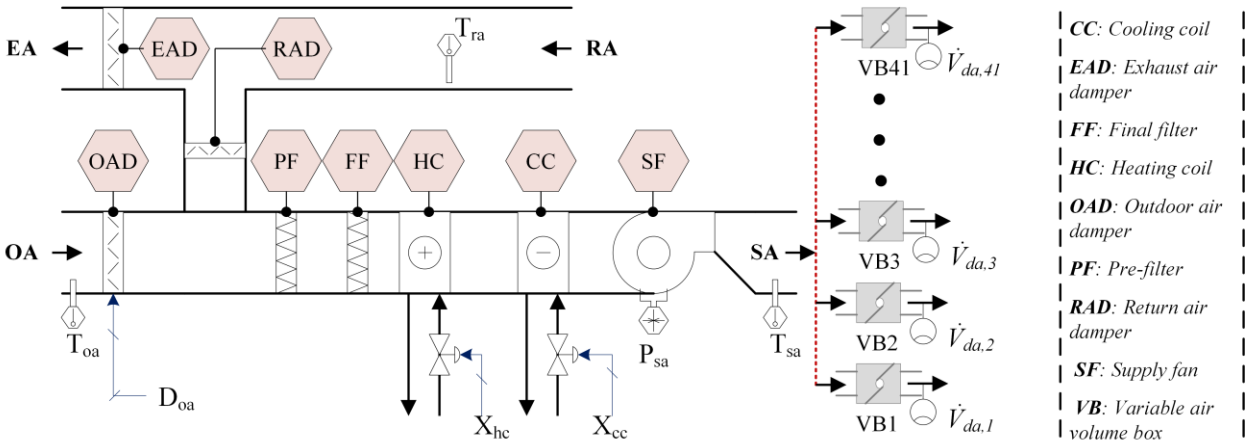

Figure 3: Schematic showing the components of the VAV AHU system in the case study

hydronic radiant heaters that use modulating valves to control the hot water flow rate into the VAV zones. At the AHU level, measurements of outdoor (T_{oa}(℃)), return (T_{ra}(℃)), and supply (T_{sa}(℃)) air temperatures, outdoor air damper position ($D_{oa}(\%)$), heating ($X_{hc}(\%)$) and cooling ($X_{cc}(\%)$) valve positions, and supply air pressure ($P_{sa}(Pa)$) are collected from the BAS. Additionally, the following data are collected from the 41 VAV zones served by the AHU: zone air temperatures ($T_{za,i}$(℃)), discharge airflow rate ($\dot{V}_{da,i}(L/s)$), radiant heater valve position ($X_{rad,i}(\%)$), and a binary occupancy signal (B_i). The subscript *i* refers to the VAV zone index number. The VAV AHU system described in this section is utilized as a case study to demonstrate modelling and parameter estimation, virtual metering, and the use of the VME visualization tool presented in the following subsections.

Modelling and parameter estimation

The data collected from the VAV AHU system are used to train AHU and zone inverse greybox models. For the AHU, the inverse model applies energy and mass balances across the components of an AHU, including the mixing box (*i.e.*, the mixing process of outdoor and return air), the heating and cooling coils, and the supply fan to estimate T_{sa} as follows (Darwazeh, Gunay, et al., 2021):

$$\begin{aligned} T_{sa} = {} & \left[\left(x_{1,ahu}\cdot D_{oa} + x_{2,ahu}\right)\cdot T_{oa}\right] \\ & + \left[\left(1-\left(x_{1,ahu}\cdot D_{oa} + x_{2,ahu}\right)\right)\cdot T_{ra}\right] \\ & + \left[\frac{3390\cdot\left(x_{3,ahu}\cdot X_{hc} + x_{4,ahu}\right)}{\dot{V}_{sa}}\right] \\ & + \left[\frac{3390\cdot\left(x_{5,ahu}\cdot X_{cc} + x_{6,ahu}\right)}{\dot{V}_{sa}}\right] \\ & + \left[x_{7,ahu}.\left(P_{sa}\right)\right] + x_{8,ahu} \end{aligned} \quad (1)$$

where $x_{1,ahu}$ and $x_{2,ahu}$ are the mixing model parameters, $x_{3,ahu}$ to $x_{6,ahu}$ are the heating and cooling coil model parameters, $x_{7,ahu}$ is the supply fan model parameter, and parameter $x_{8,ahu}$ captures the bias error of the model. $\dot{V}_{sa}$ is the volumetric supply airflow rate (L/s). Note that since $\dot{V}_{sa}$ is not measured in the AHU of the case study, $\dot{V}_{da}$ from the 41 zone VAV boxes that the AHU serves are summed to estimate $\dot{V}_{sa}$ at each timestep. The factor 3390 is the result of dividing $(\rho_w \cdot c_w)$ by $(\rho_a \cdot c_a)$, where ρ_w is the density of water, 998.2 kg/m^3, c_w is the specific heat of water, 4185 J/(kg·°C), ρ_a is the density of air, 1.2 kg/m^3, and c_a is the specific heat of air, 1006 J/(kg·°C).

The heat transfer mechanisms at a VAV zone are approximated using an equivalent thermal network comprising one resistance and one capacitance, as described by (Darwazeh, Duquette, et al., 2021). A transient inverse greybox model is utilized to estimate the heat added or extracted through the VAV terminal box for each zone as follows:

$$\begin{aligned} & c_a\cdot\rho_a\cdot\left(\dot{V}_{da,i}^{k-1}\right)\cdot\left(T_{za,i}^{k-1} - T_{sa}^{k-1}\right) \\ & = \left(\frac{\left(T_{oa}^{k-1} - T_{za,i}^{k-1}\right)}{x_{1,vav}}\right) + \left(x_{2,vav}\cdot B_i^{k-1}\right) \\ & + \left(d_{i,vav}\cdot X_{rad,i}^{k-1}\right) - \left(x_{3,vav}\cdot\frac{T_{za,i}^{k} - T_{za,i}^{k-1}}{\Delta t}\right) + x_{4,vav} \end{aligned} \quad (2)$$

where model parameters $x_{1,vav}$ to $x_{3,vav}$ estimate the effect of the zone thermal resistance, internal heat gains, and the transient response of zone thermal capacitance on the energy balance of the zone, parameter $d_{i,vav}$ estimates the capacity of the radiant heater at zone *i*, and parameter $x_{4,vav}$ accounts for unmodelled heat flow within the zone. Note that Δt (hours) represents the timestep interval, and the superscript k is the index number of measured data.

The genetic algorithm with a population size of 5000 in 12 generations is used to find optimal values for model parameters of Eqn. (1) and (2).

Virtual metering

The obtained model parameter values are used to create four virtual meters: *VM1* estimates the heat supplied by the AHU heating coil, E_{hc} (kWh). *VM2* estimates the heat extracted by the AHU cooling coil, E_{cc} (kWh). *VM3* estimates the heat gains from the AHU supply fan, E_{sf} (kWh). *VM4* estimates

the heat supplied by the radiant heaters in the VAV zones served by the AHU, E_{rad} (kWh), as shown in Eqns. (3) to (6), respectively.

$$VM1 = \sum_{n=1}^{N} E_{hc,n} = \sum_{n=1}^{N} (\rho_a \cdot \dot{V}_{sa,n} \cdot c_a \cdot \Delta T_{hc,n} \cdot \Delta t) \quad (3)$$

$$VM2 = \sum_{n=1}^{N} -E_{cc,n} = \sum_{n=1}^{N} -(\rho_a \cdot \dot{V}_{sa,n} \cdot c_a \cdot \Delta T_{cc,n} \cdot \Delta t) \quad (4)$$

$$VM3 = \sum_{n=1}^{N} E_{sf,n} = \sum_{n=1}^{N} (\rho_a \cdot \dot{V}_{sa,n} \cdot c_a \cdot \Delta T_{sf,n} \cdot \Delta t) \quad (5)$$

$$VM4 = \sum_{n=1}^{N} E_{rad,n} = \sum_{n=1}^{N} \sum_{i=1}^{41} (d_i \cdot X_{rad,i} \cdot \Delta t) \quad (6)$$

where $\Delta T_{hc,n}$, $\Delta T_{cc,n}$, and $\Delta T_{sf,n}$ represent the air temperature difference across the heating coil, cooling coil, and supply fan, given by the 3rd, 4th, and 5th terms of Eqn. (1), respectively, at each data point (n). These virtual meters aggregate the energy over a total number of data points (N) corresponding to a date range selected through a standalone visualization tool developed in the following section.

Building a standalone VME visualization tool

App Designer (MathWorks, 2021) is used to build a graphical user interface (GUI) that allows end-users to visualize the VME for VAV AHU systems. App Designer deploys MATLAB programming code into a user-friendly interactive software that can run on any machine without the need to install MATLAB. The GUI can be developed using built-in user interface (UI) components, such as buttons and checkboxes. Callback functions can be assigned to the UI components to allow a certain command to execute once a change in the UI component occurs. For example, when a checkbox is selected, a callback function assigned to the checkbox is executed. Applications created using App Designer can be compiled into a single file in the form of a .exe extension that is easy to distribute to end-users.

As shown in Fig. 4, the main interface of the VME visualization tool consists of the following panels:

A. *Load data files panel*: this panel allows users to upload the data files for the AHU and VAV zones. A file selection window pops up that enables the selection of files from the user's local drive. The required format of the files is defined in the help files that are compiled in the application software. The import data buttons execute a set of callback functions that define imported data properties and match the measurement labels to a predefined library of possible point labels. For example, the heating coil valve position signal, X_{hc}, could be labelled as hcv, vhc, hwv, or hvmod in the imported data. The App searches for any of these labels and assigns the values to X_{hc}. Finally, the user is asked to define the seasonal availability of heating and cooling for the building by entering "1" if heating is available in the winter only and cooling is available in the summer only, or "0" if heating and cooling are available year-round.

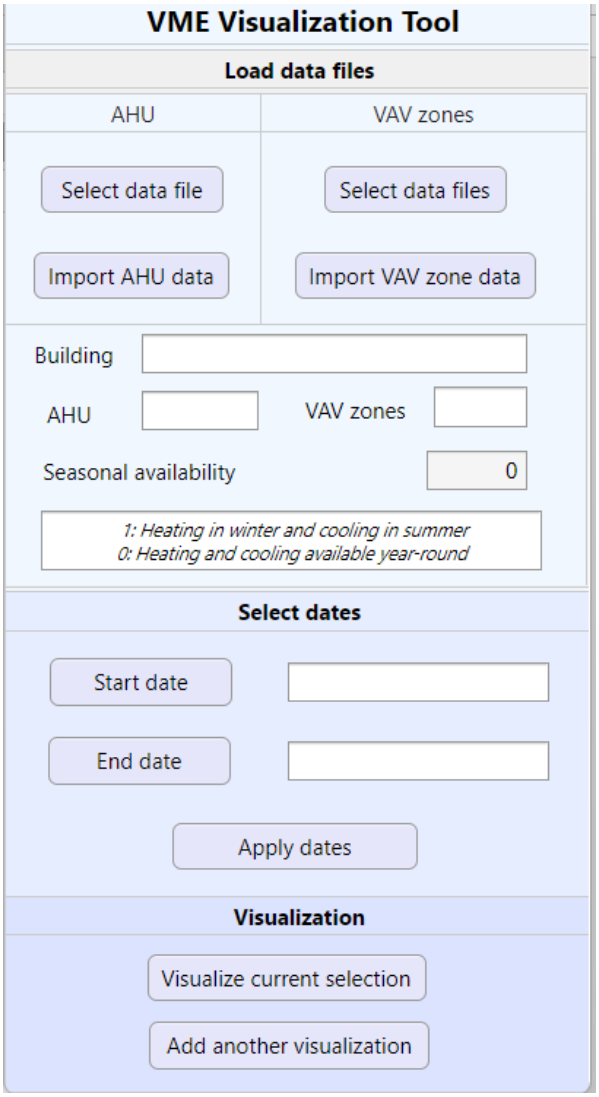

Figure 4: Main interface of VME visualization tool

B. *Select dates panel*: this panel allows users to select start and end dates for the visualization through a pop-up window that enables date selection between the minimum and maximum dates of imported data. The *Apply dates* button executes a series of callback functions that filter the data based on user date range selection and applies Eqns. (3) to (6) on the filtered data to estimate the VME of the VAV AHU system. Note that the values obtained for model parameters in Eqn. (1) and (2) are required to estimate the VME (see Modelling and parameter estimation and Virtual metering sections). These values are extracted from the genetic algorithm results into an excel file that is compiled in the application software.

C. *Visualization panel*: this panel allows users to visualize the VME of the VAV AHU system based on the

uploaded data and the selected date range. The *visualize current selection* button executes a number of callback functions that present the visualization of the current selection in a new UI panel. The plot scale is determined based on the maximum estimated VME for the date range selected by the user. The generated visualization uses a combination of Sankey diagrams, conventional equipment standards, and colour coding to present the VME in a simplified view that enables users to understand how energy flows from an AHU and radiant heaters into VAV thermal zones and identify energy consumption patterns.

The UI panel that presents the visualization is designed programmatically using MATLAB functions which allow additional control over the code structure. The MATLAB *uifigure* function is deployed to create a container that presents the visualization together with custom UI components designed to provide a convenient interface to users and allow them to interact with the visualization to gain insights that would improve operational decisions. These UI components are organized in a user interaction panel within the same visualization container to enable users to modify the existing visualization interactively through the following interaction techniques:

1. *Select*: this interaction technique allows users to select new start and end dates and apply the new selection to modify the existing visualization.
2. *Filter*: users can filter the visualization through checkboxes that allow them to apply conditions by selecting "*occupied*", which estimates the VME during building occupied hours (*i.e.*, from 9 am to 5 pm during weekdays), "*unoccupied*", which estimates the VME during building unoccupied hours, "*HC valve on*", which estimates the VME at instances when the heating coil valve is at a position more than 0%, and "*CC valve on*", which estimates the VME at instances when the cooling coil valve is at a position more than 0%. Additionally, the filter interaction technique allows simultaneous selection of filters such as "*occupied*" and "*HC valve on*", which would modify the existing visualization based on the combination of the two filters.
3. *Explore*: this interaction technique allows users to explore the details of one of the components in the visualization. Users can click on "*Rad VAV Zones*" button to explore the details of heat added by radiant heaters in the VAV zones. The details are shown in a new UI panel that presents the VAV zones and the amount of heat added by the radiant heater in each zone.
4. *Compare*: users can compare two visualizations by clicking on the "*Duplicate*" button to generate a second visualization window with full functionalities as the first one. Users can select another set of start and end dates in the second visualization window and compare the VME in the two visualizations. Users can also choose different filters in the first and second visualizations, such as "*occupied*" in the first visualization and "*unoccupied*" in the second visualization, to compare the VME when two different conditions are applied.

The functions used in the VME visualization tool are compiled using the MATLAB Compiler into a single standalone executable application file. The installation file, the MATLAB code script, and the data collected from the VAV AHU system in the case study (see Data collection and processing section) are provided as supplemental files available for download on GitHub (*DBOM*, 2022).

Results and discussion

The data collected from the commercial building in the case study are used as input files to the VME visualization tool to demonstrate its use and the usefulness of the visualizations in supporting building operations. As shown in Fig. 5, a visualization is generated using the data collected from the VAV AHU system in the case study from Jan. 2019 to Dec. 2019. The visualization presents the VME in a simplified way that allows end-users to understand how energy flows from the AHU and radiant heaters into the VAV zones. The conventional equipment standards and colour coding enable quick identification of HVAC components and heating or cooling energy. It is noticed that the radiant heaters added almost the same amount of heat into the VAV zones as the AHU heating coil, and the heat extracted by the cooling coil is nearly triple the amount of heat supplied by the heating coil. These system behaviours add to the operational knowledge of the user, who can compare the VAV AHU system behaviour with similar systems to identify any operational inefficiencies.

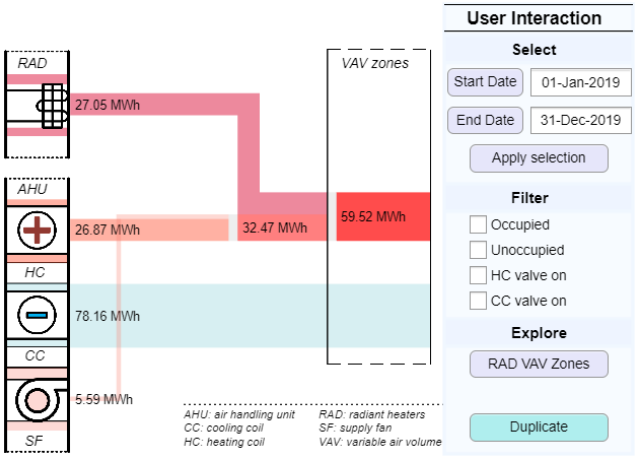

Figure 5: Visualization of VME using 1-year's worth of data from the VAV AHU system in the case study

The *select* interaction technique can be applied to identify energy consumption patterns and ensure healthy operation of the VAV AHU system. For example, the VME visualization for the system in the case study is modified to present the VME during the cooling season (*i.e.*, from June to September 2019), as shown in Fig. 6. It is noticed that the heat extracted by the cooling coil during the cooling season is around 90% of the total heat extracted during the year. Moreover, the heat added by the AHU heating coil and

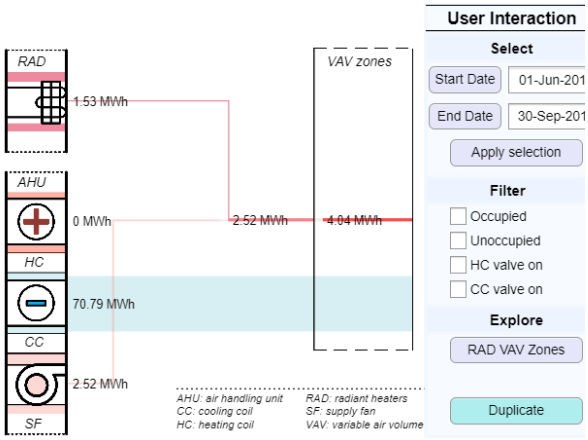

Figure 6: Visualization of VME during the cooling season

radiant heaters are 0 MWh and 1.53 MWh, respectively. These values indicate healthy operation of the VAV AHU system in the case study. However, investigating the system settings and sequences of operation is recommended in cases where the cooling coil extracts a considerable amount of heat during the heating season or the heating coil adds a considerable amount of heat during the cooling season. Therefore, the *select* interaction technique provides valuable information regarding the VAV AHU system's health.

The visualization tool allows end-users to filter the data and gain insights into potential energy-saving opportunities. The *filter* interaction technique can be used to examine the suitability of existing building operating schedules. For example, two visualization views are generated for the VAV AHU system in the case study using "*occupied*" and "*unoccupied*" filters, as shown in Fig. 7. The "occupied" filter applies callback functions that estimate the VME between 9 am and 5 pm on weekdays, whereas times outside the occupied hours are considered unoccupied. By comparing the two visualizations, it is noticed that the VME supplied by the AHU heating coil, cooling coil, and supply fan during unoccupied hours represents 64%, 60%, and 60% of the annual VME supplied by each component, respectively. The higher energy consumption of the AHU during unoccupied hours as compared to occupied hours could indicate a possible energy-saving opportunity. End-users can use this information to check the AHU start-up and shut-down schedules and apply changes to improve overall building energy performance while maintaining the minimum operational requirement during unoccupied hours. Moreover, the VME supplied by the radiant heaters during unoccupied hours represents 73% of the annual energy injected by radiant heaters into the VAV zones. End-users can utilize this information to investigate the reason behind the higher energy consumption in VAV zones during unoccupied hours and try to cut any unnecessary use of radiant heaters.

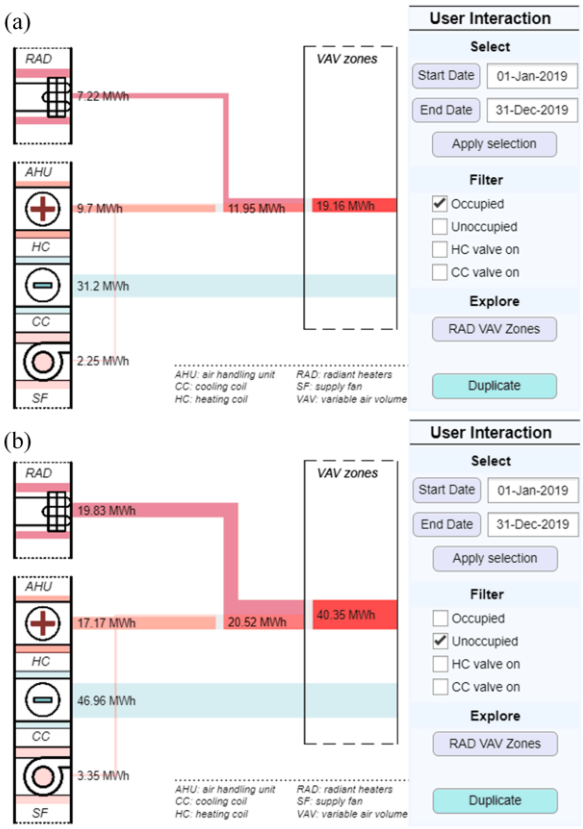

Figure 7: Visualization of VME during (a) occupied hours and (b) unoccupied hours using 1-year's worth of data from the VAV AHU system in the case study

The *filter* interaction technique can also be utilized to capture component anomalies and operational inefficiencies. For example, a visualization view is generated using the data collected from the case study from Jan. 2019 to Dec. 2019. Both *filter* checkboxes "*HC valve on*" and "*CC valve on*" were selected to check for simultaneous heating and cooling during the AHU operation. When both filters are selected, the VME visualization tool filters the data based on instances when both the heating and cooling coil valves are open. As illustrated in Fig. 8, a minor simultaneous heating and cooling is detected in the VAV AHU system of the case study, which could be related to heating or cooling coil valve position signal error. Further investigation is recommended in cases when simultaneous heating and cooling occurs more frequently, which could be related to faulty heating or cooling valve.

The *explore* interaction technique can be used to examine the details of a component in the visualization to gain a better understanding and insights. The VME visualization tool allows users to explore the details of heat added by radiant heaters in the VAV zones to identify zones of high energy consumption. A detailed visualization is generated for the heat added by radiant heaters in the 41 VAV zones for the VAV system in the case study by clicking the "*RAD*

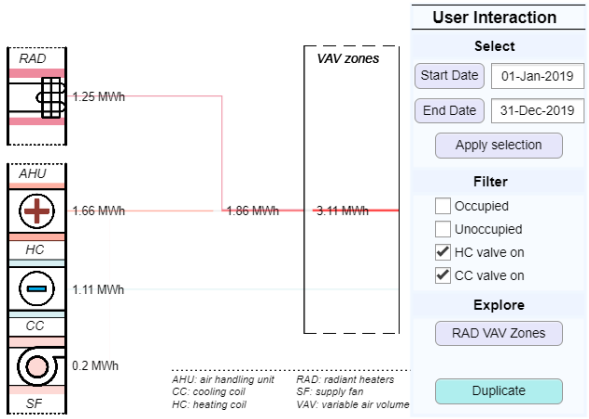

Figure 8: Visualization of VME at instances when both the heating and cooling coil valves are on using 1-year's worth of data from the VAV AHU system in the case study

VAV Zones" button in the user interaction panel. The period selected covers one operational year from Jan. to Dec. 2019. While the main visualization panel presents the total heat added by radiant heaters in the 41 zones (see Fig. 5), a new visualization panel pops up, as shown in Fig. 9, to present the heat added to individual zones. The squares in Fig. 9 represent the VAV zones with the zone number at the left and the amount of heat added by the radiant heater in that zone at the bottom. The circle size corresponds to the amount of heat added at each zone. Additionally, squares with a diagonal dashed line do not have radiant heaters, whereas squares filled with grey are unused spaces. This detailed visualization can be used as a tool by end-users to quickly identify VAV zones of high energy consumption and investigate the underlying operational conditions of the zones in order to improve the energy performance of the building. Moreover, the VME visualization tool allows the

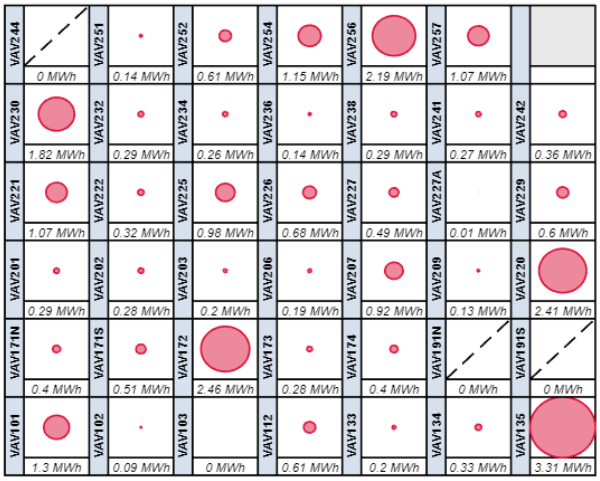

Figure 9: A detailed visualization of heat added by radiant heaters in the 41 VAV zones of the case study. Each square represents a VAV zone with the zone number at the left and the amount of VME at the bottom

users to generate two detailed visualizations for the heat added by radiant heaters. Users can generate two visualizations for two different periods and compare the energy consumed at zone-level to gain insights into any changes in operating conditions.

The use of a VME visualization tool was demonstrated in this study through illustrative examples using data from a VAV AHU system in a case study. The software tool utilizes BAS historical data to create virtual meters that estimate the energy consumed by an AHU and zone-level radiant heaters. The VME visualization tool is compiled into a single standalone executable application file available for download on GitHub (*DBOM*, 2022).

Conclusions

This paper presented a virtual meter-based energy visualization tool that uses common building automation system data to visualize the energy estimated by equipment-level virtual meters. Data collected from a commercial building in Ottawa, Canada, are used to train inverse greybox models representing heat transfer mechanisms in an air handling unit and a variable air volume zone. Model parameters are utilized for creating virtual meters that estimate the heat added or extracted by an air handling unit and the heat added by zone-level radiant heaters. The virtual metered energy is presented through a simplified visualization that uses a combination of Sankey diagrams, conventional equipment standards, and colour coding, and allows users to better understand how energy flows from an AHU and radiant heaters into VAV thermal zones. Users can interact with the visualization through a user interaction panel that allows them to select, filter, or explore the results to gain insights into building operational decisions.

The usefulness of the visualization tool in supporting building operation was demonstrated through illustrative examples from the case study. Users can utilize the functions implemented in the user interaction panel to identify energy consumption patterns, investigate system settings and sequences of operation, and capture inefficient operation and energy-saving opportunities.

The initial design of the visualization tool was demonstrated in this study; however, several issues are still unresolved and require further research to implement them in a future iteration of the visualization tool, such as: a) the model parameter estimation is carried out outside the visualization tool using the genetic algorithm. Future work is planned to integrate parameter estimation within the functions of the visualization tool, and b) the ability of the visualization tool to generate a report for the visualization results is not available. Future work is planned to include functions that allow users to download a PDF report file.

Acknowledgement

This research is supported by the research funding provided by the National Sciences and Engineering Research Council (NSERC) of Canada, Brookfield Global Integrated

Solutions (BGIS), Public Services and Procurement Canada (PSPC), and CopperTree Analytics.

References

Abdelalim, A., O'Brien, W., & Shi, Z. (2017). Data visualization and analysis of energy flow on a multi-zone building scale. *Automation in Construction*, *84*, 258–273. https://doi.org/10.1016/j.autcon.2017.09.012

Azaza, M., Eskilsson, A., & Wallin, F. (2019). An open-source visualization platform for energy flows mapping and enhanced decision making. *Energy Procedia*, *158*, 3208–3214. https://doi.org/10.1016/j.egypro.2019.01.1006

Bush, B., Brunhart-Lupo, N., Bugbee, B., Krishnan, V., Potter, K., & Gruchalla, K. (2018). Coupling visualization, simulation, and deep learning for ensemble steering of complex energy models. *2017 IEEE Workshop on Data Systems for Interactive Analysis, DSIA 2017*, *2018-April*, 1–5. https://doi.org/10.1109/DSIA.2017.8339087

Darwazeh, D., Duquette, J., & Gunay, B. (2021). Virtual metering of heat supplied by zone-level perimeter heaters: an investigation with three inverse modelling approaches. *Energy and Buildings*, 110867. https://doi.org/10.1016/j.enbuild.2021.110867

Darwazeh, D., Gunay, B., & Duquette, J. (2021). Development of Inverse Greybox Model-Based Virtual Meters for Air Handling Units. *IEEE Transactions on Automation Science and Engineering*, *18*(1), 323–336. https://doi.org/10.1109/TASE.2020.3005888

DBOM. (2022). https://github.com/Carleton-DBOM-Research-Group/VME-Visualization

Dutta, R. (2013). A Visual Analytics Based Decision Support Methodology For Evaluating Low Energy Building Design Alternatives. *ProQuest Dissertations And Theses; Thesis (M.S.)--Arizona State University*, 197. https://repository.asu.edu/attachments/125834/content/Dutta_asu_0010N_13386.pdf

Hsieh, Y. M., & Lu, Y. S. (2012). Visualization system for field monitoring data and its effectiveness. *Automation in Construction*, *26*, 54–68. https://doi.org/10.1016/j.autcon.2012.03.004

Keim, D., Andrienko, G., Fekete, J. D., Görg, C., Kohlhammer, J., & Melançon, G. (2008). Visual analytics: Definition, process, and challenges. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *4950 LNCS*, 154–175. https://doi.org/10.1007/978-3-540-70956-5_7

Li, H., Yu, D., & Braun, J. E. (2011). A review of virtual sensing technology and application in building systems. In *HVAC and R Research*. https://doi.org/10.1080/10789669.2011.573051

Lu, M., Chen, S., Lai, C., Lin, L., & Yuan, X. (2017). Frontier of Information Visualization and Visual Analytics in 2016. *Journal of Visualization*, *20*(4), 667–686. https://doi.org/10.1007/s12650-017-0431-9

MathWorks. (2021). *MATLAB App Designer - MATLAB & Simulink*. https://www.mathworks.com/products/matlab/app-designer.html

Mcnamara, D., Tapia, J., Ma, C., Luciani, T., Burks, A., Trelles, J., & Marai, G. E. (2016). Spatial Analysis of Employee Safety Using Organizable Event Quiltmaps. *Proceedings of the IEEE VIS 2016 Workshop on Temporal & Sequential Event Analysis*. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Spatial+analysis+of+employee+safety+using+organizable+event+quiltmaps&btnG=

Meyers, S., Mills, E., Chen, A., & Demsetz, L. (1996). Building data visualization for diagnostics. In *ASHRAE Journal* (Vol. 38, Issue 6). https://www.researchgate.net/profile/Evan_Mills/publication/294681171_Building_data_visualization_for_diagnostics/links/5e03f60892851c83649b455f/Building-data-visualization-for-diagnostics.pdf

Raftery, P., & Keane, M. (2011). *Visualizing patterns in building performance data CFD-ROM View project Hit2Gap View project*. https://www.researchgate.net/publication/286348376

Ruiz, L. G. B., Pegalajar, M. C., Molina-Solana, M., & Guo, Y. K. (2020). A case study on understanding energy consumption through prediction and visualization (VIMOEN). *Journal of Building Engineering*, *30*, 101315. https://doi.org/10.1016/j.jobe.2020.101315

Yang, X., & Ergan, S. (2014). Evaluation of visualization techniques for use by facility operators during monitoring tasks. *Automation in Construction*, *44*, 103–118. https://doi.org/10.1016/j.autcon.2014.03.023

Yi, J. S., Kang, Y. A., Stasko, J. T., & Jacko, J. A. (2007). Toward a deeper understanding of the role of interaction in information visualization. *IEEE Transactions on Visualization and Computer Graphics*, *13*(6), 1224–1231. https://doi.org/10.1109/TVCG.2007.70515