Engineering advance

Application of Internet of Things in academic buildings for space use efficiency using occupancy and booking data

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A B S T R A C T

Environmental sustainability in academic buildings can be improved with management interventions such as improving space use efficiency supported by large data from the Internet of Things (IoT). Due to the potentials, the interest in the use of IoT tools for facility management is high among universities. However, empirical studies on this topic are scarce. To address the knowledge gap in this area, this study proposes and examines a process model with steps to measure space use and to improve space use efficiency by IoT tools in academic buildings. The applicability of the model is investigated in 8 lecture halls in a university building by using occupancy and booking data from IoT tools. Four space use indicators are developed to visualize the data and quantify space use, and based on them, the strategies and interventions for space use efficiency are proposed and discussed.

1. Introduction

Internet of Things (IoT) and big data offer extensive opportunities to improve the operation and management of buildings [1]. IoT is the integration of several technologies to provide smart services in smart environments [2]. These smart services in the building sector can be used to obtain benefits such as energy saving and environmental sustainability. Applications of these technologies in different built environments are developing with the advancements in the related technologies, including sensing devices, their connectivity, and middleware platforms [3]. The occupant-centric applications of IoT in academic environments associated with the concept of *smart campus* can improve the student learning experience, campus security, and also operational efficiency [4]. A common application of IoT tools for operational efficiency at universities is supporting users to find spaces [5]. This application can be developed to monitor space use and to enhance space use management, which becomes more important when the need for space varies as a result of fluctuating student intakes and their participation. Such fluctuations are becoming more common with recent trends in student lifestyle and greater access to online materials, lectures, etc. [6]. Moreover, circumstances such as Covid-19 pandemic could significantly change the number of participants and the space use pattern in academic buildings.

Developing the applications of IoT to create a smart environment at universities require effective smart tools. Valks et al. (2019) define a smart tool for space management as a "service or product with which information on space use is collected in real-time to improve utilization of the current campus on the one hand and to improve decision-making about the future campus on the other hand" [5]. Thus, the data sources used for the analyses in this study are smart tools, including a monitoring system with PIR (passive infrared radiation) sensors and an online booking system. In this study, space is defined as enclosed areas in academic buildings allocated for specific activities (such as lecture halls), and space use management refers to the efforts to improve the efficiency of space use. Empirical studies that use large data from IoT tools to design interventions for space use management in learning spaces are scarce. The need for more research is underlined in a recent study referring to the vast interest of the facility managers and the variety of possible system configurations, for example, on using different sensors and data sources [7]. They also identified a knowledge gap on the connection between the technical and management aspects and inferred the need to provide management information that guides the practitioners to use smart tools for space use management [7]. This gap is restated from a broader perspective by O'Brien et al. (2020), stating the promotion of the occupant-centric applications in buildings requires studies focusing on developing guidelines that include the collection of in-situ data from sensors in the buildings and its visualization [8].

The objective of this study is to demonstrate the applicability of large data acquired from IoT tools for enhanced space use management to achieve operational efficiency at universities. The aim is to provide methodological guidance to enhance the effective use of space in lecture

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List of abbreviations

CAB	concurrent all-booked
CREM	corporate real estate management
HVAC	heating, ventilation, air-conditioning
IoT	Internet of Things
MPOR	maximum possible occupancy rate
PCU	probability of concurrent usage
PIR	passive infrared radiation
POR	planned occupancy rate
PUS	percentage of usage statuses

halls. This study develops and investigates methods for measuring and quantifying space use, which is required to prioritize and choose strategies and interventions for efficient use of existing space and inform the need for additional space. The indicators can also be used for feedback on the effectiveness of interventions after their implementation. The data collected from the innovative instrumentation of IoT tools are turned into information to support the decision-making on the management of campus. A preliminary and exploratory version of this paper was presented in a conference (NSB2020) [9]. The innovative approach of this study on combining the management and technical aspects allows contributing to IoT-enabled space use management, both theoretically and practically.

The structure of this paper approximately follows the stages provided in Fig. 1 presented in the next section. Section 2 provides an overview of the benefits that may serve as objectives for using IoT tools for space use measurement and improvement based on literature review. Section 3 explains the data collection setups in our case study lecture halls and introduces our data visualization methods introduced as space use indicators that quantify space use. Section 4 evaluates the proposed space use indicators in our case study and demonstrates how the information obtained from them can lead to identifying the potentials for improvements. Section 5 links the space use indicators from the IoT data to the strategies and interventions for space use efficiency and shows the energy saving potential of closing down redundant lecture halls. Section 6 provides final remarks and conclusions.

2. Academic buildings and IoT-based smart tools

2.1. Space use management in academic buildings

Universities have had rapid growth in recent years, so that since 1990 the number of these institutions has almost doubled worldwide [10]. The growth is more likely to continue in the future due to evolving economic needs and social aspirations [11]. Physical environment is an important aspect of universities impacting their performance [12]. The universities' real estate portfolio can lead to their growth, profitability, productivity, financial sustainability, and competitive advantage [13].

Usually, the real estate costs such as acquisition, construction,

maintenance, and use constitute the highest cost after staff salaries in universities [14]. In the UK, more than 10% of the income of the higher education sector in 2015 was spent on capital investments in buildings while another 6% was spent on their operation costs [15]. The need for efficiency and sustainability requires universities to explore new ways to optimize their resources. Real estate management and governance at universities are different between countries. In countries such as the UK, the universities can own the buildings, while in some other countries such as Hungary, universities are not allowed to own their real estate [16]. Another intermediary model being practiced in countries such as Sweden, where a public (or semi-public) agency (e.g., Akademiska Hus in Sweden) owns campus buildings, while the universities as tenants pay rent for the buildings they use [16].

Energy use in non-residential buildings, such as academic buildings, is expected to increase by 57% worldwide from 2018 to 2050 [17]. Energy use in this sector is difficult to interpret due to the diversity of activities and types of spaces such as lecture halls, laboratories, and offices [18,19]. Moreover, the occupants of such buildings may not be considerate of energy use. One reason could be that they are not aware of the energy bill, thus may not feel the responsibility to reduce the costs [20]. Today, the buildings are built relatively more efficiently with enhanced insulation in building envelope and improved ventilation systems that can reach 90% heat recovery. Further improvements in many cases are not viable, expensive, or incur excessive embodied CO_2 [21]. Occupancy features have become known as important factors that lead to a discrepancy between the predicted and real energy and comfort performance of buildings [22–24]. Improved management such as space use efficiency is low-hanging fruit as compared to many other energy efficiency measures as it usually does not require large investment [4]. Moreover, such measures are relatively less material-intensive resulting in lower embodied emission as compared to the emission from the production of materials associated with energy efficiency measures [25].

Corporate real estate management (CREM) is a field involved in optimizing physical assets or corporate real estate to improve the delivery of organizational objectives [26]. In the context of academic environments, CREM can be considered as campus management, while the organizational objectives are often to improve productivity, competitiveness, profitability, and sustainable development [13]. Physical environment plays an important role in the work performance of teachers and learners in academic institutions [27]. Promoting an institutional culture to value the physical assets is necessary to ensure the overall quality in an academic environment [27]. Improving energy efficiency, environmental sustainability, user experience, and reducing costs by reducing square meter footprint or reallocation of redundant spaces to activities demanding more space are parts of CREM. Henceforth, in this paper, closing down lecture halls or transforming them to be utilized for other activities are referred to as *avoiding lecture halls*.

The spaces, such as lecture halls and labs at universities, are limited resources that should be managed efficiently. Space use management is defined in our paper as the efforts to improve space use efficiency. Space use efficiency is about ensuring the availability of space for the intended activities while decreasing the operation and maintenance costs and
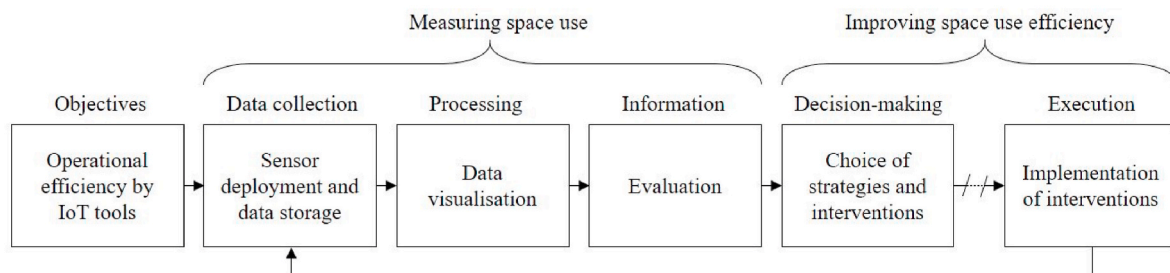

Fig. 1. A schematic of the stages in IoT-enabled space use management.

increasing the usage time and occupancy density [5,28]. Space management is an important aspect of facility management in buildings, which are physical assets [13]. The decision to allocate a specific space to a certain activity should come along with the responsibility to ensure the efficiency in space use [13]. When the demand for space in an academic environment increases, space use efficiency may save capital investment by preventing unnecessary investments such as building new lecture halls. Moreover, space use efficiency decreases the operation costs related to energy use or housekeeping [5]. In the Swedish context, improving space use efficiency can lead to closing down redundant lecture halls which in addition to saving energy can reduce the rent for university or allow the building owners (Akademiska hus) to lease such lecture halls to other interested organizations [29]. Overall, monitoring, predicting, and managing the space use for the organization's real estate portfolio can lead to economic savings and environmental sustainability [5].

The aim to improve the operation of educational institutions has driven research studies to investigate timetabling for courses and exams to improve space use [30]. Nevertheless, the outcomes from such measures might be different from expectations signifying a gap between the theoretical approaches and practical applications by administrators who facilitate academic events [30]. Moreover, the gap between predicted (timetabled) and actual use in terms of frequency and occupancy is a shortcoming of booking systems [5]. Space use surveys have been undertaken by direct observation in small areas [31]. However, this method could be challenging for large spaces during long periods. The difficulty to accurately measure the space use in buildings may be the reason for overlooking the efficiency potential of space use [32]. Identifying the demand for a specific type of space might be invalid without information on space use [33]. Estate planning in universities without adequate assessment of space use may cause space shortage or wasteful allocation of resources on investment, operation, and maintenance of under-used spaces [1].

Application of IoT for space use management and optimization has diffused faster in non-academic office environments [5]. One example is to support organizations on the transition from private offices to "hoteling-style" office management [34,35]. This approach is meant to provide fewer working desks than the number of office workers while minimizing space shortage. The potential for hoteling-style office can be examined by calculating the minimum ratio of work stations to employees so that, e.g., only 1% of the time, there would be an insufficient number of workstations [34]. Another example is devising a system to cancel unused bookings in meeting rooms by contrasting the bookings with real usage [36]. This approach is partly applied to our investigation of lecture hall usage. However, the analyses in this study use different configuration of sensors and develop several indicators to visualize the data of space use more descriptively. IoT for space use management in academic environments is investigated in a study by mathematical optimization of classroom allocation [6]. They inferred a 10% potential reduction in room costs by using a combination of the real and predicted number of occupants. Unlike them, our study does not conduct mathematical optimization however, our data visualization methods can be used as objective functions to support and improve such an approach.

The studies reviewed in this section address the problem of space use efficiency from either technical or management perspectives. However, as stated by Ref. [7,8], there is a need for better linkage between these aspects. Fig. 1 represents an adapted model by Valks et al. (2018) [5] for using smart tools in buildings. In accordance with the presented benefits, which may serve as implementation objectives, IoT tools could be deployed to measure space use in buildings. The large data generated, transmitted, and stored by IoT tools are meant to be more accessible and easy to handle. In the next step, the data would be processed by the algorithms that can handle a large amount of data and transform it into informative space use indicators. Next, the indicators would be evaluated to extract the information that describes space use and reveals the potentials for improvement. The decision on adequate strategies and

interventions would be made based on the evaluation of indicators. If the decision-makers do not envision improvement by the available options, then no further actions would be taken. The data on space use collected after the interventions are undertaken would be again processed and visualized by indicators to compare space use and to evaluate the effectivity of interventions and to decide on the need for new ones.

2.2. IoT tools for space use management

Achieving operational efficiency by space use measurement and management in buildings is infeasible without adequate data to support management decisions. IoT tools or smart tools, which are the terms being used interchangeably in this study, refer to novel technologies that can provide extensive information about space use. According to Ref. [28], space use measurement allows to realize whether, and how space is being used and the main elements to be measured are frequency rate and occupancy rate. Frequency rate is the fraction of available time that space is used, and occupancy rate is the ratio that shows how fully space is used in comparison to its capacity [28]. This paper refers to frequency rate and occupancy rate as usage time and occupancy density, respectively.

Space use can be quantified in terms of both actual use and predicted use. Online booking systems are primarily intended to support the academic activities being organized while they can be used to predict space use [7]. Moreover, this information can be cross-verified by linking the booking systems to sensor technologies to measure the actual usage of spaces [7,36]. Occupancy sensing technologies provide information that enables space use measurement and management. These systems have the advantage that can be developed gradually after assessing the outputs, which could indicate which parts of the infrastructure have priority over the others to grow [4]. Therefore the systems usually do not require large initial capital investments [4]. Occupancy sensing has been practiced more commonly for automated lighting control [37], while its application to control indoor air quality is a relatively recent and emerging field [38]. Occupancy-based building automation technologies can mitigate the adverse effects of occupants' behavior and poor building control on energy use [39].

Quality of occupancy information is often broken down into the resolution and accuracy of occupancy detection. The accuracy of occupancy detection determines the reliability of occupancy information and can be measured in two different ways (based on the application) considering the presence or absence measurements [40]. The resolution of occupancy detection is defined by Ref. [41] in 3 dimensions, including temporal, spatial, and occupant dimensions. As the resolution
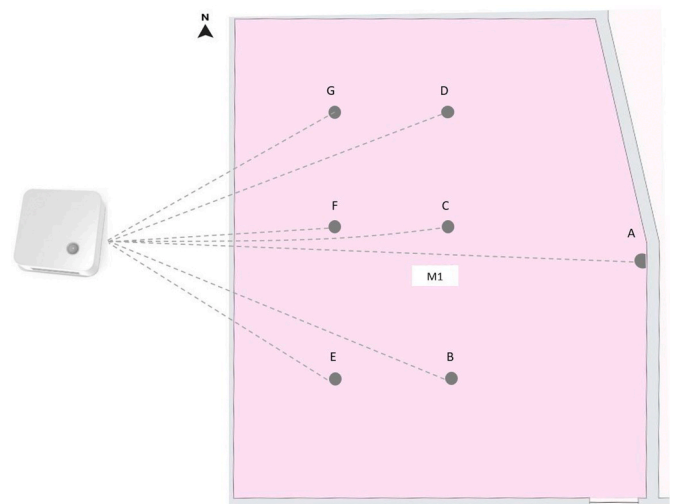

Fig. 2. Sensor installation layout in a sample lecture hall.

of a sensor increases, the information is available faster, the observed space can be studied in more detail, and the occupants become more defined. The occupant resolution is defined by Ref. [41] in four different levels:

Level 1: Occupancy; whether there is at least one person present in the space
Level 2: Frequency; how many occupants are present in the space
Level 3: Identity; who are the occupants present in the space
Level 4: Activity; what are the occupants engaged with in the space

This study uses the resolution levels 1 and 2 to measure space use and to improve space use efficiency. The resolution and accuracy of occupancy detection depend on sensor technologies. Some examples of the sensors used in the building industry are PIR sensors, CO_2 sensors, vision-based detectors, etc. Each of these sensors can provide a certain level of resolution and accuracy and have specific installation limitations and privacy concerns [42].

Research shows that occupancy detection technologies can significantly improve the energy efficiency in non-residential buildings by occupancy-based control strategies that can reach over 50% energy saving [42]. The occupancy information can also be used for other applications such as building security, demand response, conducting behavior change campaigns, and space use management [5,37,43,44]. Despite the recent research interest on occupancy-based control of energy systems, the other applications of occupancy detection by IoT devices are relatively overlooked [45]. Further, most of the papers on the subject focus on performance criteria of occupancy detection, such as accuracy for a new system design applied in small scale laboratory studies [7]. Multiple applications of occupancy detection systems make it easier to justify the cost of their deployment [42]. Therefore, it is important to pursue new applications for occupancy detection technologies and evaluate them in real-life situations to enable smart IoT-based environments. Valks et al. (2019) surveyed 34 universities and organizations to investigate the smart tools used in their buildings [7]. The majority of the respondents of that survey stated either using or developing some forms of these tools to address inefficient space use showing the topicality of this subject despite the scarcity of studies in the literature.

3. Method

3.1. Data collection

Umeå University has gradually expanded since its establishment in 1965 to its current position as the largest university in northern Sweden, with more than 34,000 students enrolled in 2019. The number of students has been fluctuating in the last decade as it dropped by 16% between 2010 and 2015 and then increased by 12% in the 4 years till 2019. The main campus comprises several buildings spread in a 244,703 m^2 area where various educational and research activities are conducted. The lecture halls are mainly managed under two forms of contracting between the facility manager (Akademiska Hus) and the university's units/departments. The departments might have a yearly rental contract for specific lecture halls. The second type of contract applies to the investigated lecture halls, which allows them to be booked by the staff from any department for various activities and their affiliated departments would be invoiced based on the booking information. The investigated lecture halls are a small portion of a broad portfolio of lecture halls at the university. They cannot be representative of the lecture halls in other parts of the campus; however, our method can be applied to other lecture halls that have similar spatial features.

The in-situ data collection method monitors occupants in their natural environment. Compared to laboratory studies, this method is cost-efficient for an extended monitoring period without the impact of the Hawthrone effect (where observation causes changes in occupants'

behavior) [46]. The data for the space use measurement was collected from the occupancy sensors in the lecture halls and the university's booking system. The sensor data was collected from 71 sensor devices in 8 different lecture halls on the 3rd floor of the Natural Science Building at Umeå University. As the sensors were battery-powered, they could be easily installed by double-sided adhesive tapes on desirable positions. Each sensor device measures PIR, temperature, humidity, and light intensity. In this study, only the PIR data was used for the analysis. The higher temporal resolution of occupancy detection may lead to more accurate information on space use [41]. However, the frequency of data logging is restricted by factors such as sensors' battery life and capacity of data storage. The sensors were set to transmit data in 10 min intervals using LoRa (Long Range) wireless network. LoRa is a low-power wide-area network technology that gained fast-paced growth in IoT applications [47]. The data was collected in a middleware database platform, which allowed easy access to all sensors. This analysis uses data collected during the four months in the spring semester of 2019.

The number of sensors in each lecture hall varies due to differences in the size of the lecture halls. The sensor installations in the lecture halls allow measurement of usage time, distribution of occupants in the lecture halls, and also rough estimation of occupancy density. To investigate the occupancy density, the sensors were installed to the maximum extent possible, with even distribution in such a way that they cover the entire area of the lecture halls' area. The sensors' accuracy could be affected by the distance from the detection target. The recommended detection range as per the sensors' vendor is 5 m, while in this study, the sensors were mostly installed to cover 2–3 m range. Further, sensors might be triggered due to heated surfaces (e.g., by sunlight) or they may fail to detect if the occupants remain overly static. The detection accuracy of sensors was briefly tested for 5 working days in 3 offices in university. For this trial, the occupants in the offices were asked to record "ground-truth" information about their presence in the offices. This information was then cross-verified with the occupancy detection data from the sensors. The results show that the average detection accuracy was about 95% when detection occurs within 2 m range. Despite the uncertainties in the data caused by sensor inaccuracy cannot be fully excluded, detections are assumed accurate enough for the analysis. This has been confirmed by previous studies in building research using PIR sensors for occupancy detection with different objectives. Some examples are adjusting room temperature set-point with occupancy [48], lighting control with occupancy [49], and building utilization monitoring [34], which are conducted relying on PIR sensors for occupancy detection. Sutjarittham et al. (2019) tested different types of counting sensors to count the number of occupants while used PIR sensors to reset the accumulated errors as they inferred PIR sensors to be *fairly accurate* [6].

The room-booking system at Umeå University allows its employees, which include teachers, and researchers (henceforth staff) of the university, to book the lecture halls for different events. In this study, an event refers to an academic event that may be organized in the lecture halls such as course lectures, presentations, meetings, etc. The system is based on a centralized coordinated timetable that allows scheduling the events. The system has a user-friendly interface that also presents the features of lecture halls such as capacity (number of occupants that the lecture hall can accommodate) and available equipment. The lecture halls can be booked by the staff affiliated to any department at the university. When the staff book the lecture halls, their affiliated department would be billed for the bookings according to the contract. The hourly price of the lecture halls differs based on room size and time slots. For example, the hourly fee is 35% more expensive for the bookings made between 10 a.m. and 03 p.m. as compared to the other time slots.

The investigated lecture halls are located in a building which is close to most of the departments in the university campus. All the lecture halls are located on the same floor and are beside each other along a corridor. Their proximity to each other diminishes the importance of their spatial

location regarding the staff's booking choices. The lecture halls are supplied with constant ventilation flow for maximum room capacity set for operation based on occupancy detection. The room temperature is set at 21 °C and maintained by a hydronic radiator system during the heating season. The lighting control varies among different lecture halls, while 3 out of 8 investigated lecture halls have manual control, and the rest have automatic lighting control based on occupancy detection. The electricity use of lighting and plug loads in the lecture halls were measured using additional sensors.

The term lecture hall often refers to larger rooms for lectures. To simplify the terminology in this study, rooms for lectures, irrespective of their size, are referred to as lecture halls. The size of lecture halls is related to their capacity, ranging from 20 to 130 persons. As presented in Table 1, the lecture halls are divided based on their capacity in different size categories. There are 3 lecture halls with capacities lower than 35 persons categorized as "small" and 3 lecture halls with capacities between 35 and 70 persons categorized as "medium". The two large lecture halls have 130 person capacity. All of the lecture halls are equipped with typical teaching and presentation facilities such as whiteboard and projector.

Fig. 2 shows the layout of one sample lecture hall, M1, with 7 PIR sensors. Sensor A is installed to detect presence in front of the whiteboard, and sensors B to G are installed to cover the sitting areas.

3.2. Data visualization

Assessment of building performance entails adopting performance indicators (or as some studies put it forward as "metrics") that can quantitatively describe an intended aspect of building performance [34]. There are currently plenty of building performance indicators available across scientific literature, some being used by standards and legislations to evaluate the building performance [50]. Those indicators involve various aspects of building performance however, the features related to occupancy are generally underdeveloped [34]. Developing relevant indicators is necessary to quantify buildings' space use, followed by the efforts to improve efficiency. As described earlier, space use consists of two aspects: usage time and occupant density. Accordingly, the indicators for space use measurement have to quantify these two aspects. As presented in Fig. 3, this paper uses the sensor and booking data to develop four indicators to measure and to describe space use. Evaluation of space use indicators provide insights on space use in lecture halls during the period of investigation. The strategies and interventions for space use management can be drawn with the assumption that the usage pattern would be the same in the future without a major change in the context, such as student intakes.

The data was pre-processed to synchronize the disordered timetables caused by missing data of a few sensors. The missing data points result from the interruptions in the wireless network. In this paper, *available time* refers to the data related to the working hours, which is considered to be from 08:00 to 17:00 during weekdays. The data pertaining to weekends and holidays were filtered out for the analysis.

Proportion of usage statuses (PUS): As per the objective of this study to improve space use efficiency, the first step is to survey how the lecture halls are being used, which can be quantified as PUS. As shown in Fig. 4 the lecture halls can be in four different statuses based on their booking and occupancy information. The proportion of time related to each status can be calculated, suggesting the efficiency of space use for every lecture hall.

The first status, "booked-occupied", is when a lecture hall is booked in the booking system, and the occupancy sensors indicate presence during that time. A high proportion of duration of this status relative to the available time is desired since it signifies high usage time, which is one of the aspects of efficient use of space. The second status is "booked-unoccupied" in which a lecture hall is booked while the occupancy sensors do not detect any presence. This could happen if the events are canceled without canceling the bookings or when an event ends earlier than it is planned. The third status, "not booked-occupied", is when a lecture hall is not booked, but the occupancy sensors detect presence. This status indicates the periods that the lecture halls are used as drop-in without prior booking. The users could be the staff who had their events such as lectures or meetings in the lecture halls without booking the rooms. However, the primary users in this status are the students who use the space for studying or group activities. The last status, "not booked-unoccupied", is when a lecture hall is not booked and not occupied. This status represents the periods that the lecture halls are neither booked nor occupied, therefore it includes the most obvious case for improving space use efficiency.

Probability of concurrent usage (PCU): PCU is an indicator that presents the probability distribution of the number of lecture halls that are being used simultaneously. A similar indicator is used in the literature to evaluate the hoteling potential in office buildings [34]. PCU in this study is based on booked periods, whether occupied or not. PCU indicates the proportion of time with space shortage if one or several lecture halls are avoided (closed down or reallocated to other activities).

This indicator allows to recognize the redundancy of lecture halls and the possibility to avoid them. The results can also provide insights for any new development if the lecture halls are found to be in high demand.

To calculate this indicator, the booking information for several lecture halls is considered together in an aggregated manner. The analysis is performed for the typical time slots of lectures in academic environments in Sweden: "8:00–10:00", "10:00–12:00", "13:00–15:00" and "15:00–17:00". The time slot "12:00–13:00" is often considered lunchtime, and is presumably rare to have lectures and meetings at this time.

Planned occupancy rate (POR): POR is a space use indicator related to occupant density that is calculated by the data from the booking system. The analysis for this indicator requires information on the number of attendees in the events organized in the lecture halls. However, in this study, this information is only available for the bookings made for course lectures, which cover 80% of bookings. When the staff, such as teachers, book a lecture hall, they require to enter certain information such as the name of the course. The number of students registered in each course is available in the university's registration system that can be compared with the capacity of the lecture hall booked to hold its corresponding lectures. POR indicates the maximum number of students that might potentially attend the lectures however, the real occupancy rate is often lower as some students would skip a few lectures.

Maximum possible occupancy rate (MPOR): Occupancy density can be directly estimated by counting the number of occupants present in a lecture hall divided by the lecture hall's capacity. However, a PIR sensor detecting motion cannot detect the number of occupants. Hence, to measure occupancy density, we introduce an alternative approach (MPOR) that enables using PIR sensor data to estimate occupancy density. Unlike the vision-based sensors used for counting the number of occupants, PIR sensors do not usually prompt privacy issues and require simpler instrumentation. Moreover, the lower volume of data generated by PIR sensors is easier to handle and process.

The calculation of MPOR was enabled by the multiple PIR sensors installed to cover the entire area of the lecture halls. Assuming no false detection by PIR sensors, when a sensor does not detect motion over a time-step, the number of occupants in its field of view has been zero. The area of the lecture hall without any detected motion can be considered as the unused section over the observed time-step. The rest of the lecture
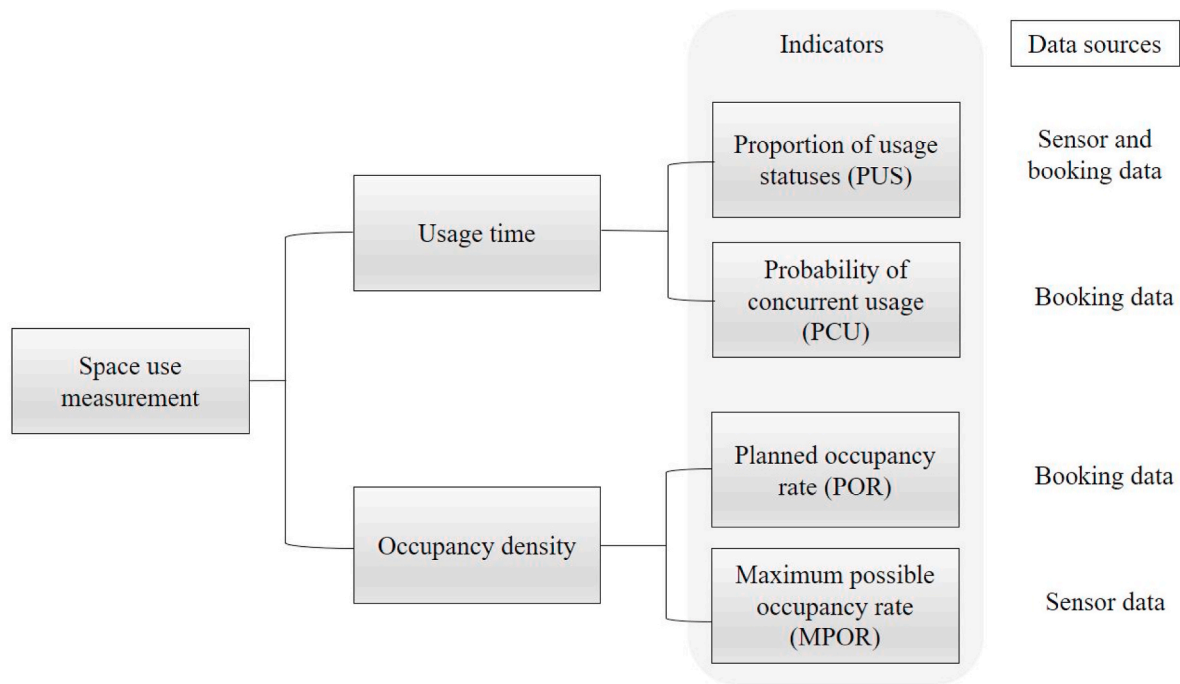
Table 1
Categorization of lecture halls based on their capacity.

Size categorization	Room ccapacity (persons)	Lecture halls
Small	Capacity<35	S1, S2, S3
Medium	35 ≤ Capacity ≤ 70	M1, M2, M3
Large	Capacity>70	L1, L2

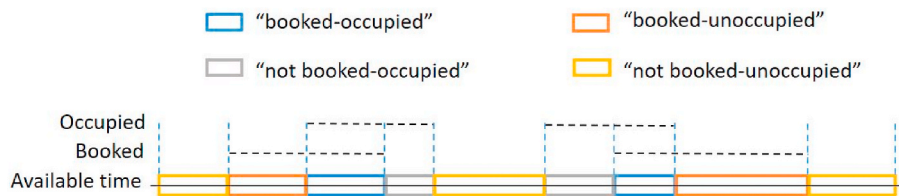**Fig. 3.** Space use indicators for space use measurement.

Fig. 4. Different statuses based on booking and occupancy information.

hall with detected motion might be occupied by one or several occupants per each sensor. The maximum potential number of occupants in the occupied portion of the room in relation to the room capacity is the maximum possible occupancy rate (MPOR). This ratio can be calculated by the number of installed sensors to cover the entire room area and the capacity of the lecture hall. MPOR can indicate the maximum number of occupants that might potentially occupy the area of a lecture hall at a certain time-step and not the actual number of occupants. For example, if there are 10 sensors installed to cover the entire area in a lecture hall, while 5 sensors detect presence and 5 sensors do not, it can be inferred that the maximum number of occupants in that lecture hall could be half of the capacity. Despite the number of occupants might be less than half of the capacity, it cannot be more than half. MPOR can be calculated for each lecture hall during a data acquisition time-step which was 10 min in this study. To use this approach for a longer period than a time-step, the MPOR values were averaged for the entire period that a lecture hall was inferred to be occupied.

MPOR is an indicator for occupancy density that can be calculated by binary outputs from PIR sensors, although it cannot be as accurate as occupancy rate inferred by the sensors designed to count the number of occupants. The precision of this indicator to describe occupancy density depends on how even the sensors are distributed within each lecture hall and how much overlap do they have on their covered area. The challenge of overlap between PIR sensors is also mentioned by Sutjarittham et al. (2019) [6]. Section 4.4 presents insights on the reliability and usability of this indicator, followed by the results of MPOR for our case study.

4. Evaluation of space use indicators

4.1. Proportion of usage statuses (PUS)

Fig. 5 presents the proportion of each of the four statuses in relation to available time in different lecture halls. The proportion of booked periods for these 8 lecture halls ranges from 26% to 80%, with an average value of 40%. These numbers indicate that the lecture halls were mostly not booked. The booked period was shorter for medium and large-sized lecture halls with 32% and 33% and longer for small-sized lecture halls with 49%. This indicates that small-sized lecture halls are preferred compared to other lecture halls although, on average, still those rooms were not booked for more than half of the available time.

4.1.1. "Booked-occupied"

The proportions of the duration of this status in relation to available time in the investigated lecture halls ranged from 21% to 52%, with an average value of 30%. The proportions of this status in small, medium, and large lecture halls were 35%, 24%, and 33%, respectively. The lecture hall S1 seems to be relatively less preferred in its size category. Other size categories do not show a high variation on the booking preference comparing the corresponding lecture halls. Efforts should be made to increase the duration of this status in the lecture halls by reducing the duration of other wasteful statuses that, on average, stood for 70% of available time.
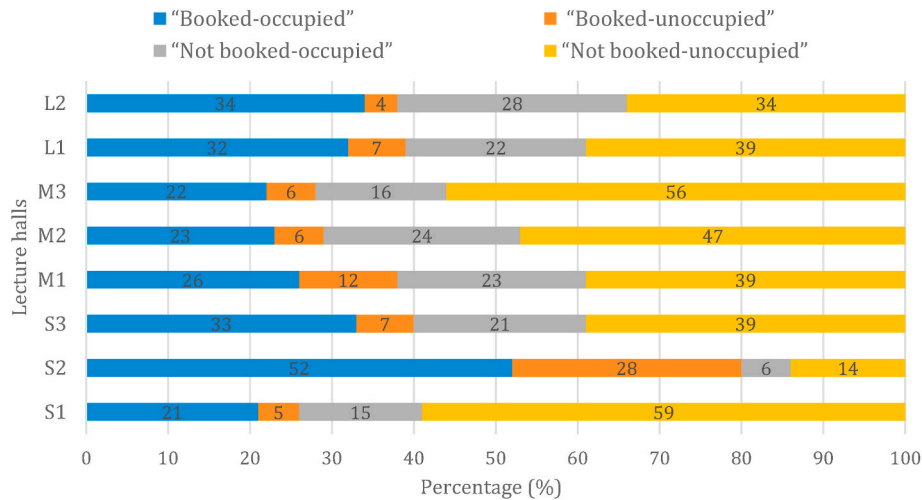
Fig. 5. Proportion of usage statuses (PUS) relative to the available time.

4.1.2. "Booked-unoccupied"

On average, about 9% of the available time of the lecture halls are in this status. Further investigation shows, on average, in 22% of the periods that the lecture halls are booked, they were unoccupied. The average unoccupied portion of booked periods for large lecture halls was 15%, which is relatively lower than other size categories. This status presents a wasteful space use as the "booked-unoccupied" lecture halls cannot be booked and used by other staff who may struggle to find lecture halls to organize their events. Despite 9% of the available time may be acceptable as having this status is ultimately inevitable, further reduction of this status is possible by the preventive actions presented in section 5.1. Further analysis could be done to improve the PUS analysis during "booked-unoccupied" status by considering the times when events are ended earlier or interrupted due to lunch break.

4.1.3. "Not booked-occupied"

On average, for the 8 investigated lecture halls, this status made up 19% of the available time. During 32% of the periods that the lecture halls were not booked, there were occupants present in the rooms. This situation was more common for large lecture halls with 40% as

compared to other lecture halls with about 29%. The problem during this period is that the lecture halls might be occupied by a few occupants, while the energy services such as lighting, space heating, and ventilation would be provided for the entire room capacity. The hypothesized lower occupancy density in this status is investigated in section 4.4 by comparing MPOR for the two occupied statuses.

4.1.4. "Not booked-unoccupied"

This status represented approximately 41% of the available time ranging from 14% to 59% in different lecture halls. The average proportion of this status in small lecture halls had a high variation from 14% to 59%, with an average value of 37%. The average proportion of "not booked-unoccupied" status in medium and large lecture halls were 47% and 36%, respectively. A high proportion of this status shows that space is not used efficiently.

4.2. Probability of concurrent usage (PCU)

Fig. 6 presents the results of PCU analysis to investigate the proportion of the number of lecture halls that were booked at the same time.
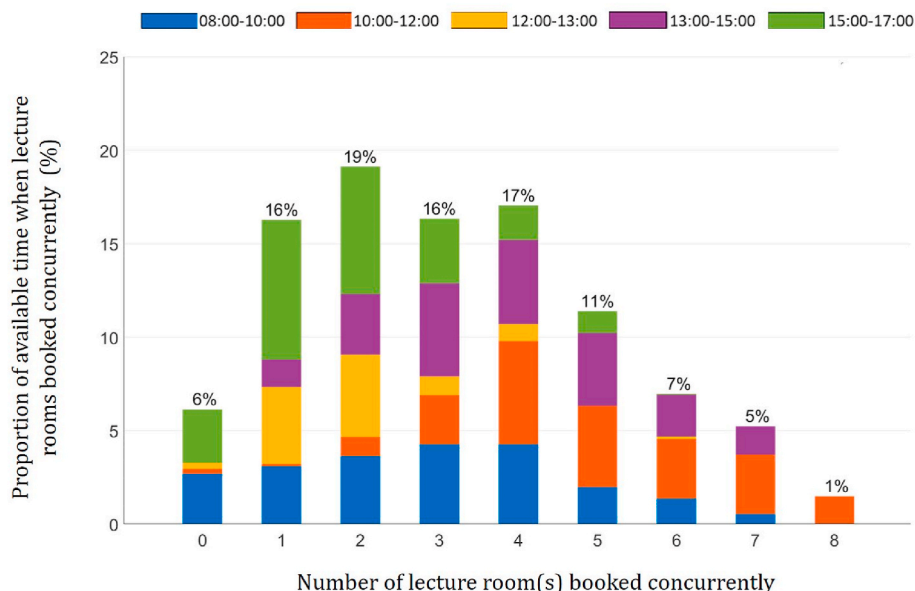

Fig. 6. The probability distribution of concurrent usage of the investigated lecture halls.

There was only 1% of the available time when all the 8 lecture halls were booked at the same time, which was during the "10:00–12:00" time slot.

The time slot "15:00–17:00" was relatively underused, as more than 5 lecture halls were never booked at the same time during that time slot (Fig. 6). This indicates the potential viability to avoid at least one lecture hall by shifting the bookings to other time slots, such as "15:00–17:00". As the lecture halls are in different size categories, there is a need for further analysis to determine which one of the 8 lecture halls should be avoided. However, if all the lecture halls have the same size, then such analysis for different size categories would not be required.

As all the lecture halls have similar equipment for teaching and presentation, the size of lecture halls is considered as the main factor determining the preference of the staff on their choice of a particular lecture hall. This implies the necessity to perform the analysis separately for each size category. Fig. 7 presents the results of the PCU analysis for each size category of lecture halls. Concurrent all-booked (CAB) refers to the result of PCU analysis, where all the similar categories of lecture halls are booked simultaneously. CAB for small lecture halls was 13%, while this proportion is 10% for the medium lecture halls. The results also show CAB was 21% in large lecture halls, although it is important to

consider there were fewer large lecture halls (2 lecture halls) compared to the other sizes. These periods indicate that there might be a possible shortage of lecture halls in some time slots if it is decided to avoid a lecture hall. Nevertheless, as the simultaneous booking of all lecture halls happened for a short duration, it provides an opportunity to explore the possibility of avoiding one or more lecture halls.

In the scenario to avoid one of the lecture halls, the staff would have several alternative solutions to find lecture halls during the CAB periods. Some examples of these potential solutions are:

- Booking a lecture hall of the same size on the same day in a different time slot.
- Booking a lecture hall of different sizes on the same day and the same time slot.

PCU can also be analyzed separately for different weekdays, which may reveal the potential for temporary utilization of the lecture halls for other activities when they are less needed. This indicator can generally provide an initial indication of the potential to improve space use. However, avoiding redundant lecture halls may require further analysis to investigate the availability of space for events. To demonstrate the usability of this indicator, the two aforementioned solutions are examined in the coming sections.

4.2.1. Booking a lecture hall of the same size on the same day in a different time slot

This analysis focuses on CAB periods defined in the previous section. In the scenario to avoid a lecture hall, finding an alternative lecture hall in CAB period might be difficult since fewer lecture halls would be in service. The analysis in this section investigates the possibility of transferring the bookings to another lecture hall from the same size category but in other time slots of the same day. The results of the weekly average for the small lecture halls show there is at least one available time slot in another small lecture hall on the same day during 58% of the available time (Fig. 8). This solution is more viable for medium lecture halls with an average 84% availability of empty time slots. Avoiding a large lecture hall would cause a more severe shortage, with an average 38% availability of free time slots to transfer the bookings to another lecture hall. This analysis is similarly conducted for every weekday to find out which days might have more problems due to the higher intensity of bookings. The small lecture halls would have more problems on Thursdays, with only a 35% possibility to transfer the bookings to other lecture halls. Medium lecture halls have their worst problem on Wednesdays, with still 76% possibility to transfer the bookings to another medium lecture hall. The large lecture halls have their worst shortage on Mondays, with only an 18% possibility of transferring bookings. This analysis shows the solution to transfer the bookings from an avoided lecture hall to another lecture hall of the same size in another time slot of the same day is most feasible, especially for medium-size lecture halls.

4.2.2. Booking a lecture hall of different size on the same day and the same time slot

Usually, the alternative to the avoided lecture hall while a lecture hall of the same size is not available, would be to book a larger lecture hall, to ensure accommodating all the potential occupants. For example, when someone wants to book a small lecture hall, but there is none available, he/she can instead book a medium-sized lecture hall. According to the analysis shown in Fig. 9, at 67% of the time when all 3 small lecture halls were booked (CAB periods), there was at least one empty medium lecture hall available to book. In other words, if one small lecture hall was avoided, the staff had instead a 67% chance to book a medium lecture hall during the CAB periods. However, this solution was not viable in about 32 h during that semester. A similar analysis for medium lecture halls shows while one lecture hall was avoided during the CAB periods, the staff had a 60% chance to book a
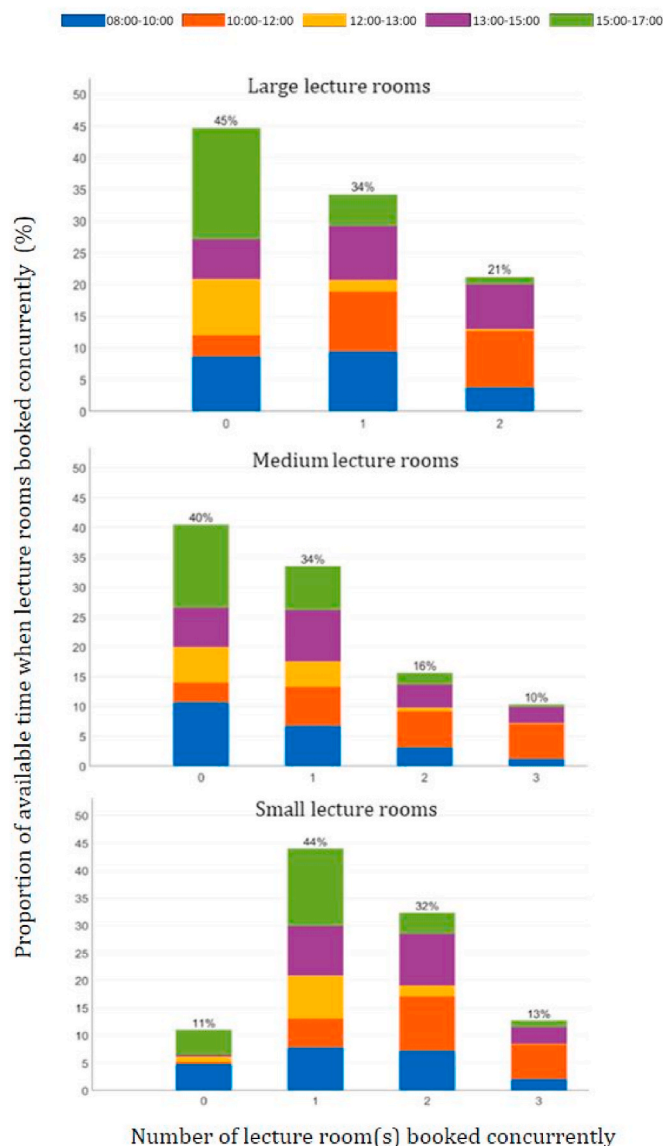

Fig. 7. The probability distribution of concurrent usage of the lecture halls for different size categories.
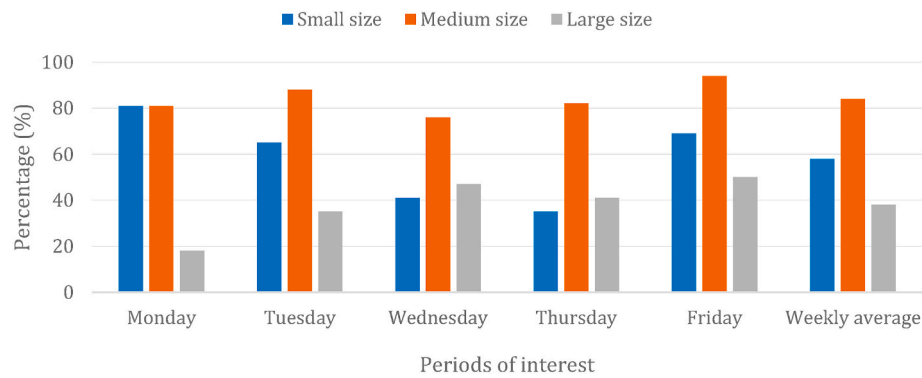
Fig. 8. The probability of transferring a booking from an avoided lecture hall to a lecture hall of the same size on the same day in a different time slot.
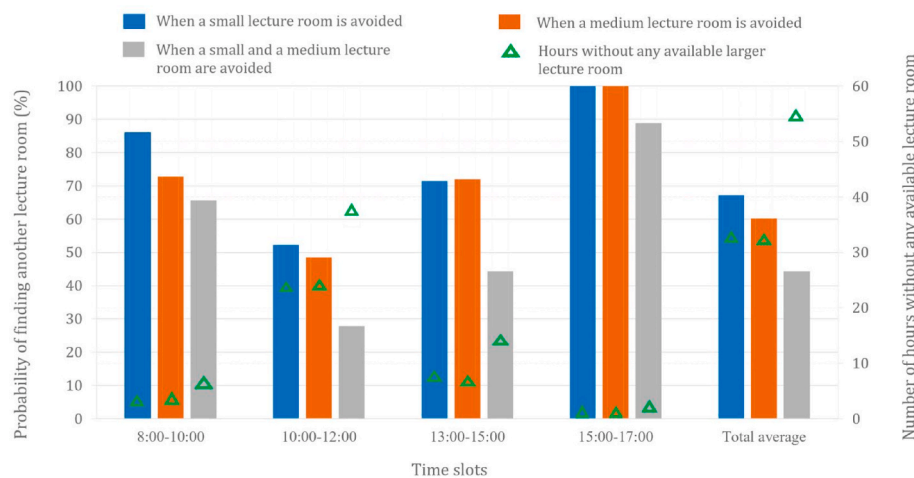

Fig. 9. The possibility to transfer the bookings from an avoided lecture hall to a larger lecture hall at the same time-slot as it was intended.

large lecture hall. This solution was not viable for 31 h during that semester. Even if one small and one medium lecture hall were avoided, there was a 45% chance during the CAB periods that the staff could book a medium lecture hall instead of the small one. Nevertheless, the option was not available in 55 h in that semester.

Repeating the analysis for different time slots shows the room shortage was significantly more likely to happen at "10:00–12:00". During this time slot, there were 23 h that booking the next larger-sized lecture hall was not possible if a small or medium lecture hall was avoided. The shortage was exacerbated when one small and one medium lecture hall were avoided simultaneously with 34 h of unavailable medium lecture hall while all the two small lecture halls were booked. However, the analysis shows this solution is almost always viable during the "15:00–17:00" time slot.

The solution to book a larger room instead of a smaller room has a drawback as it reduces the occupancy density in the lecture halls resulting in the inefficiency of space and energy use. Thus, this solution should be considered as the last option to prevent space shortage. However, considering that this would be the last option that may be required only for a few hours in a semester, the associated disadvantages could be compensated by the gains from avoiding lecture halls.

4.3. Planned occupancy rate (POR)

The possibility to transfer the bookings from the avoided lecture halls to smaller sizes depends on whether or not the staff chooses the optimal size of the lecture halls according to the number of attendees in their event. POR indicates whether the lecture halls are booked optimally for the potential number of attendees. POR is evaluated by

analyzing the booking information of course lectures held in three medium and two large lecture halls, and the results are presented in Fig. 10. POR values in large lecture halls were 60% and 77%, while the values in the medium lecture halls were 69%, 104%, and 78%. A POR value higher than 100% shows the lecture hall on average was booked for more occupants than its capacity. Further investigation shows that even in the lecture halls with POR lower than 100%, there were several bookings for potentially higher occupants than the lecture hall's capacity. The reason could be that the staff who book the lecture halls might know by their experience that a few potential attendees (registered students) would not attend the lectures.

The proportion of oversized bookings in medium lecture halls ranged from 29% to 43%. Further analysis shows that, on average, 34% of
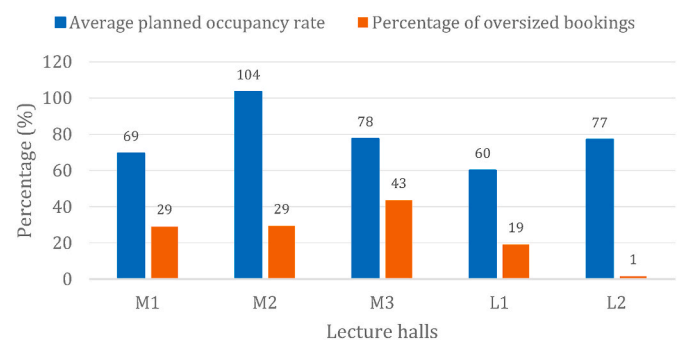

Fig. 10. Planned occupancy rate and proportion of oversized bookings related to the optimal size of lecture halls.

bookings in medium lecture halls were oversized and could be transferred to small lecture halls. The proportions of bookings in large lecture halls that were possible to be transferred to medium lecture halls were 19% and 1%.

POR can provide the number of attendees planned to participate in the events in the lecture halls. A lower value of POR may indicate the potential to increase occupancy density. However, the data required to calculate POR is not usually collected and available in booking systems. In this study, the information on the number of students registered in each course was collected from a different registration system, which could be a time-consuming process as it involves manual cross-checking of the course information. The usability of this indicator depends on the availability of data, which could be collected from the staff during the booking process.

4.4. Maximum possible occupancy rate (MPOR)

Fig. 11 presents the average MPOR values for the investigated lecture halls in the two statuses of "booked-occupied" and "not booked-occupied". The results show this parameter is significantly lower during the periods without booking compared to the booked periods while it seems to be independent of the size of the lecture halls. Average MPOR in different lecture halls during booked periods ranged from 55% to 75%, with an average value of 67%. During the periods without booking, the range was from 15% to 28%, with an average value of 22%. Results of MPOR confirms the previously stated assumption that the lecture halls are used inefficiently by a fewer number of occupants during the periods without booking. This indicates the need for interventions for the status "not booked-occupied" that associates with low space efficiency and possible energy waste. From a broader perspective, the results show utilization of space for activities other than what they are intended might be inefficient.

As stated earlier, the data collection method for the calculation of MPOR associates with uncertainties as it is challenging to install the sensors with a perfectly even distribution and without any overlap. To address the uncertainties of MPOR results caused by sensor setups, a brief trial was conducted in one of the lecture halls. The investigation on the accuracy of this indicator was conducted by counting the occupants during a 1-day test in lecture hall S1. The results showed a significant correlation between MPOR and occupancy rate with $r = 0.65$ and $p < 0.01$. This investigation was performed by a low-resolution thermal imaging sensor, which could count the number of occupants. However, since sensor density and the limitations for sensor installation can be a bit different in each lecture hall, comparing MPOR for occupancy density between various lecture halls might be less reliable. Instead, MPOR can be useful for comparing occupancy density during different statuses in an individual lecture hall as the unreliability caused by sensor installation would equally affect the results during different statuses. Nevertheless, improving the precision of MPOR and its correlation with

occupancy rate requires further research.

Multiple PIR sensors required to calculate MPOR can potentially provide further information on the distribution of occupants in space. However, the usability of MPOR in more sensitive applications such as occupant-based ventilation requires to set standards for uniformity of sensor installation features such as sensor density.

5. Discussion

In this section, first, the link between the IoT data and the strategies and interventions to improve space use efficiency in universities is discussed. This link is explained by highlighting the usability of proposed space use indicators on revealing the potentials to increase both usage time and occupancy density. We then show the energy saving benefit of one example strategy, which is to reduce m^2 footprint by analyzing the potential energy savings of avoiding redundant lecture halls.

5.1. Strategies for space use efficiency

As previously stated, the main aspects of space use are usage time and occupancy density. Thus the efforts for space use efficiency should lead to an increase in these two without incurring space shortage on university activities. Strategies for space use efficiency and the subsequent interventions should be based on the information of space use obtained from the evaluation of space use indicators. As shown in Fig. 1, leveraging the information obtained by the evaluation of these indicators for space use management requires mapping relevant strategies for effective decision-making. This section provides examples of strategies and practical interventions to improve space use efficiency based on the overarching approach of increasing usage time and occupancy density. The IoT data in the form of space use indicators can reveal the efficiency gaps which allow to prioritize and choose the most effective strategies and interventions among different options. Moreover, the space use indicators can provide feedback on the effectiveness of interventions.

PUS shows a large potential to increase the "booked-occupied" status besides reducing "booked-unoccupied" status in some lecture halls leading to an increase in efficient usage. "Booked-unoccupied" status can be high in some lecture halls reaching even 28% of available time. One reason could be that the booking system does not restrict the bookings which do not follow the standard structure of time slots. For example, if a lecture hall is booked from 9:00 to 11:00, most likely, it would not be used from 08:00 to 09:00 and from 11:00 to 12:00. Besides, the booking expense would be related to the costs of booking two time slots "08:00–10:00" and "10:00–12:00". The thresholds for the time slots should be clearly communicated to prevent the staff from booking two time slots for an event, which might require just one time slot. The staff might sometimes book the lecture halls several months in advance while the event might be canceled for various reasons without notifying the cancellation in the booking system. Communicating the benefits of space use efficiency to the staff might cause a reduction in the proportion of "booked-unoccupied" status. As booking lecture halls incur costs to the affiliated department, the emphasis on the importance of avoiding unnecessary expenses may motivate the staff to be more stringent on notifying the cancellations. It is essential to make the cost-saving visible by presenting relevant information when the staff book the lecture halls. To motivate them to cancel the bookings as early as possible, the refund could be time-dependent so that the later the booking is canceled, the less would be the refund. The booking system could send reminder emails, within a predetermined time before the actual event, to the person who booked the lecture hall and require information if there is any change in the planning. Moreover, the booking system could be enhanced by being integrated with the sensor system. This allows to send alert emails when the lecture halls are booked but not occupied and, as suggested by Ref. [36], cancel the bookings automatically.

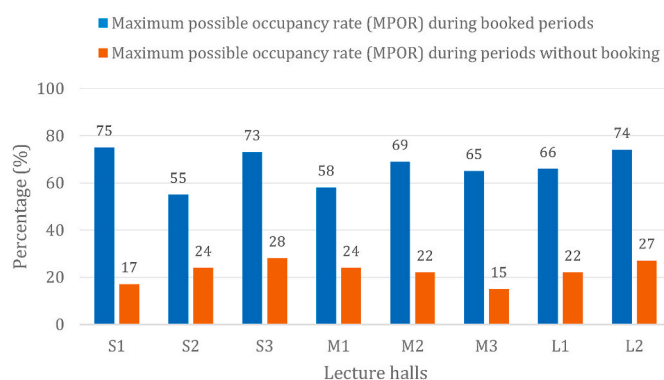The analysis of POR shows the possibility of increasing occupancy

Fig. 11. Average MPOR in the occupied periods of the lecture halls.

density by reducing the booking of the oversize lecture halls. Once again, highlighting the potential resource efficiency (costs and space efficiency) may be one approach to motivate the staff to choose the optimal size of lecture halls for their events. The price difference between different sizes of lecture halls should be visible, while the staff book the lecture halls. However, cost efficiency may not still be a concern for staff without involving them with resource efficiency, e.g., by a budgeting system that limits the spending allowance in the booking system. Instead of billing the booking costs to the affiliated departments, strategies where the staff could receive a limited credit in the booking system based on the budget allocated to their events such as course lectures could be explored.

The booking system should be able to suggest an appropriate available lecture hall based on the number of attendees and the chosen date and time slot. The booking system should provide the best suggestion, in line with space use efficiency, based on the flexibility of selected time slot and date. Optimal allocation in flexible scheduling has been studied in other areas such as flight booking and car-sharing [51,52], while the approaches and methods are applicable for room booking systems at universities. The suggestions made by the booking system could consider more details on efficient energy management when using energy systems with occupant-based control. For example, to take advantage of a pre-heated or pre-cooled lecture hall, the booking system should suggest an empty time slot adjacent to a booked time slot, especially between two booked time slots. Moreover, some teachers might book the lecture halls a long time in advance based on an estimation of the number of students that might register in a course. Discouraging such early bookings cause the choice between the lecture halls to be based on a more realistic number of attendees besides making the competitions on popular bookings (e.g., specific lecture halls or time slots) fair.

PCU can provide insights on the possibility of avoiding lecture hall (s). The energy-saving potential of closing down lecture halls is presented in the next section as an example of the potential benefits associated with space use efficiency. To decide on avoiding the lecture halls, PCU analysis should be followed by further investigations on the availability of alternative bookings for events displaced from the avoided lecture halls. The displaced bookings may be transferred to the less preferred time slots or weekdays. In the existing scenario, before any lecture hall(s) are avoided, the staff has more freedom to choose lecture halls and time-slots. Accordingly, avoiding lecture hall(s) may lead to a perception of space shortage and dissatisfaction among the staff. To reduce such a perception and dissatisfaction among the staff, they should not be forced to choose less preferred time slots. Instead, they may be encouraged to book lecture halls in less preferred time slots by interventions such as highlighting the price difference between the preferred and less preferred time slots. The price difference may be raised to affect the staff to choose time slots that suit their budget, mentioned earlier, for room booking.

The decision to reallocate the lecture halls may both lead to an increase in usage time of space and occupancy density when the lecture halls are utilized for other activities. Decision-making for such an intervention requires investigations to identify the activities demanding more space. Lecture halls can often be easily transformed to study rooms for students or open-plan offices for staff. The need for space for other activities can be identified by a similar approach using IoT tools, for example, by measuring the space use in study rooms that are used by students to study in groups. Such evaluation can be complemented by conducting surveys asking the users on their need and preferences for space.

It is important to note that each of the suggested interventions might affect the effectiveness or viability of other interventions on the efficiency of space use. For example, the intervention for the reduction of uninformed cancellations leads to higher availability of space, thus making it more feasible to avoid lecture hall(s) without causing shortage to hold the events. Combining different strategies and interventions

might lead to the most desirable results. The outcome should be evaluated by measuring the changes in space use tracked by the space use indicators used in the first place to decide on the required interventions.

5.2. Energy-saving potential

Space use efficiency, including the strategies and interventions presented in the earlier section, might reduce the energy use. This section demonstrates the significance of space use management by quantifying the benefit of closing down redundant lecture halls, which is one example of interventions for space use efficiency.

The yearly energy use of the investigated lecture halls, including electricity and heating, were measured to estimate the annual energy-saving potential of closing down the small and medium lecture halls. The electricity use during the year 2019 was measured in six of the lecture halls and was extrapolated based on the room capacity for the lecture halls S1 and M1 (Table 2). As the metering for heating supply was only available for the whole building, the heat supply to the lecture halls are estimated by calculating the average heat supply per m^2 in the case study building. The total heat supplied to the case study building with 26,061 m^2 area was 1659 MWh in 2019; thus, the building had an energy use for space heating and domestic hot water preparation equivalent to 64 kWh/m^2. year. The annual electricity use, heating supply, and total energy use related to the 8 investigated lecture halls in 2019 are estimated to be 19 MWh, 48 MWh, and 67 MWh, respectively. The approximate total energy saving potential of closing down each of the 8 lecture halls is presented in Table 2.

As per the booking records (Fig. 5), lecture hall S1 is a relatively less preferred room in the small-size category and may be considered as the priority to close down. Closing down S1 could lead to a 6% saving on the combined energy use of all the 8 investigated lecture halls. Closing down lecture hall M1 shows higher energy-saving potential as compared to the other medium lecture halls despite being almost similarly preferred for booking by the staff. Closing down M1 could result in 13% savings on the combined energy use of all the 8 lecture halls. If it is decided to close down both of these lecture halls, the potential saving is equivalent to approximately 12 MWh/year that stands for 19% of energy use in the 8 investigated lecture halls. Besides energy savings, closing down redundant lecture halls could play a part in the university's effort to reduce peak demand and the cost savings related to rent and housekeeping.

6. Conclusions

Space use monitoring allows measuring and quantifying real space use, which has been mostly unspecified to universities' facility managers. As the literature in this area is scarce, our conceptual study contributes to recognizing the possibilities, limitations, and requirements to improve space use efficiency using IoT tools. The results of this study imply the potential of IoT to improve the use of space and to facilitate the planning for remodeling or future developments. The study has made efforts to bridge the management and technical aspects of IoT-enabled space use management by demonstrating the process stages in Fig. 1. Analyzing the data from the PIR sensors and the booking system in 8 lecture halls in a building at Umeå University revealed both usage time, and occupancy density can be significantly increased. It is

Table 2

Energy-saving potential of closing down each lecture hall.

Lecture hall	Electricity saving (kWh/year)	Heating energy saving (kWh/year)	Total energy saving potential (kWh/year)
S1	557	3113	3670
S2	464	2304	2769
S3	732	3941	4673
M1	2614	5831	8445
M2	1424	5437	6861
M3	831	5437	6268

estimated for the case study that the intervention to close down redundant lecture halls to improve space use efficiency can result in a 19% reduction of energy use of lecture halls. The collected data from the case study has only local relevance and may not be generalizable to other places however, the proposed methods are applicable to other similar buildings with bookable spaces.

Without measuring space use in lecture halls for an extended time, space management decisions may be uninformed and ineffective. IoT-based smart tools enable enhanced periodic space use reporting that offers vast potential for management interventions to enhance space use management, thus improving energy management. The information generated by smart tools can be used by universities to self-monitor and assist the decision-makers in making informed choices to enhance the effectiveness of resource allocation and environmental sustainability.

Various possible configurations of IoT tools can enable data-driven space use management. The usability of our proposed IoT instrumentation for improvement in space use efficiency is demonstrated in lecture halls in academic buildings. Despite the limited binary outputs (present or not) of PIR sensors, combining the data from multiple PIR sensors with booking information can lead to illustrative information on space use. As pointed by Ref. [53], such a system offers high scalability potential as the configuration allows to deploy new nodes to easily expand the system. Moreover, the feasibility of the proposed solution can be underlined by the relatively low-cost of PIR sensors compared to counting sensors and widely available booking systems at universities.

Such a study was hardly possible without the advancements in IoT technologies that allow generating, transmitting, and handling a large amount of data. However, finding informative indicators to visualize the data might be a challenge to generate information on space use. The focus of this paper is particularly centered on how the data from IoT can be turned into useful information to enhance space use management in lecture halls. A good indicator of space use should be fit-for-purpose, reproducible, easy to obtain, comparable, quantitative, accessible, actionable, and unbiased [34]. The four introduced space use indicators enable evaluating the changes in space use resulted from various interventions. Further, these indicators can be used as objective functions for mathematical optimization in future studies. Such studies are also important for the evaluation of interlinked effects of interventions to improve space use efficiency, which might be difficult to predict. This allows finding the right balance for various interventions that otherwise require several iterations and evaluations. Besides, future studies examining the accuracy and reliability of data from the sensing systems would allow conducting sensitivity analysis on the results of space use indicators. This becomes more important in the spaces with limitations on sensor installation, such as large lecture halls with high ceilings, which deteriorates sensor accuracy due to higher distance between sensors and occupants. PIR sensors used in such spaces might require a higher range of detection or require setting up ceiling structures to reduce the distance to occupants, which could significantly increase the costs.

As suggested by Ref. [7], to avoid a shortage of space for academic activates resulted from space use management interventions, it is better to wait until a smart tool is implemented for an extended time. Due to limitations in this study, the duration of the data collection period was short, and the number of investigated lecture halls as compared to the available lecture halls was small. However, the main objective of this study is to provide methodological guidance and, based on that, demonstrates the usability of IoT tools for space use efficiency. The practical implementation of approaches presented in this study should investigate a larger share of the available lecture halls so that the measurements and evaluations would be more reliable. This is especially important for some of the space use indicators such as PCU, which aims to provide insights about space use in lecture halls in relation to each other. Further studies should follow space use indicators after the implementation of interventions and investigate the perceptions and preferences of different stakeholders such as staff and students on using the lecture halls.

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