A longitudinal study of the occupancy patterns of a university library building using thermal imaging analysis

Qian Wang [a], Dr Hiral Patel[b]*, Prof Li Shao[c]

[a,c] School of Construction Management and Engineering, University of Reading, Reading, United Kingdom; [b] Welsh School of Architecture, Cardiff University, Cardiff, United Kingdom

E-mail for the corresponding author – patelh18@cardiff.ac.uk

Qian Wang –Wang holds a Masters's degree in Design and Management of Sustainable Built Environments from the University of Reading and a Masters's degree in Intelligent Building from Xi'an University of Architecture and Technology. She is interested in studying building occupancy patterns through innovative technologies and improving the built environment by making buildings more comfortable, fit for purpose, and energy-efficient.

Dr Hiral Patel – Dr Patel's research and teaching aim to better understands clients and users of the built environment. She is interested in themes of learning, socio-material practices, holistic building performance and adaptation of buildings. Having trained as an architect from India and practised in the UK, her work has spanned from research, developing business processes, managing projects, and technical building design. Her PhD research theorises the practices of adapting academic library buildings, and her current research focuses on learning environments in the higher education sector. Her research around the DEGW archive explores the linkages between organisational practices and the built environment to help understand the changing nature of 'work'.

Prof Li Shao – Professor Shao began his academic career in 1993 and joined the University of Reading in September 2012 as the Professor of Sustainable Technologies for the Built Environment. Between 2014–18, Professor Shao was Academic Director of the Technology for Sustainable Technology Centre, an EPSRC-funded centre for training 50 industry-based engineering doctorate researchers. Professor Shao has published over 90 papers in refereed journals and international conferences. Supported by the UK and European funding bodies as well as industry, Professor Shao has led a range of projects in sustainable energy technologies for buildings.

A longitudinal study of the occupancy patterns of a university library building using thermal imaging analysis

Current debates around the 'performance gap' have highlighted the need to study building occupancy patterns to improve design solutions and better understand space utilisation. However, capturing occupancy data is resource intensive. There is a need for solutions that gather real-time occupancy data while maintaining the users' privacy. In response to this challenge, this paper discusses applying a thermal imaging-based method for measuring occupancy in buildings and generating behavioural insights. A longitudinal analysis of the occupancy patterns over a full academic year is conducted for a university library building in the UK. The granular data collected through the thermal imaging analysis reveal insights into the building's occupancy patterns over academic terms and vacation periods. The findings debunk conventional conceptions of library use during weekends/weekdays and terms/vacations. The application of thermal imaging sensors to monitor occupancy within the library building suggests the potential use of real-time data to improve the library's space and organisational management. The paper makes a case for having an occupancy monitoring strategy in place that corresponds to the data needed for making effective interventions.

Keywords: building performance; occupancy detection; occupancy monitoring system; occupancy patterns; thermal imaging sensors; time use; user behaviour

Introduction

Reducing energy consumption is a central pillar of effectively designing a low-carbon built environment and, by extension, a low-carbon economy and society. However, several studies have found that low-energy building designs may not achieve their anticipated energy-saving goals due to how buildings are used and occupied (cf. Guerra-Santin and Itard 2010; Janda 2011; Palmer, Terry, and Armitage 2016). The current debates on the 'performance gap' have further highlighted the need to study changes in building occupancy patterns over time to improve design solutions and better understand space utilisation (Patel and Green 2020; Coleman, Touchie, Robinson, and

Peters 2018; Lowe, Chiu, and Oreszczyn 2017). In order to close the performance gap, better tools and methods to collect building use data, including building occupancy data, are required (Coleman, Touchie, Robinson, and Peters 2018; Palmer, Terry, and Armitage 2016; Gupta and Chandiwala 2010). Capozzoli, Piscitelli, Gorrino, Ballarini, and Corrado (2017) noted that good-quality occupancy data with high resolution could be expensive to obtain and analyse, while low-quality data can lead to poor analysis. Additional difficulties in collecting building use data include the high installation costs of monitoring equipment and sensors, data accuracy, and privacy issues. Addressing these challenges, this paper presents insights on thermal imaging analysis to understand variations in the occupancy patterns of an academic library building over one year. The paper also discusses the 'performative' aspects of sensors, which provides a critical lens to review occupancy monitoring strategies.

This paper addresses two research gaps. Firstly, the paper reports data collected from an academic library building in the UK over a full academic year. Such longitudinal studies with granular data are not currently available for higher education buildings. Longitudinal studies of university buildings are important because their occupancy patterns vary substantially throughout the academic year. Moreover, adopting blended working and learning in post-COVID-19 scenarios requires a better understanding of occupancy patterns (Filimonau, Archer, Bellamy, Smith, and Wintrip. 2021). Insights into building occupancy patterns enable a better understanding of space demand (cf. Duffy 1997), and real-time occupancy data is vital in improving space utilisation (Oseland, Gillen, Verbeemen, Anderson, Allsopp, and Hardy 2013). Secondly, thermal imaging sensors are not widely discussed in the studies of occupancy patterns of university buildings. These sensors offer a unique advantage in regard to the privacy of occupants and the low cost of installation. This paper demonstrates the application of these sensors in a university library building and investigates occupancy patterns over a full academic year through longitudinal data analysis. It compares the performativity of the thermal imaging sensors with other monitoring systems and offers useful insights to decision-makers in selecting appropriate occupancy monitoring approaches for their universities.

Monitoring occupancy patterns within higher education buildings

Higher education buildings are occupied by various users such as staff, students and visitors for different durations. Mallory-Hill and Gorgolewski (2018) found that academic buildings' predicted and actual occupancy on a typical day varies from 20% to 45%. Moreover, the predicted and actual number of opening hours also range from 27% to 75%. Jafary, Wright, Shephard, Gomez, and Nair (2016) and Tang (2012) have further reported that occupancy patterns vary between academic term times and vacations. However, these studies rely on electricity consumption data as a proxy of occupancy rather than actual occupancy data. Such approaches may not capture granular changes in occupancy over time, which could impact the demand for teaching or study spaces. The efficacy of using electricity consumption data to monitor the occupancy of university buildings has been challenged by Gul and Patidar (2015). They compared electricity consumption data and occupancy data collected using a bi-directional infrared beam sensor for an academic building at Heriot-Watt University. They found that the electricity consumption did not drop when the occupancy of the building was low and identified that the building management system needs to be responsive and re-configured according to the occupancy patterns of the building. Thus, electricity consumption data may not give an accurate view of a building's occupancy levels, and other methods are needed to measure or estimate actual occupancy.

Moreover, occupancy patterns vary according to the function of buildings within a university's estate (Ding, Wang, Wang, Han, and Zhu 2019), making it crucial to understand occupancy patterns for different building types. This paper reports a study of the occupancy patterns of a library building within a UK university. Libraries are an indispensable part of most universities. A YouthSight omnibus panel survey of 1000 full-time undergraduate students at UK universities revealed that 84% of the students would study in the library outside teaching hours (HEDQF, 2019). Also, 71% of students would use the library more than once a week. These indicators demonstrate a higher demand for library spaces than other university spaces. With increasing student numbers and decreasing public funding per student, it becomes paramount for universities to use their estates efficiently and effectively through a better understanding of occupancy patterns (Valks, Arkesteijn, and Den Heijer 2019).

Research on occupancy patterns also reveals insights into user behaviour. Wang and Shao (2017) identified four different occupant profiles based on the occupancy duration within an academic library building using a Wi-Fi detection system (see next section for more details about this method). The authors found that adjusting library opening hours based on actual building occupancy data could reduce energy consumption and save staff-related costs. Moreover, they also found that the users who occupied the room for more prolonged durations did not take enough breaks. Such occupancy patterns reveal health and well-being risks and could prompt interventions to encourage users to take regular breaks. Ganji, Budzisz, Debele, Li, Meo, Ricca, Zhang, and Wolisz (2015) identified significant variations in the usage of wireless local area networks between day and night as well as between weekdays and weekends in their study of the main campus of Politecnico di Torino, Italy. The authors concluded that by considering such variations, substantial energy savings could be achieved by dynamically managing the operation of access points of the wireless network. Ciribini, Pasini, Tagliabue, Manfren, Daniotti, Rinaldi, and De Angelis (2017) present a case study of the University of Brescia, where Building Information Modelling (BIM) was connected with sensor data to provide opportunities for users to visualise and act upon real-time occupancy data. Thus, research on the occupancy patterns of university buildings becomes critical for reducing energy consumption, optimising space use, decreasing operational costs, nudging users to adapt their behaviours and improving their well-being.

The Higher Education Statistics Agency (HESA) captures occupancy-related data of the UK university buildings under the Estates Management Records. In those records, frequency rate and occupancy rate are two relevant ratios for understanding building occupancy (HESA 2021a, HESA 2021b). While these statistics are useful in assessing the utilisation of university spaces and are often collected manually, they only provide a snapshot view at a particular time in the academic year. The variations in occupancy patterns and space utilisation of university spaces over a given academic year are not captured. By using appropriate sensors for real-time occupancy monitoring, better alignment of the user demand with existing space could be achieved. For example, Hentschel, Jacob, Singer, and Chalmers (2016) propose a range of use cases, including improvements in space utilisation, for installing ‘supersensors’. This paper complements their study by introducing an additional type of sensor, the thermal imaging sensor, to monitor occupancy.

Valks, Arkesteijn, Den Heijer, and Vande Putte (2018) surveyed 13 Dutch universities about their adoption of smart tools to improve space use on campus. They found that while all universities measured occupancy and frequency of space use, half of the universities considered adopting real-time monitoring systems instead of manual counts. However, current studies of occupancy of university buildings using sensors are often conducted for a short period. There is a dearth of studies that monitor occupancy patterns over an extended time period (Azizi, Nair, Rabiee, and Olofsson 2020). Responding to this research gap, this paper compares different monitoring systems and highlights the benefits of thermal imaging sensors in understanding the occupancy patterns of a university building over an entire academic year.

A comparison of occupancy detection and monitoring systems

Each sensor technology frames the 'occupant' or 'user' differently. The methods chosen to monitor occupancy are performative in nature (Patel, 2019). As Law (2009) posits:

> “Methods practices are performative. They help to enact the world that they describe.” (p.249)

For example, a commonly used non-terminal sensor for occupancy detection is the Passive Infrared Sensor (PIR) motion sensor. However, PIR technology has its limitations. Occupants cannot be detected if they remain motionless, thus compromising the accuracy of the data collected (Chen, Jiang, and Xie 2018). The monitoring results can be further interfered with if people walk in a group (Wang and Shao 2017). Similar concerns arise when determining building occupancy using web traffic data, Wi-Fi detection systems and Bluetooth detection systems. Bluetooth low power (BLE) is compatible with most mobile devices and computers and can provide proximity information with sufficient accuracy (Filippoupolitis, Oliff, and Loukas 2016; Montanari, Nawaz, Mascolo, and Sailer 2017). Owing to the universal ubiquity of Wi-Fi in indoor environments on university campuses, an emerging technology called the Wi-Fi-based positioning system has been adopted to detect indoor occupancy. The simple configuration and low-cost components are the system's merits (Wang and Shao 2017), which is used in libraries such as UC San Diego Library to display the occupancy levels of study spaces and assist students in finding study spaces (Lippincott 2021, 164). However, Chen, Jiang, and Xie (2018) reported that BLE and Wi-Fi detection systems have limitations as the users may turn off Wi-Fi or Bluetooth on their devices and may have multiple devices. Lee, Chong, and Chou (2020) monitored stationary (such as faculty members and graduate students) and non-stationary occupants (such as students) in the Arizona State University building using Ethernet traffic flow and Wi-Fi connections, respectively. The authors noted the limitations of assuming occupant types solely based on whether they connect their devices to Wi-Fi or Ethernet. Labeodan, Zeiler, Boxem, and Zhao (2015) discuss six types of occupancy information that can be collected: presence (when an occupant is present or not), location (where an occupant is present), count (how many people are present), activity (what is the person doing), identity (who the person is) and track (where was this person before). Thus, it becomes crucial to reflect on the performativity of the sensors as each sensor system frames' occupancy' differently and foregrounds a different reality than the other (Patel, 2019).

Comparative studies of occupancy detection systems, their accuracy, ease of installation, and the type of data collected have been extensively covered (Stevenson 2019; Shen, Newsham, and Gunay 2017; Yang, Santamouris, and Lee 2016; Labeodan, Zeiler, Boxem, and Zhao 2015). However, these studies do not include thermal imaging sensors. Addressing this research gap, this paper discusses the thermal imaging sensor, its appropriateness for occupancy detection, and its performativity in framing 'users' and 'occupancy'. The thermal imaging sensor is akin to a thermal imager which works by detecting the thermal condition of the human body and converting thermal radiation into a visible image. Such images are collected longitudinally and analysed for calculating the occupancy of a room or a building. Thermal imaging sensors offer unique benefits compared to other systems. The thermal imaging sensors are non-terminal detection systems which do not require a terminal to be carried by the users, as in the case of BLE and Wi-Fi detection systems. Thermal imaging sensors provide a 'count' of occupants present in a building. Such data is useful to determine the space demand and utilisation and energy requirements for a building. The count of occupants could also be monitored by using CO_2 sensors and image/video sensors. While the CO_2 sensor has the advantage of low cost, it suffers from poor reliability compared to the thermal imaging sensors. Gunay, Fuller, and O'Brien (2016) noted that the readings of a CO_2 sensor have a time delay, as the CO_2 diffusion rate can be affected by different variables, such as the interior arrangement, the distance to occupants, and the speed of ventilation. Image/video occupancy detection systems using high-precision cameras have been increasingly used because of their accuracy. However, it requires high computational resources and illumination conditions while widespread privacy worries (Chen, Jiang, and Xie 2018). The thermal imaging sensors have better accuracy than CO_2 sensors, and they do not collect personal information of building occupants as in the case of visible image/video occupancy detection systems. Virginia Tech Library used thermal cameras to comply with their privacy guidelines of not recording student faces on networked cameras (Bradley, Tomlin, and Mathews 2018). Thermal imaging sensors have been used to monitor and predict the occupancy of university classrooms (Sutjarittham, Gharakheili, Kanhere, and Sivaraman 2019), and there is a potential to expand their application to other university spaces such as libraries. Building on this body of literature, this paper analyses occupancy data gathered over the entire academic year through thermal imaging sensors to understand occupancy patterns of the URS Building at the University of Reading.

Method

URS Building

This research undertakes a secondary analysis of the data collected through the sensors installed as part of the URS Building refurbishment. It was built in the 1970s and is a

Grade II listed building located right at the heart of the award-winning green campus of the University of Reading. The library on the Whiteknights Campus of the University of Reading was renovated from 2016 to 2019. During the renovation, most study spaces and services of the University Library were relocated to the URS Building (University of Reading 2020). The seating capacity of the provisional library in the URS Building was 616 seats. Figure 1 shows the library's opening and closing times from September 2017 to September 2018.

Data Collection using thermal imaging sensors

This research used a commercial occupancy sensor called Irisys Gazelle Thermal Counters, developed by Infrared Integrated Systems Ltd, as part of their 'People Counting' system. Thermal images without facial information were collected through the overhead infrared camera and transmitted directly to the company’s server for analysis. The thermal image is not a standard colour image where one's facial features could be identified. The occupancy counts were obtained from the thermal images. Therefore, no personal information was collected in this research. The sensors were installed on the ceiling of the three entrances (the east entrance, the middle entrance, and the west entrance) of the URS Building at the University of Reading. All the sensors used at the three entrances are the same. The wiring requirements for these counters are low due to their use of power over ethernet. The set-up of the sensors is shown in Figure 2.

The sensors counted the number of people crossing the library entrances bi-directionally. A counting error could occur when too many people pass by simultaneously (Amin, Taylor, Junejo, Al-Habaibeh, and Parkin 2008). The thermal image analysis algorithm developed by the manufacturer addresses this error by differentiating two people walking side by side and not recording it as a single person.

The manufacturer reports that the sensor has an accuracy rate of up to 98% in different environmental conditions (Axiomatic Technology Limited 2022). It should be noted that a systematic evaluation of accuracy was beyond the scope of this study, which is to investigate the potential usefulness of a specific type of occupancy data for studying user behaviour in university buildings. Moreover, there is no existing protocol to conduct occupancy analysis of a university building over a long period of time (full academic year in this case), and future work could consider developing a protocol for other researchers to use thermal imaging sensors.

The sensor counts the number of people entering and leaving the library building and continuously sends the information to the analytics platform. The platform can automatically generate daily, weekly, and monthly occupancy information (number of people in and out) summary tables and display them in a spreadsheet using Microsoft Excel. Based on an analysis of daily occupancy information, library managers could manage the peak in space demand by redirecting users to available or underutilised study spaces in the building or across the university campus. The weekly and monthly occupancy data could assist in predicting occupancy while considering the changes in space demand across different times of an academic year. Such insights could inform interventions to reduce energy consumption, identify optimal spatial requirements, and achieve savings in staff costs (cf. Sutjarittham, Gharakheili, Kanhere, and Sivaraman 2019). This paper demonstrates how such occupancy data could be further analysed to draw insights into the building's use and debunk conventional conceptions of library use during weekends/weekdays and terms/vacations.

Data analysis and assumptions

Data collected by the sensors from September 2017 to September 2018 were analysed to identify differences in occupancy patterns during the academic year (see Figure 3). The academic year consisted of winter, spring, and summer terms, and a vacation followed each term. Due to the large amount of data collected, three weeks were selected for further analyses during each term and the summer vacation. These three weeks represented the early, mid, and late periods of a given term or vacation. The Winter and Easter vacations were shorter, so all data from those periods were used. The library was closed from December 22 to January 1 and from March 29 to April 3 because of the holidays. Since no data was collected during these periods, these parts of the year were excluded from the analysis.

The occupancy data were recorded every 5 minutes (referred to as reporting period). A total of 196992 raw data points over 114 days are analysed in this research. The types of raw data recorded include the number of people in and out and the average occupancy. It is assumed that there is no significant system delay in the transmission of data records. The number of occupants in the building at each moment is the number of occupants at the previous moment plus the number of people who entered and minus the number of occupants who left. The number of people entering, leaving, and present in the building constitutes the basic data of this research. These data have been further analysed in this paper to identify the total number of occupants entering the building on a given day (footfall), start and end time of peak period, earliest arrival time and latest departure time, and average duration (estimated dwell time). A peak period is defined as the period when the occupancy level rises above 85% of the maximum occupancy level of the day. In other words, the library building is most occupied during the peak period. The earliest arrival and the latest departure times are defined as the earliest and latest times when the number of people reaches 25. This value considers the number of staff in the library, and once the occupancy is beyond 25, it means there are students in the library. This number is assumption-based, and future research could investigate the actual number of staff members present during the different times of a day across the academic year. The estimated dwell time measures students' occupancy duration in the building. The average estimated dwell time of library users during a day is calculated as follows:

$$t = \frac{\sum_{i=1}^{k}(T_i \cdot m_i) - \sum_{i=1}^{k}(T_i \cdot n_i)}{\sum_{i=1}^{k} n_i}$$

where

t is the estimated dwell time of the day.

t is the estimated dwell time of the day.

k denotes the total number of reporting moments in a day. For a reporting period of 5 minutes, k=288;

i denotes the sequence number of a reporting moment; it is also the sequence number of the reporting period for the reporting moment;

T_i is the time of the i^{th} reporting moment;

m_i is the number of people who have left the library during the ith recorded period;

n_i is the number of people who have entered the library during the i^{th} recorded period.

The daily duration of 24 hours was set from 4:05 in the morning to 4:00 the following day. The system has been set up to record the last time of a given day at 04:00. It then resets the occupancy to zero to record data for the following day. However, since the building is open 24 hours most of the time (see Figure 1), there might be people in the building at this time. Such an assumption may record the occupancy of the following day as less than the actual number of occupants present in the building. This study assumes that this will not affect the overall data analysis. The number of people staying in the library at 4:00 in the morning is usually few, with no occupant expected to remain over 24 hours. Future research can validate such assumptions through manual headcounts and investigate the implications of such assumptions on the accuracy of data analysis.

Results

Footfall

The number of occupants entering the building on a given day, referred to as footfall, is shown in Figures 4 and 5. The footfall during the terms was often higher than during the Autumn and Summer vacations. This trend aligns with the common perception that students study during term time and take breaks during vacations. However, the footfall during the Easter vacation was higher than during certain term periods as students started preparing for the examination following Easter vacation.

The weekend is generally considered a period of rest for a given week. Therefore, the footfall during weekends is expected to be significantly lower than on weekdays. However, according to the data, there was substantial footfall during the weekends. For instance, during the mid-stage Autumn term, the footfall on weekends was higher than on weekdays. Another example is the weekend of the late-stage Easter vacation compared to early and mid-stage weekdays for the same period. Moreover, the footfall on Sundays was usually higher than that on Saturdays. This difference shows that students' routines for weekdays and weekends are not fixed on a university campus. Sundays play a vital role as a working day in the life of university students.

Estimated dwell time

The estimated dwell time, which gives an average duration of occupancy, varied throughout the terms and vacation period (Figure 6 and Figure 7). The values during weekends were usually higher than on weekdays. In particular, low dwell times were estimated on Fridays during the mid and late periods of the terms. The exam period began on the first day after the Easter vacation at the start of the summer term. More students are expected to go to the library for exam preparation and stay longer to study. While the footfall was significantly higher during this period than during the Easter Vacation, the dwell times stayed reasonably stable before and during the examination period (the standard deviation is about 0.14%).

Peak occupancy period

The peak occupancy period captures the duration when the demand for space within the library building is high. It was found that the end of the peak occupancy period was concentrated between 3:30 pm to 5:30 pm for both term-time and vacations (See Figure 8 and Figure 9). This finding is surprisingly consistent throughout the year regardless of variation in student workloads and departure times (see the section below). However, the start of the peak occupancy period varied throughout the year, implying that the duration of the peak occupancy period was not constant. For example, the peak occupancy period started earlier for most of the summer term and summer vacation compared to the rest of the year, while it ended within the range consistent with the rest of the year. Moreover, there was a gap in the peak occupancy period, particularly during lunchtime, as users might leave the library building for lunch breaks.

Earliest arrival and latest departure times

The earliest arrival and the latest departure times are defined as the earliest and latest times when the number of people reaches 25. While most of the earliest arrival times were within a short range of 7:30 am to 9:30 am during the term time (see Figure 10), most departure times were between 7:30 pm and 3 am (see Figure 11). The arrival time during the spring term was considerably late compared to the summer term. The earliest arrival time in the early and mid-stages of the summer term ranged from 7:30 am to 8 am. This period also recorded the latest departure time of approximately 3 am, thus indicating intensive use of the library building. On the other hand, earliest arrival times remained relatively constant across the three vacation periods, although the departure times varied (see Figure 12 and Figure 13).

Discussion

Performativity of thermal imaging sensors

There are multiple factors to consider when evaluating the usefulness of the occupancy monitoring method. Such factors include cost, accuracy, granularity, invasiveness and scalability (Oseland, Gillen, Verbeemen, Anderson, Allsopp, and Hardy 2013). Thermal imaging sensor as a method to monitor building occupancy offers unique benefits in terms of ease of set-up and efficient way to measure occupancy compared to manual headcount surveys. However, it may require an initial investment to create a data analysis platform and develop data-related skills within the facilities management staff.

The thermal imaging sensors method offers a less invasive approach to monitoring building occupancy as it does not record images or use Wi-Fi or BLE technology on occupants' devices. It frames 'occupants' by creating their thermal image. Thus, the method could be a monitoring solution for contexts where privacy is paramount (Bradley, Tomlin, and Mathews 2018; Sutjarittham, Gharakheili, Kanhere, and Sivaraman 2019). The method is scalable as multiple thermal imaging sensors could be installed. In this research, the sensors were only installed at the entrance of the library building. However, they could further be installed at the entrances to the floors or rooms to obtain a more detailed understanding of occupancy patterns within a building. The method's accuracy in measuring footfall could be relatively high compared to the Wi-Fi and BLE methods, as proxies are not used. Regarding granularity, the data is recorded every 5 minutes, which gives a detailed view of changes within a building's occupancy levels in real-time. There is no lag in inferring the occupancy, as observed in the methods that use CO2 levels to estimate building occupancy.

As seen from the footfall results as well as the start and the end of the peak occupancy period, the thermal imaging sensor method could indicate the busyness of the building to building users and facilities managers. Such insights could help them develop alternative space strategies, including redirecting users to other underused spaces to flatten the peaks in demand for study spaces or workspaces.

However, this thermal sensing method does not provide details of seat usage or the activities that occupants are undertaking. These insights are critical in making space-related interventions, and hence, the thermal imaging sensors need to be complemented by a monitoring strategy involving other methods to understand user behaviour (Patel, 2019). In the context of libraries, Lippincott (2021) draws our attention to the need for a data collection strategy which could meaningfully inform future interventions:

> "Few libraries have implemented networked monitoring devices at scale because equipping an entire building with sufficient beacons and other sensors to generate useful data remains expensive, and thoughtfully outfitting an entire library building to collect meaningful data takes intensive planning. As data analysts constantly caution, poor data collection methods lead to misleading or inaccurate conclusions." (p. 165)

Change and constancy of occupancy patterns

Compared to other published studies on the occupancy patterns of university buildings, this paper presented an analysis of occupancy patterns over a full academic year. The findings reveal the changes in the occupancy patterns as well as the aspects that stay constant throughout the year. For example, dwell time stayed reasonably stable (1.4% standard deviation) before and during the examination period, while the footfall during the exam period rocketed (more than a 50 % increase). Despite the footfall being considerably lower during the summer vacation, the dwell time and the end of the peak occupancy period were similar to other periods of the year, including the exam period. These observations suggest that the library building was used consistently throughout the academic year, albeit the number of users might vary. Thus, building design and operation decisions solely based on footfall might not be adequate, and attention should be given to dwell time (cf. Spearpoint and Hopkin 2020).

Moreover, the gaps during the peak occupancy period on a given day imply that space demand might shift from one room or a building to another. The adjacency of different amenities might become crucial in predicting occupancy patterns (such as cafes for lunch breaks). Hence, a campus-wide view becomes important in managing peak demands for space.

On the other hand, the data gathered through the thermal imaging sensors could help optimise the library's organisational management. For example, the latest departure times varied throughout the year depending on the changes in the students' workloads. It was substantially later than 7 pm when the library was open for extended hours. The users might benefit from the presence of a few library staff during the late evenings, particularly to access the information literacy expertise of the librarians.

Moreover, the variations in the footfall and peak occupancy period throughout the year suggest opportunities to restrict the areas of a building that remain open during extended periods. Such an intervention could significantly reduce the energy consumption of the building through (re)configuring building management systems (Gul and Patidar 2015). The kind of data collected and analysed in this research could inform the development of alternative building performance scenarios (Coleman, Touchie, Robinson, and Peters 2018). In addition to benefits to individual institutions deploying sensor technologies, incorporating real-time granular occupancy data in the sectoral statistics and key performance indicators such as those collected by the Higher Education Statistics Agency (HESA) can bring a step change in designing and managing higher education buildings across the sector.

Conclusions

This paper presented findings from a longitudinal study of occupancy patterns of an academic library building in the UK. This study posits the feasibility of using thermal imaging sensors to collect occupancy data while maintaining users' privacy. Based on the analysis of the sensor data of users arriving and departing the building, the key findings from this study are:

- The dwell times remained consistent throughout the academic year, including the vacation periods, suggesting that the library building is used consistently across the year.
- The end time of the peak occupancy period remained between 3:30 pm to 5:30 pm throughout the academic year, despite variations in student workloads and the library's closing times and latest departure times.

- The footfall, the duration of the peak occupancy period and the latest departure time varied according to the rhythm of the academic year.

The key contribution of this study is identifying the occupancy patterns over a full academic year using thermal imaging sensors and generating new insights about user behaviours in university library buildings. This knowledge could be beneficial for designing and operating library buildings and improving organisational performance.

The purpose of this research is not to promote thermal imaging sensors as the only method to study occupancy patterns. Each method is limited in its coverage. Being wedded to a particular method is not effective in gaining a detailed understanding of occupancy patterns. Moreover, each method is performative and frames the 'occupant' or 'user' differently; thus, the data may not be directly comparable. It is essential to have a monitoring strategy that builds on reflexively addressing the limitations of different monitoring methods and is apt for the problem at hand.

Disclosure

No potential competing interest was reported by the authors.

References

Amin, I. J., A.J. Taylor, F. Junejo, A. Al-Habaibeh, and R.M. Parkin. 2008. "Automated people-counting by using low-resolution infrared and visual cameras." *Measurement* 41(6): 589–599. doi:10.1016/j.measurement.2007.02.010.

Axiomatic Technology Limited. 2022. "Irisys Gazelle Thermal Counters." Axiomatic Technology Limited. Accessed September 8 2022. https://peoplecounting.co.uk/glossary/irisys-gazelle/

Azizi, S., G. Nair, R. Rabiee, and T. Olofsson. 2020. "Application of Internet of Things in academic buildings for space use efficiency using occupancy and booking data." *Building and Environment* 186(2020):107355. doi:10.1016/j.buildenv.2020.107355.

Bradley, J., P. Tomlin, and B. Mathews. 2018. "Building Intelligent Infrastructures: Steps toward Designing IoT-Enabled Library Facilities." In *Libr Spaces Smart Build Technol Metrics, Iterative Des,* edited by Jason Griffey, 23-27. Chicago: Americal Library Association.

Capozzoli, A., M. S. Piscitelli, A. Gorrino, I. Ballarini, and V. Corrado . 2017. "Data analytics for occupancy pattern learning to reduce the energy consumption of HVAC systems in office buildings." *Sustainable Cities and Society* 35(August): 191–208. doi:10.1016/j.scs.2017.07.016.

Chen, Z., C. Jiang, and L. Xie. 2018. "Building occupancy estimation and detection: A review." *Energy and Buildings* 169: 260–270. doi:10.1016/j.enbuild.2018.03.084.

Ciribini, A. L. C., D. Pasini, L. C. Tagliabue, M. Manfren, B. Daniotti, S. Rinaldi, and E. De Angelis. 2017. "Tracking Users' Behaviors through Real-time Information in BIMs: Workflow for Interconnection in the Brescia Smart Campus Demonstrator." *Procedia Engineering* 180: 1484–1494. doi:10.1016/j.proeng.2017.04.311.

Coleman, S., M. F. Touchie, J. B. Robinson, and T. Peters. 2018. "Rethinking Performance Gaps: A Regenerative Sustainability Approach to Built Environment Performance Assessment." *Sustainability* 10(12): 4829. doi:10.3390/su10124829.

Ding, Y., Q. Wang, Z. Wang, S. Han, and N. Zhu. 2019. "An occupancy-based model for building electricity consumption prediction: A case study of three campus buildings in Tianjin." *Energy and Buildings* 202. doi:10.1016/j.enbuild.2019.109412.

Duffy, F. 1997. *The new office*. London: Conran Octopus Limited.

Ganji, F., Ł. Budzisz, F. G. Debele, N. Li, M. Meo, M. Ricca, Y. Zhang, and A. Wolisz. 2015. "Greening campus WLANs: Energy-relevant usage and mobility patterns." *Computer Networks* 78: 164–18. doi:10.1016/j.comnet.2014.10.033.

Filimonau, V., D. Archer, L. Bellamy, N. Smith, and R. Wintrip. 2021. "The carbon footprint of a UK University during the COVID-19 lockdown." *Science of The Total Environment* 756. doi:10.1016/j.scitotenv.2020.143964.

Filippoupolitis, A., W. Oliff, and G. Loukas. 2016. "Occupancy Detection for Building Emergency Management Using BLE Beacons". International Symposium on Computer and Information Sciences.

Guerra-Santin, O., and L. Itard. 2010. "Occupants' behaviour: Determinants and effects on residential heating consumption." *Building Research & Information* 38(3): 318–338. doi:10.1080/09613211003661074.

Gul, M.S., and S. Patidar. 2015. "Understanding the energy consumption and occupancy of a multi-purpose academic building." *Energy and Buildings* 87:155–165. doi:10.1016/j.enbuild.2014.11.027.

Gunay, H., A. Fuller, W. O'Brien, and I. Beausoleil-Morrison. 2016. "Detecting occupants' presence in office spaces: a case study." Paper presented at eSim 2016.

Gupta, R., and S. Chandiwala. 2010. "Understanding occupants: Feedback techniques for large-scale low-carbon domestic refurbishments." *Building Research & Information* 38(5): 530–548. doi:10.1080/09613218.2010.495216

HEDQF. 2019. "Social learning environments: student views of their university." Accessed April 6 2021. https://www.hedqf.org/wp-content/uploads/2019/05/HEDQF_Social-Learning-Spaces_Final.pdf

Hentschel, K., D. Jacob, J. Singer, and M. Chalmers. 2016. “Supersensors: Raspberry Pi devices for smart campus infrastructure.” *Proceedings - FiCloud 2016: 2016 IEEE 4th International Conference on Future Internet of Things and Cloud*, 58–62. doi:10.1109/FiCloud.2016.16.

HESA. 2021a. "Frequency rate." Estates Management Record 2019/20. Accessed April 6 2021. https://www.hesa.ac.uk/collection/c19042/a/frequencyrate

HESA. 2021b. "Occupancy rate." Estates Management Record 2019/20. Accessed April 6 2021. https://www.hesa.ac.uk/collection/c19042/a/occupancyrate

Jafary, M., M. Wright, L. Shephard, J. Gomez, and R. U. Nair. 2016. "Understanding Campus Energy Consumption - People, Buildings and Technology." 2016 IEEE Green Technologies Conference (GreenTech), Kansas City.

Janda, K. B. 2011. “Buildings don’t use energy: People do.” *Architectural Science Review* 54(1): 15–22. doi:10.3763/asre.2009.0050.

Labeodan, T., W. Zeiler, G.Boxem, and Y. Zhao. 2015. "Occupancy measurement in commercial office buildings for demand-driven control applications - A survey and detection system evaluation." *Energy and Buildings* 93: 303–314. doi:10.1016/j.enbuild.2015.02.028.

Law, J. 2009. "Seeing like a survey." *Cultural Sociology* 3(2): 239–256. doi:10.1177/1749975509105533.

Lee, S., W.O. Chong, and J. Chou. 2020. "Examining the Relationships between Stationary Occupancy and Building Energy Loads in US Educational Buildings–Case Study." *Sustainability*. 12(3): 893. doi:10.3390/su12030893.

Lippincott, S. 2021. *Mapping the Current Landscape of Research Library Engagement with Emerging Technologies in Research and Learning: Final Report*. Washington, DC: Association of Research Libraries. https://www.arl.org/wp-content/uploads/2021/04/2021.04.09-emerging-technologies-final-report.pdf

Lowe, R., L. F. Chiu, and T. Oreszczyn. 2018. "Socio-technical case study method in building performance evaluation." *Building Research & Information* 46(5): 469–484. doi:10.1080/09613218.2017.1361275.

Mallory-Hill, S., and M. Gorgolewski. 2018. "Mind the Gap: Studying Actual Versus Predicted Performance of Green Buildings in Canada." In *Building Performance Evaluation: From Delivery Process to Life Cycle Phases*, edited by Wolfgang F.E. P., A. Hardy, and U. Schramm. 2nd ed. 261-274. Cham, Switzerland: Springer International Publishing AG.

Mazhar, M. U., R. Bull, M. Lemon, and S.B.S. Ahmad. 2018. "Carbon management planning in UK universities: A journey to low carbon built environment." In *University Initiatives in Climate Change Mitigation and Adaptation*, edited by W. L. Filho, and R. Leal-Arcas, 33-56. Cham, Switzerland: Springer International Publishing AG.

Montanari, A., S. Nawaz, C. Mascolo, and K. Sailer. 2017. "A Study of Bluetooth Low Energy performance for human proximity detection in the workplace." 2017 IEEE International Conference on Pervasive Computing and Communications (PerCom), Kona, HI.

Oseland, N., N. Gillen, G. Verbeemen, M. Anderson, P. Allsopp, and B. Hardy. 2013. "*The WCO Guide to: Utilisation & Occupancy Studies.*" The Workplace Consulting Organisation.

Palmer, J., N. Terry, and P. Armitage. 2016. "*Building Performance Evaluation Programme: Findings from non-domestic projects.*" Innovate UK. Accessed March 9 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/497761/Non-Domestic_Building_performance_full_report_2016.pdf

Patel, H. 2019. "Are we looking at the same thing? Multiple methods to frame "occupancy" of a library building." 35th Annual ARCOM Conference, Leeds, UK.

Patel, H, and S. D. Green. 2020. "Beyond the performance gap: reclaiming building appraisal through archival research." *Building Research & Information* 48(5): 469–484. doi:10.1080/09613218.2019.1672517.

Petri, I., H. Li, Y. Rezgui, Y. Chunfeng, B. Yuce, and B. Jayan. 2014. "A modular optimisation model for reducing energy consumption in large scale building facilities." *Renewable and Sustainable Energy Reviews* 38: 990–1002. doi:10.1016/j.rser.2014.07.044.

Shen, W., G. Newsham, and B. Gunay. 2017. "Leveraging existing occupancy-related data for optimal control of commercial office buildings: A review." *Advanced Engineering Informatics* 33: 230–242. doi:10.1016/j.aei.2016.12.008.

Spearpoint, M., and C. Hopkin. 2020. "How dwell time affects the determination of occupant density in retail occupancies using footfall data." *Safety Science* 131(July). doi:10.1016/j.ssci.2020.104916.

Stevenson, F. 2019. *Housing Fit for Purpose: Performance, Feedback and Learning*. London: RIBA Publishing.

Sutjarittham, T., H. H. Gharakheili, S. S. Kanhere, and V. Sivaraman. 2019. “Experiences with IoT and AI in a Smart Campus for Optimizing Classroom Usage”. *IEEE Internet of Things Journal* 6(5): 7595–7607. doi:10.1109/JIOT.2019.2902410.

Tang, F.E. 2012. "An energy consumption study for a Malaysian University."

International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering 6 (8): 100-105. doi:10.5281/zenodo.1059663.

University of Reading. 2020. "Library Refurbishment Project 2016-2019." University of Reading Library. Accessed September 3 2020. https://www.reading.ac.uk/library/about-us/lib-news-refurbishment.aspx

Valks, B., M. Arkesteijn, and A. Den Heijer. 2019. "Smart campus tools 2.0 exploring the use of real-time space use measurement at universities and organizations." *Facilities* 37(13–14):961–980. doi:10.1108/F-11-2018-0136.

Valks, B., M. H. Arkesteijn, A. C. Den Heijer, and H. J.M. Vande Putte. 2018. "Smart campus tools – adding value to the university campus by measuring space use real-time." *Journal of Corporate Real Estate* 20(2):103–116. doi:10.1108/JCRE-03-2017-0006.

Wang, Y., and L. Shao. 2017. "Understanding occupancy pattern and improving building energy efficiency through Wi-Fi based indoor positioning." *Building and Environment* 114:106–117. doi:10.1016/j.buildenv.2016.12.015.

Yang, J., M. Santamouris, and S. E. Lee. 2016. "Review of occupancy sensing systems and occupancy modeling methodologies for the application in institutional buildings." *Energy and Buildings* 121:344–349. doi:10.1016/j.enbuild.2015.12.019.

<table>
<tr><th></th><th>Terms</th><th>Winter Vacation</th><th>Easter Vacation</th><th>Summer Vacation</th></tr>
<tr><td>Monday</td><td rowspan="5">Open 24 hours</td><td rowspan="5">Open from 8:00 to 19:00</td><td rowspan="5">Open 24 hours</td><td rowspan="5">Open from 8:00 to 17:00</td></tr>
<tr><td>Tuesday</td></tr>
<tr><td>Wednesday</td></tr>
<tr><td>Thursday</td></tr>
<tr><td>Friday</td></tr>
<tr><td>Saturday</td><td>Close at 21:00</td><td rowspan="2">Open from 9:00 to 17:00</td><td>Close at 21:00</td><td rowspan="2">Closed</td></tr>
<tr><td>Sunday</td><td>Open from 8:30</td><td>Open from 8:30</td></tr>
</table>

Figure 1 Opening hours of the library

Figure 2 Irisys occupancy sensor installed at the west entrance

Figure 3 Schedule of the academic year 2017-18. The dates in bold letters represent the weeks that have

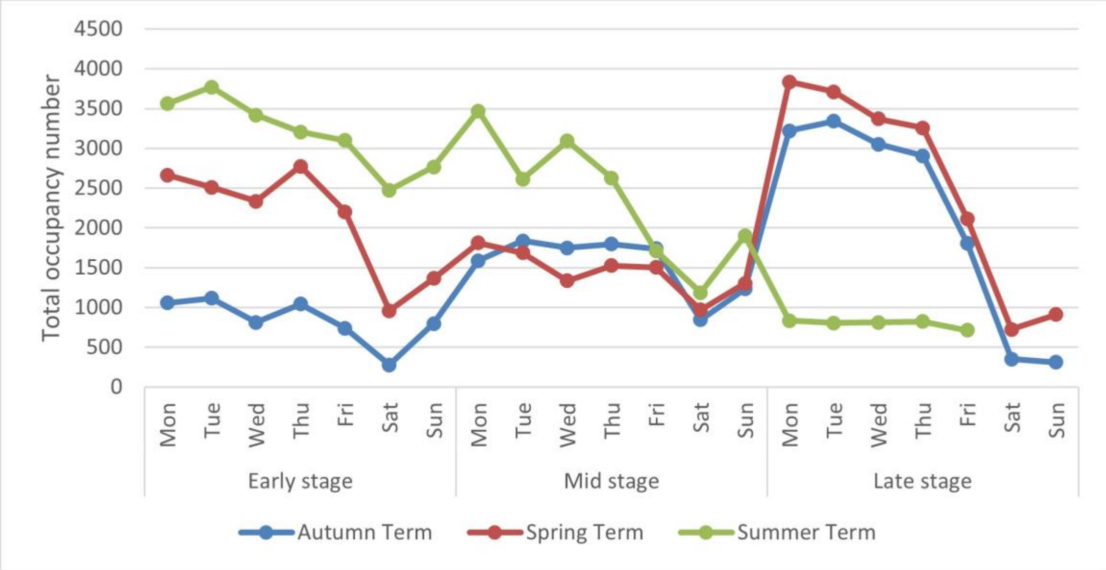

Figure 4 Footfall - Total daily users during terms

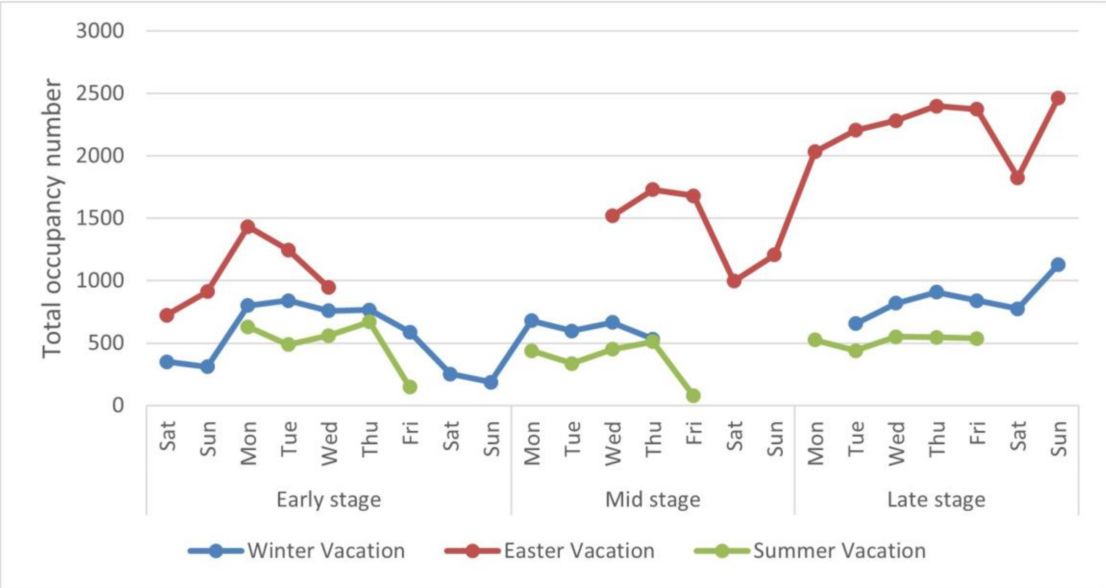

Figure 5 Footfall -Total daily users during vacations

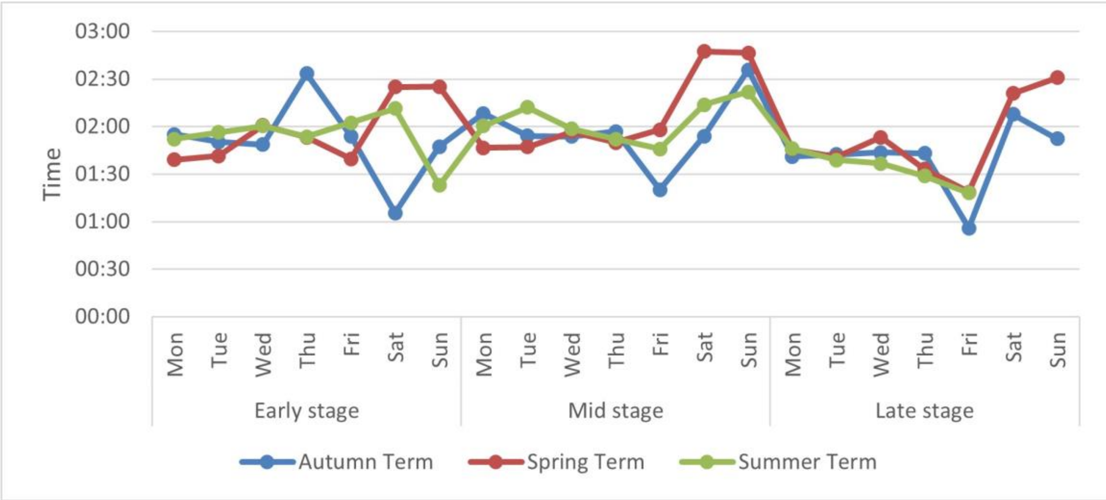

Figure 6 Estimated dwell time during terms

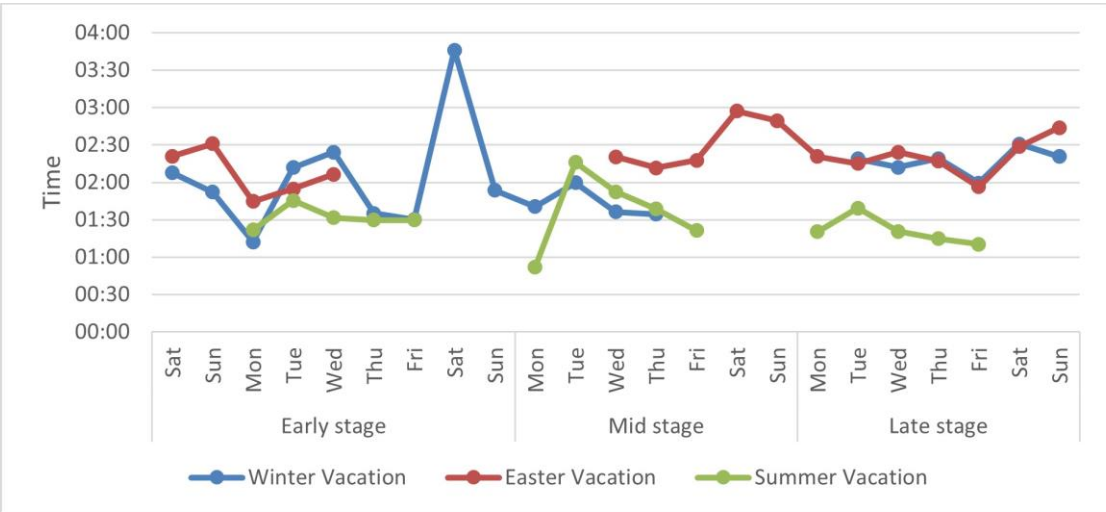

Figure 7 Estimated dwell time during vacations

Figure 8 Peak occupancy period (85%) during terms

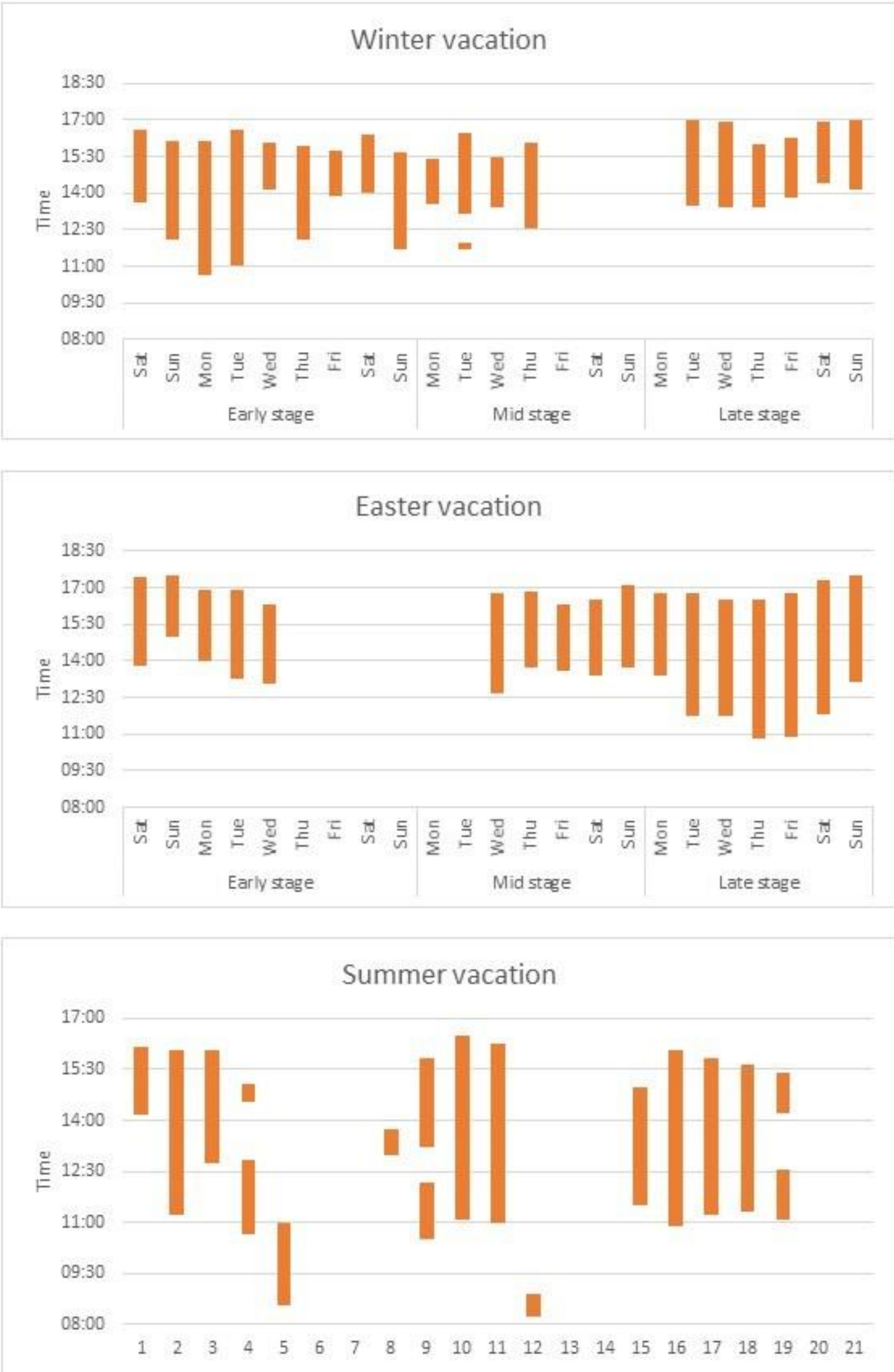

Figure 9 Peak occupancy period (85%) during vacations

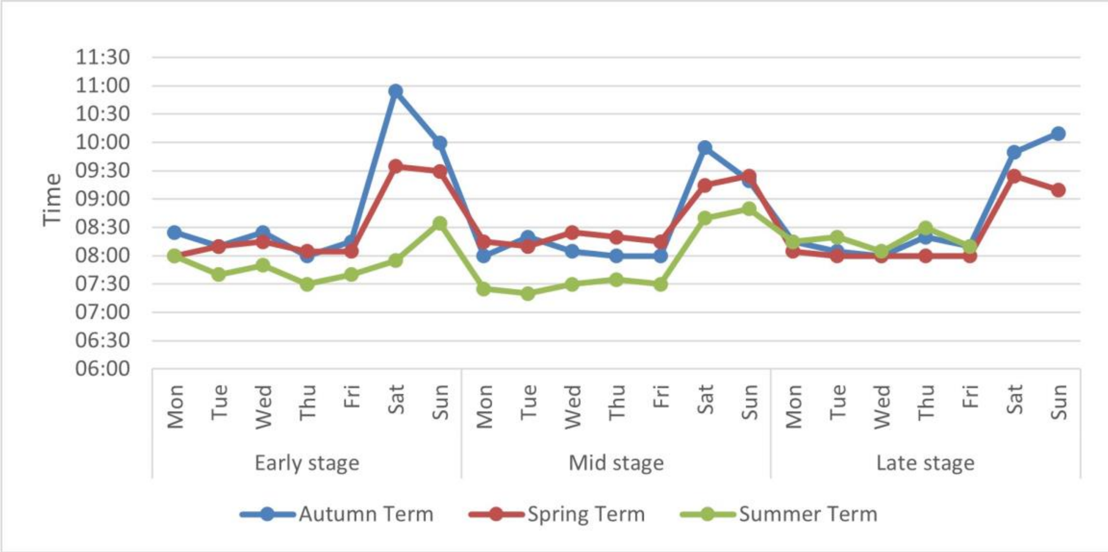

Figure 10 The earliest arrival time during terms

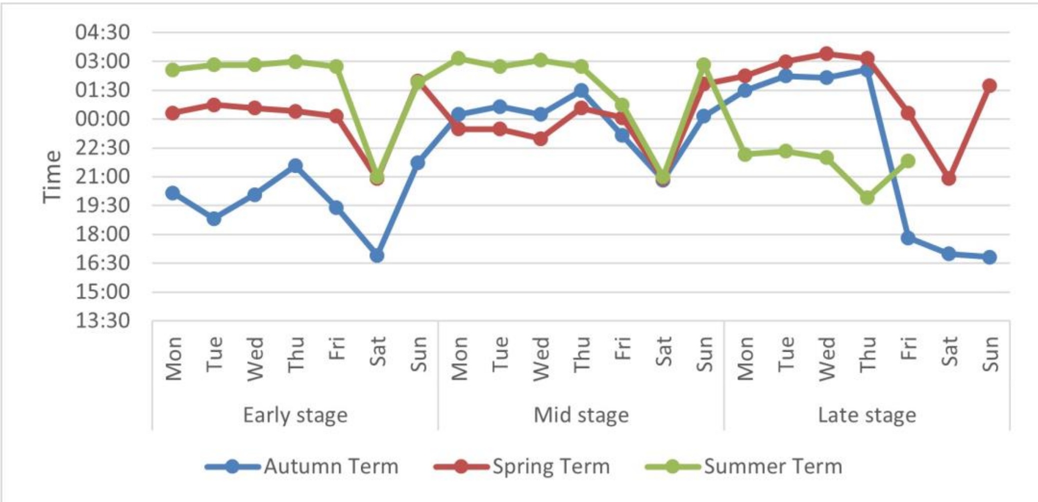

Figure 11 The latest departure time during terms

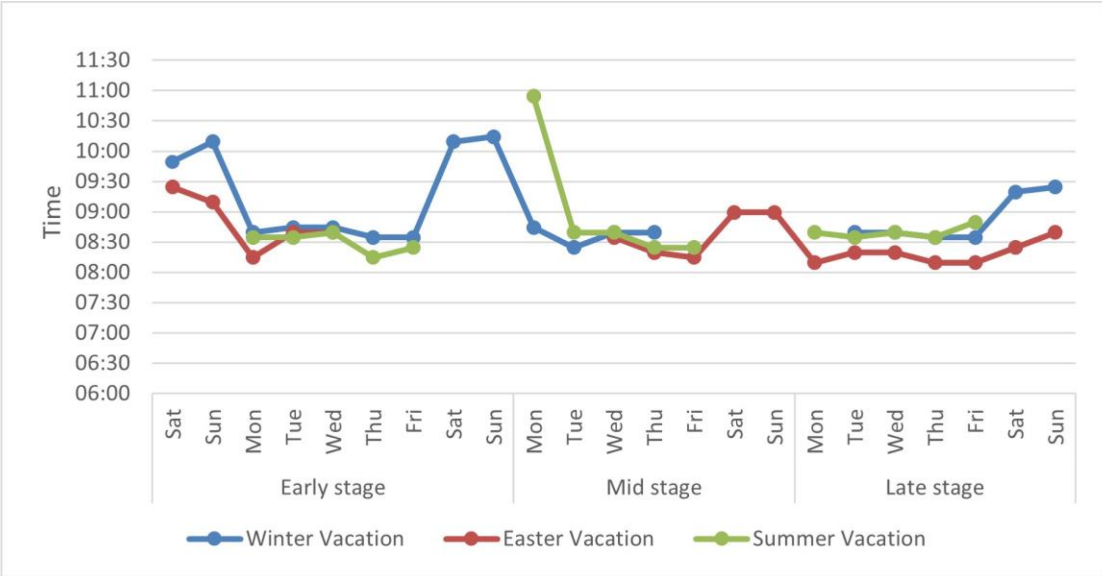

Figure 12 The earliest arrival time during vacations

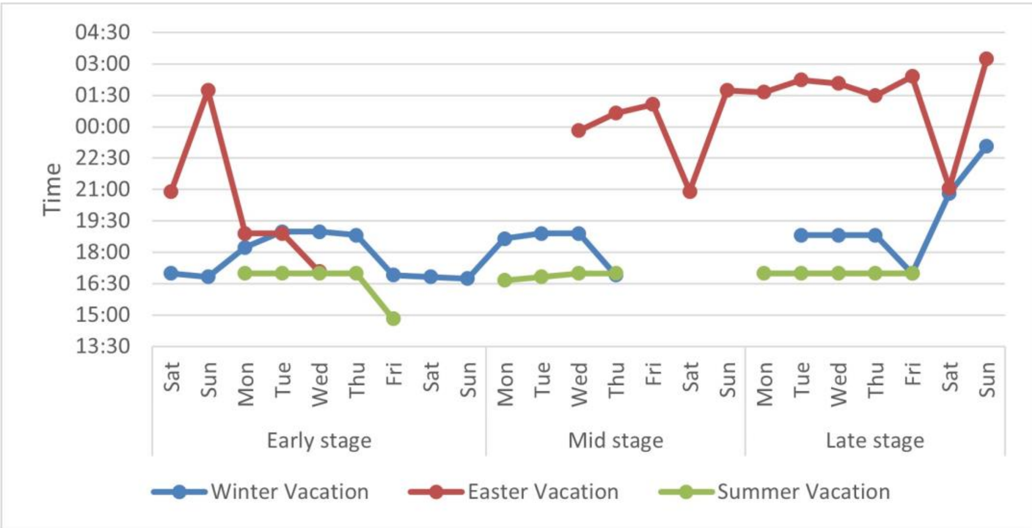

Figure 13 The latest departure time during vacations