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An energy-aware, agent-based maintenance-scheduling framework to improve occupant satisfaction

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ABSTRACT

Facility management has become increasingly challenging due to complex building systems that generate more diverse and complex maintenance issues. Facility managers and staff must deal with many daily maintenance requests despite various limitations, such as limited budgets and staff, which can cause delay in responding to some maintenance requests. A scheduling framework is proposed in this paper to assist in improving facility management. In practice, maintenance work is scheduled according to various priorities. For example, facility managers first consider the impact of each problem in terms of system failure and safety. In addition to those two factors, the framework proposed in this paper considers both energy efficiency and occupant satisfaction. It first quantified occupant satisfaction with data from current building maintenance work. An empirical study on occupant satisfaction was done based on classical disconfirmation theory and referenced post-occupancy evaluation (POE) research. A survey was designed to collect data to quantify occupant satisfaction. Based on the disconfirmation theory, an agent-based model was then developed to prioritize maintenance work to achieve maximum occupant satisfaction. Subsequently, a building energy model was simulated in EnergyPlus to quantify the impact of different aspects of a faulty HVAC system on energy consumption. Finally, the framework was tested through simulation and the results showed that occupant satisfaction level and building energy efficiency were improved by 30 and 97%, respectively, when using the framework.

1. Introduction

Current building systems are increasingly complex and the number of requests for building maintenance work has increased exponentially. In a typical medium-sized building (between 5000 and 50,000 ft^2), occupants may submit more than 50,000 requests for facility management (FM) service every year [1]. In most situations, facility managers schedule work orders are subjectively based on work experience, while considering limited budgets and human resources [2]. However, this approach inevitably leads to inefficient operation and maintenance, which results in two significant problems: poor energy efficiency and decreased occupant satisfaction [3,41].

1.1. Building energy efficiency

In 2013, commercial and industrial buildings comprised more than 50% of the total energy consumption in the United States [4]. More than 60% of the energy consumed by buildings was attributable to their various systems, such as electrical and HVAC systems [5]. Improving energy efficiency during the building operation phase is significant for building sustainability improvement. During building operations, facility managers have an important role in improving energy efficiency.

In the FM handbook, Cotts et al. [1] emphasized the importance of a sustainable concept for the work of facility managers. One example is the energy audit. The FM book points out that one responsibility for building stakeholders is to determine the total energy consumption of a building and identify possible reduction measurements through an energy audit [1]. Compared to the design and construction phase of a building's life cycle, FM has greater potential for energy savings, even from handling regular service requests. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) estimated that daily faults in HVAC systems account for 1–2% of the energy consumption in commercial buildings [6]. This extra energy consumption is due mainly to delays in detection of problems and the time it takes to solve the problems [7].

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1.2. Occupant satisfaction

Occupant satisfaction is another important aspect for facility managers to consider. Improved satisfaction will ultimately help to assure profitability for building owners. Post-occupancy evaluation (POE) has been a prevalent research topic for more than fifty years. POE focused on determining occupant satisfaction and comfort levels with respect to the indoor environment of buildings [8–10]. However, few research efforts have been conducted with the aim of determining the impact of maintenance work on occupant satisfaction, when in fact, inefficient operation and maintenance of building systems can waste a large amount of energy and also significantly reduce overall occupant satisfaction [3,42].

Meir [10] reviewed twenty years of recently published materials concerning POE to discuss its conceptual and methodological background. He is one of the few researchers who have focused on the operation phase with the purpose of determining its deficits and shortcomings. Cheong et al. [11] also conducted a survey to identify the impacts of poor HVAC operation on occupant satisfaction. They pointed out that maintenance of the HVAC system must be planned and conducted effectively to ensure occupant satisfaction.

2. Literature review

2.1. Occupant satisfaction

With more focus on the operation phases of a building's life cycle management, many researchers proposed the idea of determining factors that affect service quality and occupant satisfaction. Derren and Barry [13] suggested that facility managers use service quality concepts originated in the external consumer market to learn how occupants feel about their service. The approach is called a service quality model (SERVQUAL). It uses a multi-item (such as communication, credibility and security) scale to evaluate the perception of occupants toward a service. The results help facility managers improve the performance of existing management methods and provide better delivery of appropriate services to meet specific customer requirements. In other research, Siu [14] assessed the quality of mechanical and engineering services in building maintenance. He posited that service providers with a clear sense of client expectations are in a better position to provide service that meets those expectations, which in turn results in a higher level of service quality.

The above research demonstrated the importance of improving the quality of service in FM. Joseph [9] did further research using an analytical hierarchy process to define high quality and cost-effective FM from five aspects: security, leisure and landscape, repair and maintenance, general management, and cleaning. The results showed that good service in repair and maintenance has a significant impact on occupant satisfaction. In addition, Meir et al. [10] determined factors that are related directly to occupant satisfaction. The most well-known research in this area is the post-occupancy evaluation (POE), which is a platform for the systematic study of occupied buildings to determine building functioning and performance in terms of indoor environment quality (IEQ), thermal performance, as well as subjective factors, such as user satisfaction. The purpose of POE is to improve current building conditions and guide the design of future buildings [10]. According to Meir et al. [10], POE and IEQ include five aspects: thermal, lighting, acoustic, space and indoor air quality, and comfort. These aspects are summarized from empirical studies of occupant comfort requirements in buildings thru work by Wang and Zamri [15], as well as Huber et al. [38]. The service quality of FM affects the indoor environment and thus it can be evaluated based on the above factors to quantify occupant satisfaction.

2.2. Energy impact of HVAC faults

In 2014, half of the energy consumption of the United States was attributable to buildings, and more than half of this energy consumption was due to the HVAC systems [4]. In the past, research was focused on the design of the HVAC system to minimize energy consumption. Later, it was determined that different maintenance practices associated with HVAC systems can result in substantial differences in a building's use of energy, maintenance costs, and also lifecycles of the equipment [22]. To learn more about improving energy efficiency, people started to evaluate the energy change from daily HVAC faults. Several sources of information regarding commonly occurring HVAC faults were identified. The most useful source was a report produced by the International Energy Agency's (IEA) document "*IEA Annex 25*" [24], which is a collection of reports on fault detection and diagnosis from researchers in a number of different countries such as Canada, France and Germany. In addition to the IEA Annex documents, useful information was also found in doctoral theses [25–27], which documented the energy penalty associated with various air-side system faults. These findings suggested that a single variable air volume [VAV] box damper being stuck open on every floor could increase the use of energy for cooling by 36%. As part of their fault detection and diagnosis studies, Katimapula [28] and Ashuri and Durmus-pedini [39] highlighted the waste of energy caused by HVAC faults in buildings. It was determined that poorly maintained, degraded, and improperly controlled equipment wastes an estimated 15 to 30% of the energy used in commercial buildings.

However, due to the difficulty of collecting the data directly, from the 1960s, researchers have resorted to simulating the use of energy in buildings to learn more about the energy impacts. Although this new method was very convenient for simulating the systems in large buildings, most programs available today that simulate the energy consumed by a building have limited capabilities for directly modeling HVAC operational faults or maintenance issues, which occur in almost every building [23].

Researchers at the Lawrence Laboratory [12] recently proposed new ways to evaluate the energy impacts of individual maintenance issues as well as combined scenarios for an office building with central VAV systems and a central plant by EnergyPlus simulations using three approaches: 1) direct modeling with EnergyPlus, 2) using the energy management system feature of EnergyPlus, and 3) modifying the source code of EnergyPlus. Their approach can be summarized in two steps: 1) collect the changed mechanical data for HVAC faults from an empirical study and 2) use the collected data to adjust the database in the simulation model. This paper refers to the data from their research.

2.3. Multi-agent system in the construction industry

The agent-based model is a new approach to model systems and the effects of change of the agents in the model, where the agent is a basic component that learns from the environment and dynamically change behavior in response to experiences [29,30]. Agent-based modeling and simulation (ABMS) is able to work on dynamic and complicated problems [30]. These characteristics make this method suitable for solving problems in infrastructure maintenance and repair, which also are dynamic and complex [31].

The agent-based model (ABM) has been applied in the construction field for some time. This phenomenon is due to an awareness of the inherently complex nature of construction problems and the difficulty in working on them. For example, the construction process is complex due to its interactivity with the outer environment [32]. The key to improvement is to analyze the problem by considering a human agent. One example is an ABM highway system composed of pavement, bridges, signs, signals, and decision makers [33]. They creatively solve the interactive process through an agent model. The study, however, did not develop a very complex framework. Watkins applied ABM to a construction site to predict and analyze congestion that might have an adverse impact on the efficiency of the project [34].

Although ABM is already a prevalent method used in construction management, its applications in infrastructure management and facility management are limited [35]. There is only very limited research that