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Occupant perceptions of building information model-based energy visualizations in eco-feedback systems

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HIGHLIGHTS

- Different visualizations have been used to represent energy consumption.
- However, the effectiveness of such techniques varies across studies.
- We introduce a new eco-feedback information representation method.
- The method integrates energy information into a building information model.
- We validate the method and find users understand and prefer 2D visualizations.

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ABSTRACT

While technology advancements are improving the energy efficiency of buildings, occupant behavior remains a critical factor in ensuring the effectiveness of such enhancements. To this end, numerous eco-feedback systems have been developed to reduce building energy use through influencing occupants' behaviors during building operations. Information representation is a critical component in eco-feedback systems, affecting the users' interpretation, engagement, and motivation to reduce energy consumption. Many studies have focused on using different charts and technical units or abstract and artistic visualizations to represent energy consumption. However, the effectiveness of such techniques varies across studies. Recent research emphasizes the need to integrate information representation strategies that balance numeric and aesthetic appeal. Concurrently, studies have called for increased adoption of a Building Information Model (BIM) during a building's operations phase to improve facility management. In this paper, we introduce a new eco-feedback information representation method that combines numeric and aesthetic appeal through leveraging spatial and color-coding techniques in BIM. The BIM-integrated energy visualization approach developed in this paper uses the Revit Application Program Interface (API) and allows users to visualize and compare energy consumption values in 2D and 3D views of a multi-family building through a color-coding scheme in an as-built BIM. The method is validated through a user survey that quantitatively and qualitatively assesses the proposed 2D and 3D BIM eco-feedback compared to more traditional bar chart based eco-feedback. Our findings suggest that 2D spatial, color-coded eco-feedback provides the optimal information representation, as it is easy to understand, while evoking engaging and motivating responses from users. This study advances our understanding of eco-feedback information representation while expanding BIM applications during building operations. These are important steps to address the human dimension of energy efficiency in the built environment.

1. Introduction

The efficient use of energy resources has gained global attention as scarce resources are being depleted and greenhouse gas emissions continue to rise. In the United States, approximately 39% of the total energy consumption and its associated CO_2 emissions are attributed to building-related activities [1]. The percentage of CO_2 emissions from buildings in the U.S. has been projected to increase by 1.8% per year [2]. In order to address this, many approaches have been introduced to improve energy efficiency in buildings, such as: building retrofits, utilizing energy efficient equipment, and implementing energy efficient technologies recommended by various energy rating organizations.

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However, these approaches cannot be fully exploited if they do not consider the impact of building occupants' behavior. It has been demonstrated that occupants' energy consumption behavior is critical to building energy efficiency [3–6], providing the potential to offset up to 7.4% of the associated CO_2 emissions [7].

Recently, researchers have examined occupant-based energy efficiency approaches (e.g., eco-feedback systems) that can encourage building occupants to conserve energy [3,7–9]. Eco-feedback systems provide feedback on individual or group behaviors with a goal of reducing environmental impact. The research is based in part on the premise that people lack awareness and understanding of how their everyday consumption behaviors affect the environment. The feedback system may bridge this gap by automatically providing energy consumption feedback on building-related activities by sensing these activities through computerized means [10,11]. Through informative feedback, eco-feedback systems can improve users' awareness of their own energy use impacts, and positively reinforce or promote change of users' behaviors [12]. Although there are numerous factors that impact the effectiveness of an eco-feedback system in promoting user awareness and behavior change, two critical features are information content and information representation [3,11,13,14]. Information content includes the energy consumption data of an individual and/or group of individuals. Information representations of eco-feedback data are diverse and include units such as direct kilowatt hour units, monetary units, or CO_2 emission units [13,14]. Additionally, different representation techniques, such as tables, line charts, and bar charts, have been examined based on descriptive and injunctive norms. Researchers continue to explore ways to create more effective and impactful information representation techniques in eco-feedback systems. One recent promising trend is the integration of energy use information into a building information model (BIM).

Researchers have begun to examine the effect of building-based visualization in the design of eco-feedback systems by using BIM [15–17]. In the current practice, BIM is a widely used form of information storage and visualization in the architecture, engineering, and construction (AEC) industry, which allows users to build accurate computer-generated models [18]. These models can incorporate simulation and visualization tools to support energy-efficient design decision making [19]. Most previous studies have focused on using BIM for energy efficiency to facilitate better design integration in the early design phase [20–22]. However, research on the potential of using BIM for energy efficiency and energy use visualization in the operational phase of a building's lifecycle is in its infancy, and studies lack consideration of users' impact beyond facility management [23,24]. Integrating energy use information into BIM to reflect the actual operating conditions of buildings will provide many benefits to not only building operators, but also *building occupants*. For example, BIMs displaying energy use that is accessible to occupants can enable an occupant-operator feedback loop. Studies have indicated such communication exchanges can increase occupant trust and understanding of energy information [25]. As BIM adoption increases in the AEC industry, an increasing number of new buildings have BIM as a part of the required project documentation and deliverables. These models could be employed as an energy use visualization framework in eco-feedback systems. This would help occupants easily and intuitively determine their energy use levels if a comprehensive color-based energy use information visualization were established. It is thus necessary to establish a user-friendly communication method that does not require a priori knowledge of energy units or values, which may result in improved energy conservation outcomes when eco-feedback systems are implemented. In this paper, we develop a technique to integrate measured energy consumption data into an as-built BIM and empirically validate our approach to examine its potential in driving behavior change.

2. Background

2.1. Eco-feedback system overview

There are numerous eco-feedback studies on residential and commercial buildings investigating the effectiveness of underlying system components such as information representation methods, psychological motivators, and interface design on motivating occupants to reduce energy consumption. However, some components, such as information content and information representation in eco-feedback systems, have been found to be critical factors heavily affecting the efficacy of these systems [10,13,14], particularly if consumers have an interest in conservation [26].

Prominent examples of information content include appliance-specific feedback and social comparison feedback. In a review of eco-feedback studies, Fischer [3] found both of these features are likely to promote energy conservation behaviors. Appliance-specific feedback can improve the relevancy of eco-feedback by connecting the user with the energy use impact of their interactions with a particular appliance. This enables occupants to relate eco-feedback information to specific activities [27] and can improve the sense of control a person feels they have over changing their energy consumption [3]. In addition, normative comparison is a type of social comparison feedback method in which an individual or a group is compared to a norm (i.e., a reference value or benchmark), thereby using social norms as a motivation to encourage the conservation of energy. Studies have demonstrated that the normative comparison component of eco-feedback systems can drive energy efficient behavior from users through competition and public perception [3,11], and increase user responses to feedback system notifications [28]. Notably, the predominant visualization strategies adopted in normative eco-feedback deployments have generally been limited to bar and line charts, in both research studies [10,11,29,30] and industry applications [31,32].

Information representation techniques in eco-feedback are diverse and have explored a variety of energy units. Jain et al. [13] investigated the effect of environmental externality units (i.e., numbers of trees needed to offset CO_2 emissions) feedback versus energy unit (i.e., W or Wh) feedback, and concluded that participants who received feedback with environmental externality units saved more than participants receiving direct energy units relative to a control group. Furthermore, Asensio and Delmas [14] implemented a health-based feedback motivator to drive behavior changes for occupants in an 8 month-long study of 118 family apartments in Los Angeles. The study determined that the energy consumption of the group who received health-based feedback (i.e., the effect of energy use associated CO_2 emissions on childrens' health) was reduced by 8%. The savings increased to 19% for families with children.

Despite the effectiveness of the above approaches, the information was presented to users by numerical units and various bar and line charts, which studies have found much of the population has difficulty understanding [33–35]. Karjalainen [34] conducted 14 interviews involving people from different educational levels and ages in Finland to examine occupants' interpretation of various energy use representation methods. This study determined that participants encountered difficulties in interpreting various kinds of charts and scientific units, and tended to understand monetary unit representation. However, monetary representations in eco-feedback have not been an effective approach to increase occupant energy efficiency in some studies [14,36]. Moreover, Piccolo et al. [35] determined in a cultural analysis study that 70% of the population (from 15 to 64 years old) lacked essential skills to understand the charts and energy units in Brazil. In addition, Rodgers and Bartram [33] reported that in a study of 23 participants, around half had difficulties in comprehending energy units or were confused by traditional feedback visualizations including bar graphs and tables.

Recognizing limited user understanding of energy information