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Building occupancy diversity and HVAC (heating, ventilation, and air conditioning) system energy efficiency

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Approximately forty percent of total building energy consumption is attributed to HVAC (heating, ventilation, and air conditioning) systems that aim to maintain healthy and comfortable indoor environments. An HVAC system is a network with several subsystems, and there exist heat transfer and balance among the zones of a building, as well as heat gains and losses through a building's envelope. Diverse occupancy (diversity in terms of when and how occupants occupy a building) in spaces could result in increase of loads that are not actual demands for an HVAC system, leading into inefficiencies. This paper introduces a framework to quantitatively evaluate the energy implications of occupancy diversity at the building level, where building information modeling is integrated to provide building geometries, HVAC system layouts, and spatial information as inputs for computing potential energy implications if occupancy diversity were to be eliminated. An agglomerate hierarchical clustering-based iterative evaluation algorithm is designed for iteratively eliminating occupancy diversity. Whole building energy simulations for a real-world building, as well as virtual reference buildings demonstrate that the proposed framework could effectively quantify the HVAC system energy efficiency affected by occupancy diversity and the framework is generalizable to different building geometries, layouts, and occupancy diversities.

1. Introduction

In the United States, people spend more than 90% of their time indoors [1] and approximately 40% of all energy consumption is attributed to the 120 million buildings [2]. Sustainability and energy conservation have become increasingly important topics, as nearly 50% of the energy consumed by buildings is wasted, and the total energy consumption by the building sector is projected to increase by 15.7% between 2013 and 2035 [3,4]. In commercial buildings, nearly 40% of the energy is used by HVAC (Heating, Ventilation, and Air Conditioning) systems to maintain comfortable and healthy indoor thermal environments [3,5]. Occupancy (when and how occupants occupy a building) is one of the most influential factors to determine the actual demands for an HVAC system, thus matching HVAC system controls with actual occupancy is an effective approach to reduce energy consumption without sacrificing occupant comfort and system functionality. In general, when a space is not occupied, loads in that space do not need to be fully addressed by the HVAC system. Occupancy could be incorporated with HVAC system controls to reduce the loads for heating and cooling. It has been demonstrated in our previous research [6] and by others [7,8] that if an HVAC system is controlled based on actual occupancy, energy efficiency could be significantly improved. Commercial buildings usually have multiple zones that are the basic thermal control units. The loads at the zone level are the sum of loads in all spaces of that zone. Diversity in occupancy among different spaces could lead to reduction in energy efficiency as the loads from an unoccupied space might still be considered as demands by the HVAC system [9]. In addition, there exist heat transfer and balance among the zones, as well as heat gains and losses through a building's envelope. Given the fact that different zones may have same supply air, loads exchange, shared or similar boundary conditions [10], occupancy diversity among those zones could result in diverse distributions of loads for the HVAC system, hindering system efficiency.

The objectives of this paper are to quantify the heating/cooling loads associated with occupancy diversity and to provide a generalizable framework to evaluate energy efficiency affected by eliminating the diversity. Occupancy is stochastic in nature with varied patterns, creating diverse schedules and requirements for heating and cooling. In this paper, occupancy diversity is analyzed from two perspectives of real-time occupancy and long-term occupancy.

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Real-time occupancy is the time-sequenced occupancy status at each time point, representing how an occupant occupies a space for a specific time. Long-term occupancy is the probability of how an occupant typically occupies a space as a function of time, representing occupancy patterns. An HVAC system usually responds to the heating/cooling loads through the control of setpoints, which determine the desired temperature ranges for spaces. Therefore, in this paper, setpoint is used as the medium to control the heating/cooling loads based on occupancy. To quantify the energy implications of diversity, we compare the loads before and after the load rearrangement (based on long-term occupancy) using an occupancy driven setpoint control (based on real-time occupancy). Specifically, occupancy driven setpoint control allows the setpoint to float to another temperature (setback), when the space is unoccupied for more than a certain waiting period and then is restored to setpoint, when the space becomes occupied again. An agglomerate hierarchical clustering algorithm is designed to cluster occupants based on their presence similarities while considering the connectivity between the clusters. Since the process of eliminating occupancy diversity is restricted to hierarchical constraints of the ways how occupants use a building, an iterative evaluation algorithm is developed. The algorithm integrates BIM (building information modeling) to support the understanding of hierarchical constraints, and therefore, aims to increase the quality of evaluation. Whole building energy simulation is used to validate the effectiveness and generalizability of the framework in quantifying the HVAC system energy efficiency affected by occupancy diversity at the building level through a well-informed analysis of occupant–space relationships. Specifically, for the effectiveness validation, a real-world testbed building with actual occupancy is used to examine the performance of the proposed methodology for eliminating occupancy diversity and analyzing corresponding load reduction. For the generalizability validation, virtual reference buildings are used to examine the consistency of the proposed methodology for other buildings with different building geometries, layouts and occupancy diversities. The numbers of building models, simulations and trials of eliminating diversity are determined based on the distributions and patterns of results.

The paper is structured as follows. Section 2 introduces the importance of occupancy diversity and how to measure it. Section 3 describes the methodology to eliminate the occupancy diversity based on hierarchical constraints for quantifying the energy implications of diversity, and its integration with BIM. Section 4 presents the validation of the proposed framework by using whole building simulation for a testbed building. Section 5 tests the generalizability of the proposed framework using virtual reference buildings, representing different commercial buildings. Section 5 discusses the limitations and concludes the paper.

2. Occupancy diversity analysis

Load is the quantitative measure to describe the demands of energy for HVAC systems to maintain thermal conditions in buildings. The majority of the energy consumed by an HVAC system is to satisfy the loads from interior sources (e.g., due to occupant metabolisms and device/equipment related heat gains) and exterior sources (e.g., due to conduction and convection). Occupancy is associated with heating/cooling schedules and effects, which determine the amount of loads and energy efficiency of an HVAC system. Extensive research has been conducted to model building occupancy [11–13] and a range of occupancy driven setpoint control strategies has been developed [6,14,15]. The basic principle is that energy efficiency could be improved by not considering the loads in vacant zones as demands for HVAC systems. Substantial energy savings have been reported by prior research by not maintaining static setpoints in unoccupied zones. Instead, zone temperatures were allowed to float within a certain range [16–18]. However, since zones usually consist of more than one space, if only one space in a zone is occupied, heating/cooling is required for the entire zone, and the loads of the zone are the sum of loads in all spaces of that zone. Studies have found different spaces may have different or in some cases inverse occupancies that undermine the effects of occupancy driven setpoint control strategies [12,19,20]. Simply aggregating disparate occupancy information of different spaces might create an inaccurate representation of how each zone is occupied, which may lead to unnecessary heating/cooling loads and further reduce energy efficiency.

In addition, a building usually has multiple zones and there exist heat transfer and balance among the zones. Loads in one zone could increase because of the different thermal conditions of neighboring zones resulting from occupancy diversity. Several researchers have studied this issue and analyzed occupancy diversity at the building level from the supervisory control perspective [17] with a focus on global controller optimization, from the occupant classification and segmentation perspective [21] with a focus on constructing energy-use scores and behavior interventions, from the human-building interaction perspective with a focus on different levels of thermal preferences [22], and from the system operation scheduling perspective [23] with a focus on energy performance for single zones. However, a quantitative study for measuring the amount of heating/cooling loads that are associated with occupancy diversity is still needed [24], and it is still not clear how occupancy diversity at the building level quantitatively influences the energy efficiency of an HVAC system. In this paper, we introduce a framework to analyze energy implications of diversity at the building level with the following factors being considered: (1) HVAC layout. Commercial buildings may be segmented and served by different sets of HVAC systems or secondary systems (e.g., air handling units). HVAC layout determines the zones with shared supply air [25,26]. (2) Zone adjacency: adjacent zones share boundaries and there are load exchanges through heat transfer and balance among the zones when there is temperature difference or mutual ventilation [27]. If the adjacent zones have distinct schedules and requirements for heating/cooling, excessive energy might be consumed due to the thermal circulation. (3) Orientation: zones with the same orientation usually have similar boundary conditions and are therefore impacted similarly by the outside environment [28].

3. Methodology for eliminating occupancy diversity

The objective of quantifying the energy implications of occupancy diversity is to rearrange heating/cooling loads by virtually rearranging occupancies until the diversity is eliminated. Occupancy profile, the typical presence probability as a function of time, representing long term occupancy patterns, is used as a measure to calculate the level of diversity. There might be more than one profile representing one space (e.g., different profiles for an occupant for different days of the week). If so, for each time point, the highest probability among the profiles is chosen to account for the majority of the time. The process is restricted by hierarchical constraints, which represent how a building is utilized. After higher-level constraints are satisfied, the lower-level constraints are included. If there is a conflict between the two sets of constraints, higher-level constraints are given the priority. In this paper, primary constraints are individual requirements, e.g., different room sizes for different occupants, and group requirements, e.g., occupants of the same department should be spatially close. To be clear, individual requirements are for individual spaces and mainly consider physical conditions and preferences, such as orientation while group requirements are for connections between spaces and