Building and Environment 98 (2016) 1–10

Contents lists available at ScienceDirect

Building and Environment

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

Long-term experimental analysis of occupancy and lighting in religious facilities

Trevor J. Terrill*, Franco J. Morelli, Bryan P. Rasmussen

Energy Systems Laboratory, Texas A&M University, 402 Harvey Mitchell Pkwy S, College Station, TX, 77845, USA

ARTICLE INFO

Article history:
Received 31 August 2015
Received in revised form
2 December 2015
Accepted 10 December 2015
Available online 13 December 2015

Keywords:
Religious building
Experimental study
Building occupancy
Occupancy based lighting control

ABSTRACT

Buildings of religious worship constitute nearly 8% of all commercial buildings in the United States. However, to date, religious facilities have received inadequate attention in the literature. Religious facilities exhibit unique patterns of occupancy and energy usage that do not reflect the general patterns of office, education, and other commercial buildings. This paper characterizes building lighting consumption and occupancy patterns in religious facilities to identify potential energy-saving opportunities through a long-term, in-depth experimental study.

Occupancy and lighting schedules are experimentally determined for two architecturally identical church buildings in different climates. General trends of occupancy reveal intermittent, but consistent, use of the building. The feasibility of occupancy based lighting control in these buildings is evaluated. Experimental results of occupancy based lighting control in the church buildings demonstrate the limited potential for energy savings and that individual areas of the building should be considered and evaluated separately given the varied usage patterns.

1. Introduction and literature review

Reducing building energy consumption has the potential to make significant progress in reduction of total building energy use [1]. Religious facilities constitute approximately 8% of commercial buildings in the United States and represent a significant percentage of the total floor space and energy consumption of the commercial sector [2], yet there have been limited studies characterizing their occupancy and energy use. This paper present s the results of a long-term study that investigates the occupancy patterns and energy use of churches in different climates. This paper focuses on lighting and occupancy; a previous paper benchmarked the building energy use, detailed the building energy study setup, and determined the breakdown of energy use [3].

Multiple papers have emphasized the importance of knowing building occupancy on total energy consumption and use, and many of these papers are summarized in Ref. [4]. Building occupancy significantly affects the energy consumption and the potential for reduction in energy use [5,6]. Accurate estimation of building occupancy profiles are important to predict savings for potential energy retrofits, especially when using building energy simulation software to predict energy reductions [7,8]. The studies further show the strong importance of knowing accurate occupancy schedules to accurately predict energy consumption [9,10].

Other papers demonstrate the significant errors generally observed between default and actual occupancy schedules in buildings. A study by Duarte found that actual building occupancy in a studied office building varied 46% from the default office occupancy schedule recommended by ASHRAE [11]. Zhao et al. also found that the occupancy schedule of an actual building varied significantly with the default schedule of an office building. Their estimated energy usage changed significantly due to this difference in occupancy, and this difference was magnified by differences in climate [4]. These errors, which occur in office buildings with default office building schedules, will be exacerbated when predicting energy use in religious buildings with default office occupancy schedules. Since churches have very atypical usage patterns, knowledge of actual occupancy patterns in religious facilities is necessary to accurately predict energy usage in these facilities.

Erickson demonstrated that predicting actual building occupancy schedules, even with training data, is difficult [12]. He demonstrates in simulation the potential for accurately estimating energy savings when HVAC systems are controlled with accurate occupancy schedules. Yang et al. demonstrated through simulation

* Corresponding author. Tel.: +1 208 881 3999.
E-mail addresses: tterrill@tamu.edu (T.J. Terrill), francojmorelli@gmail.com (F.J. Morelli), brasmussen@tamu.edu (B.P. Rasmussen).

http://dx.doi.org/10.1016/j.buildenv.2015.12.007
0360-1323/

and occupancy ground truth data that the fixed occupancy schedule by ASHRAE deviates significantly from actual occupancy schedules, and that this significantly affects energy usage [13]. The paper uses long-term data to develop expected patterns of occupancy and shows close agreement between predicted energy consumption and actual consumption. The paper further illustrates the importance of knowing actual building occupancy in order to accurately determine building energy use. When estimation of energy usage is coupled with accurate occupancy schedules, a representative occupancy schedule of religious buildings will facilitate accurate prediction of energy usage. No established occupancy characteristics have been published to date for religious buildings, and one of the goals of this paper is to experimentally determine a representative building occupancy schedule for religious facilities in the United States.

The churches selected for data collection are architecturally identical and exhibit similar occupant behavior, despite being located in different climates. The base occupancy and lighting characteristics of the buildings are analyzed for each church. Additionally, the economics of occupancy based lighting control in reducing energy consumption from lighting are experimentally evaluated in the two buildings.

2. Building setup and study

Two church buildings with identical floorplans, located in different climate zones, were analyzed in this energy study. The first church is located in College Station TX, USA, and the second church is located in Orem UT, USA. A total of 130 different data loggers were installed throughout each building to determine the occupancy, lighting, temperature, and relative humidity of each space. Full details of the energy study setup are included in Ref. [3]. The focus on the current paper is to analyze data obtained from the light/occupancy (LO) data loggers. Fig. 1 shows the location of each sensor and the range of the occupancy sensors. Each sensor was placed in a location to maximize occupancy coverage while still being able to capture the state of the lighting. Additionally, at least one LO data logger was installed to capture the lighting under a single light switch. In other words, in hallways with multiple light switches, sufficient occupancy sensors were installed so that the lighting from each light switch could be identified.

The LO loggers are state dependent and consequently only record data when a change of state is recorded. The light sensor triggers when the light level exceeds a defined threshold, which can be calibrated to ensure each sensor triggers appropriately. The occupancy sensors only have an on/off state and provide no information on the number of people. Getting a high fidelity measurement of the number of people in a space is difficult and requires expensive sensing equipment.

In analyzing the building lighting, the building is divided into four different types of rooms, each type with a different expected pattern of occupancy: meeting areas, hallways, classrooms, and offices. There are two large meeting areas in the center of the church. Hallways wrap around these meeting areas, and smaller rooms are located along the perimeter of the building. The division of different areas is displayed in Fig. 2.

2.1. Expected building occupancy

The majority of the building occupancy is expected on Sundays. There are three different congregations that meet in each church, with staggered starting times at 09:00, 11:00, and 13:00. Each congregation meets for 3 h. There is an initial meeting in the main worship area for the first hour, after which members of the congregation attend classes and meetings over the course of the next 2 h in the other areas of the church. In addition to Sunday use, there are various meetings and activities throughout each week. Most of these meetings happen either in the early morning or in the

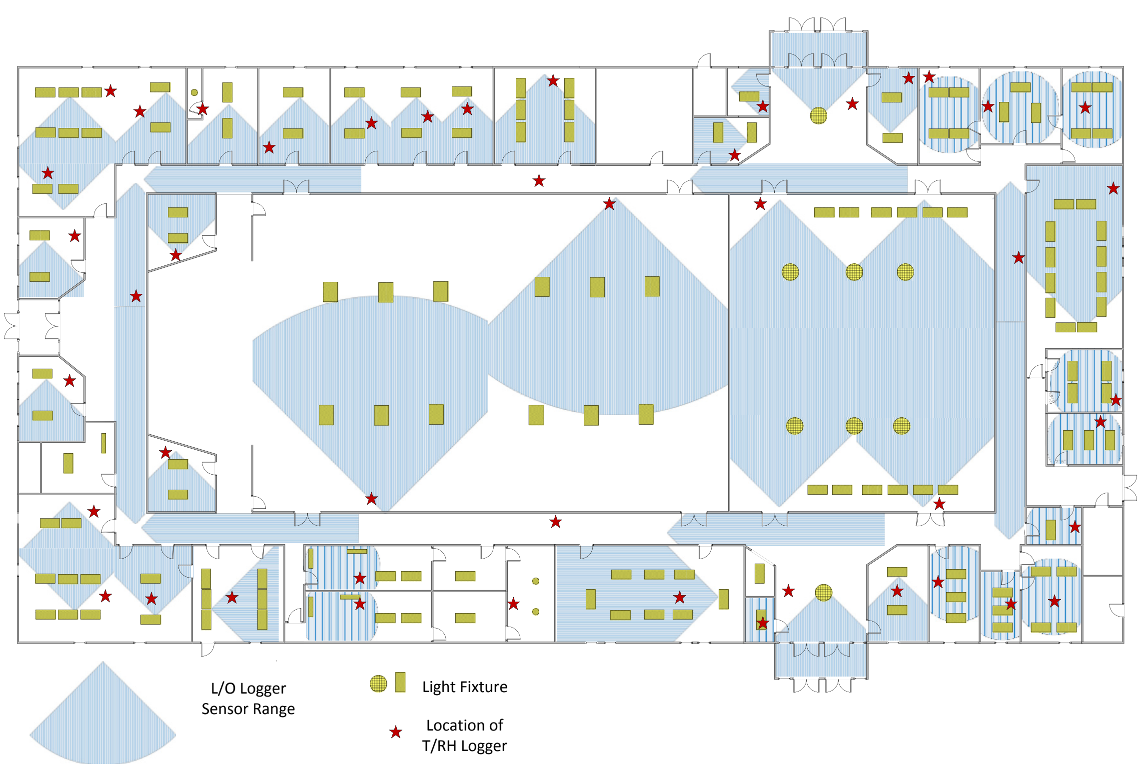

Fig. 1. Building layout with coverage area and location of data loggers.