Resources, Conservation and Recycling 123 (2017) 219–229

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Spatiotemporal analysis and visualization of power consumption data integrated with building information models for energy savings

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ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 5 March 2016
Accepted 8 March 2016
Available online 16 March 2016

Keywords:
Building information modeling
Spatiotemporal analysis
Net-zero energy building
Unity game engine
Energy savings

ABSTRACT

Using a visualization engine to display the analyze results of power consumption data in a building can provide immediate and informative feedback for energy conservation research. Previous research has demonstrated that change of residents' behavior can facilitate achieving the net-zero energy goal for a building. This research proposed a system called iARTS (interactive Augmented Reality system for Temporal and Spatial analysis of power consumption data integrated with building information models) that was designed to: (1) integrate building information model data into power consumption data sets in order to visualize the analysis results in Unity, which is a visualization engine originally designed for game development; (2) perform a spatiotemporal analysis mechanism to help residents realize an energy-saving tip, by identifying the appliances to be turned off; (3) perform another spatiotemporal analysis mechanism to identify the appliances that can be used jointly in order to consume all the solar PV-generated electricity at a maximum; (4) provide residents with query forms, scenes retrieval functions, and animations to educate residents as to where and when to implement the aforementioned energy-saving tips. With the use of iARTS, the temporal relationships between power sockets and appliances can be accurately described along with timestamped power consumption data. Residents are expected to be able to identify the electricity usage patterns that are wasteful, as well as to see any potential adjustment plan for using as much generated electricity as possible.

1. Introduction

A recent survey showed that buildings account for 40% of the total energy usage in the European Union and constitute the largest sector followed by transportation (EC, 2015). While buildings share more electricity usage, previous research has also indicated that currently prevalent solar photovoltaic (PV) systems in Germany may equip buildings for generating a significant amount of electricity, to be consumed by various appliances in the buildings or to be fed into the grid (Wirth, 2015). Similar results can be found in reports for other regions of the world (Torcellini et al., 2006; NSTC, 2008; Peng et al., 2011). Indeed, if the total power consumption of a building is equal to the amount of the power generation its renewable energy systems can produce, such a building can be called a net-zero energy building, because it does not require the electricity to be supplied by any external source. Hence, realizing the net-zero energy goal for a building or for a facility will create a new opportunity for overall energy conservation and is presently an active research area.

Since human activities are the primary contributor to power consumption in buildings, previous research has been devoted to altering human behavior in order to reduce electricity usage (Laskey and Kavazovic, 2010). Similar studies on behavioral change and demand-side management (DSM) have been conducted in order to use all the electricity generated by renewable energy devices for achieving the net-zero energy goal (Torcellini et al., 2006; NSTC, 2008). Therefore, comprehensive collection and analysis of the power consumption data in a building must be performed, so as to identify the circumstances in which residents should change their habits.

However, currently, such power consumption data sets collected are often fragmentary and contain only recorded time and appliance or power meter-related data such as voltage and wattage values and appliance or sensor identifications (IDs). Neither the position nor the service area of each appliance in use are properly stored and managed, although they are very helpful

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http://dx.doi.org/10.1016/j.resconrec.2016.03.008
0921-3449/

for power consumption data analysis. In other words, a data fusion process that can be used to combine power consumption data with each appliance's spatial data might be needed for potential change of residents' behavior, in order to reduce their overall power consumption as well as to use all the solar PV-generated electricity. Although collection of such spatial data is time-consuming and error-prone, with the use of a modern technology from the construction industry called building information modeling (BIM), fusion of detailed spatial data fields of stationary appliances in a BIM file is straightforward and can be seamlessly performed by developing a customized tool. In fact, BIM has been regarded as a significant technological advance that is capable of providing the most comprehensive geometry and attribute data of a building. Moreover, BIM can be used to play a central role in the management of a building's assorted information during its entire lifecycle and has been successfully applied to many information-intensive activities performed during the design and construction phases of a building, such as clash detection and constructability analysis (Becerik-Gerber et al., 2012). Therefore, in this study, residents are supposed to provide a BIM file representing their real-world building, which will be used to create a virtual world, so that residents can easily indicate the position of each appliance as well as its service area in a more intuitive and interactive way.

In addition to the aforementioned data fusion work for power consumption and BIM data, new mechanisms capable of analyzing the fused spatiotemporal data sets might be needed. Nevertheless, previous researchers have not investigated the use of temporal databases or spatiotemporal query engines to process such power consumption data. Finally, if a BIM file representing a real-world building can be successfully transformed into a virtual one, many energy-saving suggestions can be implemented inside the interactive environment, so that residents can better understand how to realize them in their daily activities, to name a few.

To this end, this study is aimed at development of a data fusion process that can be used to integrate BIM data into power consumption data sets collected. The fused data sets can be managed and analyzed using a spatiotemporal database, i.e., a spatial database with customized temporal data processing functionality, in order to identify the circumstances in which residents should change their behavior. An interactive game-like environment was created to replay the analysis results to encourage change of residents' behavior in the hope of achieving the net-zero energy goal discussed above. The manuscript is structured as follows. Section 2 presents related literature, while Section 3 describes the overall data fusion process for power consumption and BIM data, which are in the Revit format and include spatial and materials-related data fields, with discussion on the major components of the proposed iARTS (interactive Augmented Reality system for Temporal and Spatial analysis of power consumption data integrated with building information models) for this study. Sections 4 and 5 present how to use iARTS to help residents realize two demonstrative energy-saving tips, i.e., one for reducing power consumption and the other for changing electricity usage periods from nighttime to daytime periods. Section 4 highlights the first proposed spatiotemporal data analysis mechanism that can be used to identify the circumstances for possible behavioral change for reducing power consumption. Section 5 then presents another mechanism that can be used to identify the circumstances for potential use of all the solar PV-generated electricity, and discusses the customized Unity platform that can be used to render a given building and to replay the power consumption events. Finally, Section 6 summarizes the conclusions derived from this study, highlights important functionality of iARTS, and discusses future work arising from this research.

2. Related work

The need to investigate power consumption data has been advocated in the fields of smart home and ubiquitous computing for years (Edwards and Grinter, 2001; Harper, 2003; Chetty et al., 2008). Some studies have argued that consumption of assorted resources be monitored, collected and managed in order to make a home smarter (Fogarty et al., 2006; Patel et al., 2008), while other research has concentrated on how to display real-time energy consumption information for each appliance monitored (Wood and Newborough, 2003; Ueno et al., 2006). Recently, a greater number of researchers have examined the strategy regarding installation of one sensor for one appliance to obtain its real-time power consumption data (Hoque and Stankovic, 2012; Chen et al., 2013; Alhamoud et al., 2015). Furthermore, the ultimate goal of this strategy was often about recognizing human activities to save energy (Darby, 2006; Crossley, 2007; Martinez-Gil et al., 2013), and various researchers have claimed that with proper design of its feedback system to encourage change of residents' behavior, a 5–10% reduction of power consumption could be expected (Cho et al., 2010). Indeed, the psychological interventional approach has been proved to be effective in reducing other resource consumption (Ohtomo and Ohnuma, 2014).

In fact, there are several types of methods that can be used to obtain power consumption data for an appliance. Mustafa et al. (2014) employed a questionnaire-based survey to collect such information. As numerous types of sensors have been increasingly designed and deployed inside a building, physical quantities such as room temperature, humidity, carbon dioxide concentration, and electricity usage or generation can be accurately measured by the sensor technology (Sinopoli, 2009). Due to recent remarkable technological advances, especially IoT (Internet of Things), the sensed data can now be seamlessly processed and transmitted to a central information system to perform further data fusion work, as well as being adequately persisted and managed by a data warehouse system for a long period of time. Hence, nowadays, facility managers or building residents can rely on the sensed data to define the best strategy for facility maintenance, to support energy-related decisions for facility operations, and to help them better protect and supervise the facility's surrounding environment (Teicholz, 2013). It should be noted that another technique called NILM (nonintrusive load monitoring) can be utilized to estimate appliance-level power consumption data as well, which requires installation of a specialized sensor on the main circuit panel of a household to disaggregate its total power consumption data so as to determine how much electricity each connected appliance has consumed (Carlson et al., 2013; Stephen et al., 2014). Nevertheless, none of the data collection methods discussed in the literature incorporates the BIM data into their power consumption data sets. Spatial data fields such as appliance positions and service areas cannot be directly obtained, or they can be estimated in an approximate manner (Cho et al., 2010), which might cause a problem if exact or flexible location information is critical in the analysis.

In addition to the aforementioned collection work of power consumption data sets, since the amount of electricity consumed by one appliance should be evaluated and recorded in a database very frequently, it can be expected that such data sets will grow very rapidly, with a large portion pertaining to temporal data. Theoretically, temporal data should be best handled and managed by a temporal database to provide users with the sophisticated query and temporal data processing functionality (Date, 2014). Nevertheless, previous researchers have not investigated the use of temporal databases or spatiotemporal query engines to process power consumption data. There are several useful algorithms currently implemented in temporal databases that may benefit power consumption data analysis. For example, the temporal coalescing