Hidden Presence: Sensing Occupancy and Extracting Value from Occupancy Data

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Abstract. In this paper we review various technical architectures for sensing occupancy in commercial real estate spaces and discuss the potential benefits of applications that could be built upon the collected data. The technical capabilities reviewed range from simple presence detection to identifying individual workers and relating those semantically to jobs, teams, processes or other elements of the business. The volume and richness of accumulated data varies accordingly allowing the development of a range of occupancy monitoring applications that could bring multiple benefits to an organization. We find that overall occupancy-based applications are underappreciated in the Smart Buildings mantra due to occupancy's inability to align to traditional building engineering silos, a lack of common view between stakeholders with respect to what is 'value' and the current client assessment tendencies which use predominantly demonstrator-based logic rather than a combination of practical demonstrators and theoretical value. We demonstrate that in commercial office buildings, occupancy-based Smart Building concepts have the potential to deliver benefits that can be orders of magnitude greater than current practice associated with silos such as energy and lighting. The directness of value in these is far more variable however, and the barriers and enablers to its realization are non-trivial. We identify and discuss these factors (including privacy, perceived additional capital expenditure, retrofitting requirements etc.) in more detail and relate them to stages of design and delivery of the built environment. We conclude that, on the presumption costs of development and implementation are relatively similar, the value streams of occupancy-based systems, while requiring more careful and bespoke design in the short term, could produce greater lifetime value in commercial office scenarios than leading smart building technologies.

Keywords: Smart built environments · Occupancy detection

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1 A Quiet Digital Revolution Transforming the Built Environment

The optimization of urban spaces and resources has become increasingly challenging since the rapid globalization and urbanization that took place in late 20th Century, causing a tremendous transformation in cities' economy, environment and society. Since then, cities have become very powerful drivers of environmental problems [1, 2] at the local, regional and global scales.

Buildings are expensive both in financial (operational costs, real estate) and environmental (climate change, green-house emissions) terms. The built urban environment is responsible for the enormous consumption of energy and natural resources, being responsible for 68–80 % of all energy consumption and greenhouse-gas emissions in the world [3]. The US Department of Energy estimates that buildings consume 70 % of the electricity in the US [4].

Businesses seek to reduce the operational costs of buildings, transforming them into a more efficient and sustainable infrastructure. Often, buildings have multiple technology systems, possibly upward of 14 or 15 [5], and typically may have over 250 sensors going into the building management system (BMS), SCADA, and Element Management System. Nonetheless, these component systems of buildings have evolved and operated through many different paths, often separately. This scenario is clearly not optimal as one component system depends upon the other. For instance, the access control system may block the access of a particular part of the building because the fire alarm on that area was raised.

The integration of a building's component systems facilitate communication of data among systems therefore optimizing the operation and maintenance of the physical environment. In order to reduce costs, interconnect activities, and integrate systems, buildings have increased their reliance on automated machine-to-machine (M2M) interactions [5]. Such an integrated and intelligent environment has formed the basis for the concept of Smart Buildings. The term Smart Buildings covers the technologies of advanced and integrated systems for building automation, life safety and telecommunication systems.

The IoT is one of the key components in building automation systems, as buildings can be instrumented and interconnected using modern digital technologies (e.g. sensors, actuators, etc.), and often wireless communication technologies, providing information about the state and health of the physical infrastructure of buildings. This enables efficient monitoring of resources and prompt reaction to unpredicted situations. For example, pumps and motors in elevators can monitor safety limits in order to avoid damaging their infrastructure or harm their users. Energy, water, oil or gas meters can measure energy consumption in much more detail than conventional meters, offer two-way, near or real-time, information transmission between the customer and the authorized parties (e.g. utility providers, service operators, etc.).

Recent efforts have focused on making buildings more energy efficient, including research that target specific areas such as HVAC [6, 7], lighting [8] and managing IT energy consumption [9, 10] within buildings, and IoT [e.g. 7, 9, 14–18]. Most IoT solutions rely on wireless sensors network and the use of temperature sensors, air conditioning and passive infrared (PIR) technologies. In the next section we review some approaches used to detect occupancy in smart buildings. Although definitions and interpretations are of course highly varied, a building that harnesses the increased connectivity of the IoT and the increased data prevalence of big data, can be said to be a Smart Building.

2 Occupancy and Presence Detection

2.1 Occupancy Definition

In this paper we define occupancy as the combination of: (a.) the detection of presence, (b.) associated with a special context (e.g. space or activity) and (c.) associated with a time context, combined to create occupancy data. There is of course variation in the nature of occupancy depending on exactly how these three criteria are fulfilled.

Variations in the nature of (b.) and (c.) are typically one dimensional and generally result in changes in data resolution. The first point however has considerable room for multi-dimensional variation. This is far more significant, and affects what we will describe as the 'richness' of the data, demonstrated in Fig. 1.

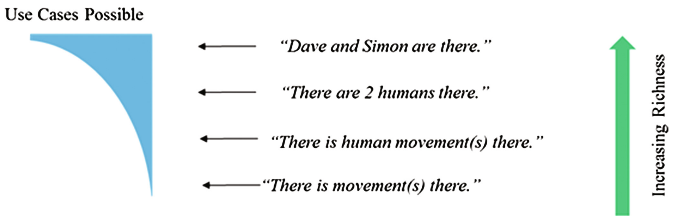

Fig. 1. Variation in richness of occupancy data.

While variation of space and time may indeed affect the performance of a use case, variation in actual presence determines, in a very binary manner, what use cases are and what use cases are not possible.

2.2 Occupancy Use-Cases

In this section we will explore a range of Smart Building use cases that harness occupancy data, spanning form those relatively understood to the most contemporary. We shall categorise these into the themes of Office Resource Management, User Experience, Analytics and Building Management.

Office Resource Management (desk allocation). Under this set we classify systems that manage non-territorial working (i.e. not firmly allocated desks per person) and distribute spare desks to arriving members of the work force. Particularly Intelligent Hot Desking Systems that undertake the above process, but with improved allocation of desks based on criteria of additional data sources, including environmental conditions, noise levels, work themes of adjacent employees, desk configuration and so on.

Analytics and Insight Development. This category includes instances of insight building through analysis and visualization of relevant data. In particular we identify:

- Desk Heat Maps– Displaying utilization of individual desks in an office;
- Origin/Destination Staff Maps– Displaying relative frequency of various internal trips of specific staff groups.
- Energy Benchmarking– developing meaningful insights on energy use.
- Real Estate Utilization Strategic Analytics– Scenario analysis for exploring reconfigurations of a staff group's location and real estate use, and expansion/consolidation of the real estate portfolio itself, both now and in varying incarnations of the future.

Building Management

- Meeting Room Management– Understanding the relationship between meeting room bookings and actual utilization, as well as suitability of meeting room configuration to use types.
- Guest Management– Improving the expectation of, greeting of and monitoring of external visitors.
- Deductive Security– Comparing automated visual recognition of individuals with the absence of the individual's ID presence data to deduce intruders.

User Experience

- Users Specific Signage – Displaying specific information or graphics on a screen depending on those in proximity.
- Geolocating Events –provide information on open, close-proximity events based on a series of predefined interests.
- Geolocating Individuals –provide locational information on individuals.
- Room User Recognition – customisation a room's setup and building services based on predefined preferences of a specific person for a specific type of room activity.

All of the above are overviewed by relative characteristics, as seen in Fig. 2.

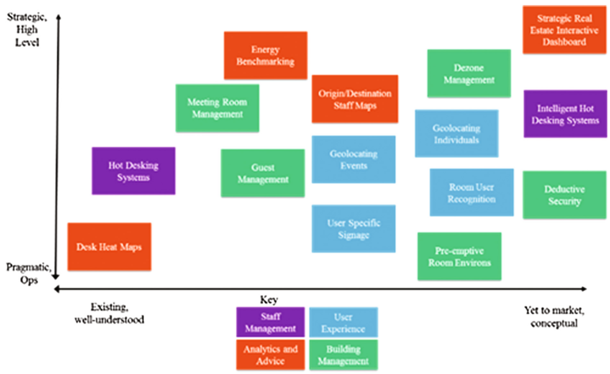

Fig. 2. A portfolio of occupancy use-cases.

3 Technologies for Occupancy Detection in Smart Buildings

Using occupancy as a driver for intelligent control of smart buildings has been increasingly investigated. Most research on occupancy detection within smart buildings focuses on the use of occupancy data to optimize energy consumption. For in-stance previous research on HVAC control systems shows that occupancy information can be used to drive a more optimized HVAC schedule [11, 12]. However, due to the difficulty in obtaining real time accurate occupancy data, many of these techniques focus on using pre-determined schedules.

The advent of low-cost wireless sensor networks has enabled wider deployment opportunities of a large number of connected sensors [13] thus allowing for improved sensing (such as occupancy detection) in buildings. Many modern buildings use passive infrared sensors (PIR) to drive lighting control and detect movement/presence of people inside rooms. PRI technologies relies on "line of sight" coverage to detect occupancy by sensing the difference in between the background space and the heat emitted by humans in motion. The current trends involve using sensor data fusion in order to gather richer details about the environment and the occupants.

For demand response HVAC control, occupancy detection needs to be accurate, reliable, and able to capture occupancy changes in real time. Estrin et al. [7] the use of microphones and PIR sensors to drive more efficient scheduling of conference rooms has been investigated. They have built a wireless sensor network to gathered data from air conditioning, temperature and microphone to estimate the utilization of conference rooms and to calculate the wastage of electricity. The test bed was developed using off-the shelf wireless sensor platform (micaZ) of crossbow. Using their solution – iSense - the WSN based conference room management solution the utility of conference room can be increased from 67 % to 90 %.

Padmanabh et al. [14] used PIR based wireless occupancy sensors to measure wasted energy in lighting even when there are no occupants [8]. They have implemented a wireless tool called LightWiSe (LIGHTting evaluation through WIreless SEnsors), which collect data from light sensors that are placed on used surfaces (desk, wall) to determine a comprehensive model of the perceived light level in the office. The authors claim that LightWiSe can highlight savings in the region of 50 % to 70 % that are achievable through optimizing the current control system or installing an alternative.

Delaney et al. [9] proposes modelling occupancy data using linear regression models. This approach involved collecting data from lighting and electrical loads, and occupancy data is estimated using a walkthrough survey of the building. This set of data were used as an input for the linear regression model which estimated occupancy for weekdays, weekends and holidays. The key limitation of this approach is to rely on energy usage to estimate if someone is present as in the case a large group of people is using a particular room, there will be no additional energy loads in the system and the model may report the room is empty.

Abushakra and Claridge [15], utilize a deployment of PIR and door sensors to obtain a binary indication of occupancy. They use a reactive strategy that adjusts the temperature based on current occupancy and estimate potential savings EnergyPlus.

Using this occupancy information as input to a simulation model of a building, they claim that the HVAC energy consumption can in fact be reduced from 10 % to 15 % using EnergyPlus. This approaches neglects the time required for a room to be brought to temperature and the impact of ventilation on energy savings.

Agarwal et al. [16] propose using a belief network for occupancy detection within buildings. By evaluating multiple sensory inputs (PIR and telephone on/off hook sensors) using a Markov Chain and an agent-based model, they determine the probability that a particular area is occupied. Markov Chain uses a transition matrix probabilities which are calculated by examining the exponential distribution of the sojourn times of the observed states. While these strategies are more suitable for predictive demand control strategies, they are are aimed for modeling occupancy for individual offices and cannot be applied to spaces with larger occupancies.

Dodier et al. [17] proposes a solution to provide input to a control strategy for energy savings in office buildings thought indoor activity recognition by using simple sensors (infrared, pressure and acoustic). Marchiori et al. [18] proposes a occupancy solution which uses a PIR sensor inside the room and one door sensor (magnetic reed switch). Nguyen and Aiello [19] use pressure pads to measure whether the user is sitting or lying on the bed as well as sitting on the desk chair, while collecting computer-related activities of the user.

Other approaches focus on using user's preference data to manage buildings consumption. For instance, Hagras et al. [20] proposes a solution to optimize the tradeoff between meeting user comfort and reduction in operation cost by reducing energy usage. Singhvi et al. [21] propose a smart building architecture that keeps track of workers' real-time location in an office and retrieve their personal preferences of lighting, cooling, and heating. Erickson et al. [23] proposes a smart building system using PIR sensing alongside algorithms supporting user profiles to determine occupancy within a smart building. The advantages of passive infrared are that they are highly resistant to false triggering, relatively inexpensive, and do not radiate any. However, they are strictly for line of sight use, and cannot see around objects, and doors, stairways and partitions have a tendency to block motion detection and reduce effectiveness.

More advanced systems for occupancy detection involves the use of cameras and computer vision algorithms. For instance, Chen et al. [22] proposed a wireless camera sensor network to determine real-time occupancy across a larger area in a building, which gathers floor-level traces of human mobility patterns in buildings. As proof of concept, they deployed a 16-node wireless camera sensor network in a multi-function building to determine the occupancy resolution. Erickson et al. [23] proposes a sonar based technique to detect the presence of computer users. This approach relies on sonar using hardware that already exists on commodity laptop computers and other electronic devices. The authors report that it is possible to detect the presence or absence of users with near perfect accuracy after only ten seconds of measurement. However, such solutions bring up concerns relating to cost, deployment and privacy issues.

CO2-based occupancy detection has also been examined. Barbato et al. [24] pro-poses a solution to estimate actual occupancy in indoor spaces by measuring the carbon dioxide concentration of the return air and the outdoor air flow rate. Wang and chin [26] developed an algorithm based on the mass balance equation of the carbon dioxide in rooms and delivers occupants presence profiles. To evaluate the algorithm, a presence matching index (PM index) and an occupants matching index (OM index) have been introduced. Nevertheless, CO2 buildup is slow and the sensors may take a long time to detect high levels of CO2.

Intelligent Systems have also been used to detect occupancy in buildings. For in-stance, Hagras [20] have proposed a fuzzy expert system to learn user's preferences and to predict their needs with regards lighting intensity, temperature. The system is self-adjust its behavior when users change their habits is proposed the system. Mozer [28] applies neural networks to create a system able to optimally controlling temperature, light, ventilation and water heating within buildings based on data collected from inside the building environment.

Despite these efforts, less attention has been paid in detecting occupancy for desk usage optimization within smart buildings. Workspace management is among the most discussed subjects of facility managers, as growing cost pressures drive organizations to uncover under-utilized facilities and significantly reduce occupancy costs by downsizing and associating real estate portfolios. The current approaches used in previous work are also applicable in the workspace management scenarios, and people involved in the planning and management of buildings must innovate new ways to use the component pieces that already exists to study of how well the workstations, offices and meeting rooms are used over time within the corporate space.

4 Occupancy Value Analysis

The value types that underlie occupancy data are broadly related to the realm of smart buildings and span many stakeholder perceptions. These have been identified through relevant literature (e.g. [16, 29, 30] etc.) broken down further and can be seen in more detail Fig. 3. Identified value types have no universal equity or ranking, and different building design clients will favour them differently. For the purposes of this paper, we will exclusively examine the financial benefit of the examined use cases. To this end, we will use the commercial tenant's end profitability as the fundamental metric. Working backwards from this, we will use a traditional business metric of *profit* being decomposed as:

$$profit = (price\ of\ service/good * volume\ of\ sales) - (fixed\ costs + variable\ costs) \tag{1}$$

To translate the outcomes of a specific use case to a series of consequences that map as variables to formula (1), it is necessary to create a basic framework to understand the possible paths involved in the value calculations. The purpose of this framework is to create broad estimations of value, whilst taking note of confidence levels in estimation along the way. It is designed to neither be exhaustive nor rigid, but to simply categorize immediate consequences of a use case, and direct the calculation process to the final financial figure.

Due to the primarily order-of-magnitude nature of these estimates, we will rate the accuracy of estimates on a qualitative scale. This will span from 1, which is accurate to

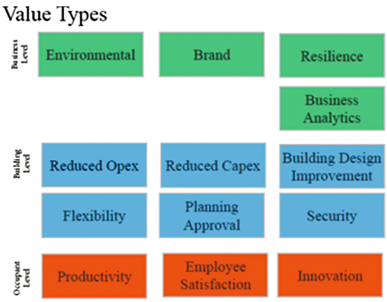

Fig. 3. Types of value cases in the smart built environment.

less than or equal to 2 orders of magnitude accuracy, to 10, with accuracy equal to, or better than, ±10 % accuracy, with a logarithmic scale spanning between each.

While we aspire to create a currency of value that is equivalent across all concepts, this ideal is of course not what is realized in practice. Not all values are equally realizable. Rather than attempt to quantify how easy-to or hard-to materialize value affects its utility, we will simply categorize any estimated value into the following categories:

Immediate Savings - These are costs for something that is on a quantity or time-basis, and as such can be easily renegotiated to suit a new, better requirement. An example of this is the reduction in electricity used to power a building; the costs can easily be realized in liquid terms at the next monthly billing date.

Intermediate Savings - These are costs for something that is on a quantity or time-basis, and as such can be renegotiated to suit a new, better requirement, albeit considerable barriers to change stand in the way. An example of this is relocating a particular business team to a different part of a company's real estate portfolio.

Capacitive Conditional - These are savings in kind that can be reused to create value elsewhere, dependent heavily on the state of other factors in the organization. An example is a time saving of middle-ranking employee hours; these could be used to work on new client work, but only if more client work exists to work on.

Capacitive Unconditional - These are savings in kind that can be reused to create value elsewhere, regardless of other conditions. An example is the saving of time of a business development employee; time savings could be reinvested in what can be assumed to be an incompletable task.

Quality Gains - This is an improvement in the quality of a product or service, without specifically creating it in a shorter period of time. An example of this is being able to charge more for a service due to an increase in its quality due to more empowered staff.

Work Volume Gains - These are value gains similar to Quality Gains, but rather than allowing you to gain more per unit for a service or product that you offer, you are able to take a larger market share. An example of this is a concept that allows you to ensure

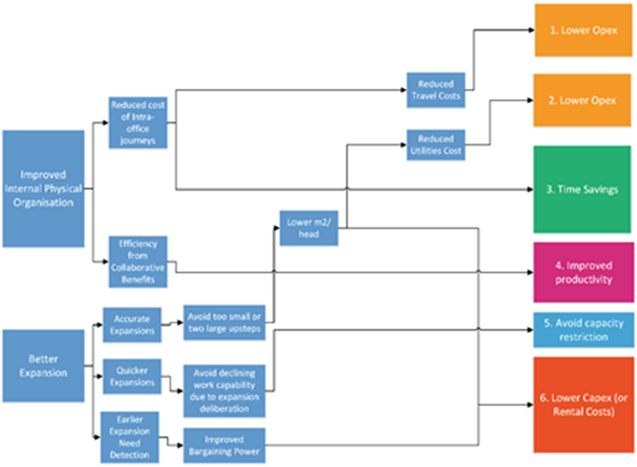

Fig. 4. Occupancy data value chain and calculation paths.

water-tight client confidentiality, thus improving client retention. The distinction here is that capacity to undertake the work is required before the value can be obtained Fig. 4.

For our scenario analysis we use the assumptions of Table 1 to explore the specific magnitude of value each instance of occupancy data use-case can realise for an organisation. These are based on figures from state of art reports such as [31, 32].

Table 1. Scenario analysis assumptions.

Staff	*Value*
Employees	200
Average Wage	£ 13.67
Hours/Week	37.5
Weeks/Year	48

Finances	
Yearly Wage Bucket	£4,921,200
Assume Total Overheads	2.5
Assume Profit Margin	0.15
Assume Revenue	£17,962,380

Office Dimensions	
Desk area per capita	$15m^2$
Small Meeting Room Area	61 m^2
…of quantity	3
Medium Meeting Room Area	84 m^2
…of quantity	2
Large Meeting Room Area	137 m^2
…of quantity	1
Area Total	3488 m^2

Building-Specific Costs	
Gas £/m2	£ 4.57
Elec £/m2	£ 12.84
Other Space Based Overheads £/m2	£ 5.00
Rent £/m2	£ 102.00
Total £/m2	£ 124.41

We will now examine a sample use case using this logic, namely Room User Recognition. In Fig. 5 we can apply assumptions and numerical values to the chain to arrive at our estimates. The scenario assumptions are derived from real-world second

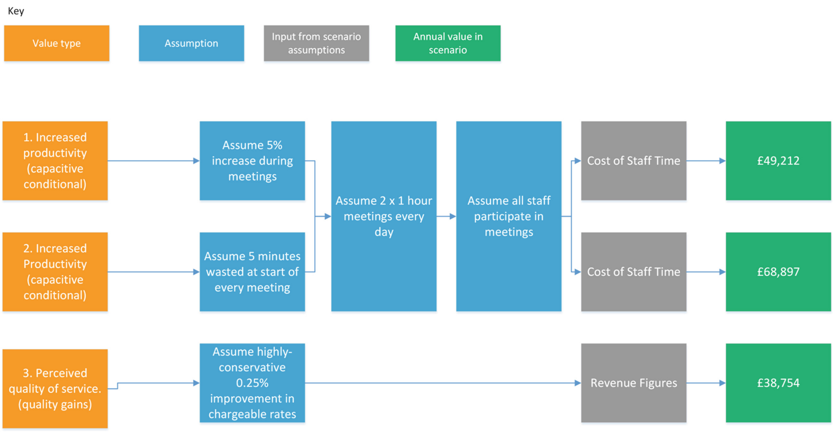

Fig. 5. Computing the benefits of a single use case through its value chain.

hand empirically reported data [31, 32] and the use case assumptions are conservative order-of-magnitude estimates. By computing all of the value chains we arrive at a value of £156,863. Reviewing the confidence level of each individual chain, and weighting this to a confidence level for the entire use case, we arrive at a value of ‘5’ on the qualitative scale, i.e. this is believed to be accurate to 1 order of magnitude.

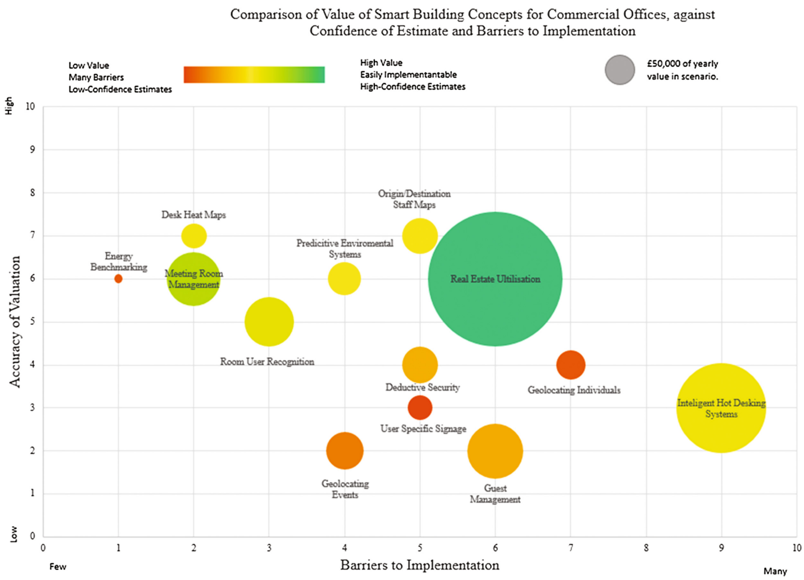

Fig. 6. A mapping of use cases across value perceptions based on value chain analysis.

Using the same method across the use case portfolio, the results of which can be viewed in Fig. 6, it can be observed that there exists no real categorization across the performance of the use cases and their results span different sizes of value. Crucially however, even the most moderately performing ones can be seen to be at least on par with more popular smart building concepts, such as Smart Lighting, which in our scenario would have a benefit of between £6,000 and £10,000 of yearly benefit. It is also important to note that no consideration has been made of value chains here, namely that the pursuit of several of these concepts in parallel may well create synergies in terms of value and shared implementation and infrastructure costs.

5 Discussion and Conclusions

Many of the use cases herein will have varied effectiveness depending on the specific tenant in question. It appears from first instance that the strongest differentiating theme is the value-per-hour the business operates on. This operates in practice by changing the relative value of price increases/time savings vs operating costs, and typically the solidity of working culture and the corresponding willingness to adjust.

As Occupancy-Based systems involve the detection of human movement, and then in turn advise the nature of further movement, additional enablers and barriers are realized over those applicable to current popular Smart Building concepts. A common consideration to all Smart Building markets, there is evidence that building occupants may oppose increased sensing in the workplace, particularly through use case categories that have highly granular datasets – occupancy, for example. This is exacerbated in commercial offices by the complex relationships of employer and employee [30].

Aside from strong employee-employer consultation, the most convincing solution to this thus far appears to be the use of personal IT devices. By having the ability to opt-out, strong objectors to such use cases can be appeased. This also allows selective participation to preserve privacy, activating and deactivating engagement accordingly.

Another common obstacle is the issue of data ownership and interfacing in a con-text where the data has tangible financial data. The relatively segregated stakeholder landscape in commercial offices (tenant, operator, owner) exacerbates this. The legal and business models to answer this vary wildly between use case and exact stakeholder setup and as of yet, there appears to be no overall trends that have emerged.

Increased power devolved to automated IT systems within a building raises the question of whether this presents opportunities to outside hackers to have increased control over the building's systems with risk of breaches that not only undermine the assets within the building, but potentially the safety and welfare of occupants. While there is no immediate reason to suspect that there is a specific risk from this, for many it is a strong physiological barrier and research and evidence will be necessary to win over such stakeholders.

In this paper we focused primarily on the context of new build properties. In reality, the vast majority of building stock in the Western world in 2050 has already been built today. The ability to use these concepts in a retrofit situation has not been fully explored and requires considerable thought.

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