Evaluating the Value of Intelligent Building Systems: A Review and Case Study

by

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Thesis directed by Prof. Gregor P. Henze

The overall goal of this thesis is to provide a high level framework and motivation for intelligent building development by using data available in typical base building systems and finding synergies between these data streams to evaluate questions progressing beyond the traditional building operational metrics. This is done by exploiting a highly underutilized data point in buildings, the occupants, and relating this to the business objectives of tenants, property managers, and other key stakeholders to develop more interesting and valuable key performance indicators.

This framework is then deployed in a living laboratory, commercial office environment in Boulder, CO, to evaluate a portion of the developed metrics using commercially available building systems. These metrics mainly focus on space utilization and energy/power characteristics, but evaluates the effectiveness of grouping them according to the spatial hierarchy of the building and the internal business groups of the tenant.

The most significant contribution of this thesis is to evaluate two means by which energy consumption characteristics can be better evaluated with respect to the actual occupancy and spatial utilization patterns of the building. Since commercial office spaces are designed to be used by people, these methods consider the energy consumption in reference to the actual building occupancy, and are therefore referred to as "Occupancy Normalized Energy". These metrics are a step beyond evaluating the efficiency of a building by looking solely at energy consumption, but provide a basis for evaluating the effective usage of commercial offices.

Dedication

To my parents, Dave and Gisela Mosiman, and my brothers, Pete, Mosi, and Mikey Holloway.

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Without the industry experience, overall vision, and technical guidance of the following people, this project wouldn't have gotten very far. I am very grateful to: Gregor Henze, Herbert Els, and Isaac Chen for giving me a chance on this project, believing in me throughout, and always motivating me to push farther; Aswin Ramakrishnan for sticking with me even when my first question was "Can you help me understand what an API is?"; Ethan Neslund for Mitch Hedberg references; Rachel Kennedy, Ben Weerts, Michael Witecki, Nicole Hammer, Jay Wratten, Ben Stanley, and Joshua Radoff for answering many, many, many questions; Paul Bergquist for answering my first phone call; and all of the industry/academic folks working on making intelligent building applications possible through open source projects like Project Haystack and Brick Schema.

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Introduction

1.1 The Current Landscape of the Smart Buildings Industry

The buildings industry is at a critical point as the hyperbole and promise of the Internet of Things (IoT) to disrupt and revolutionize the way buildings are designed, built, commissioned, operated, maintained, and engaged with increasingly becomes reality. The IoT is defined as "encompassing of the internet networks that connect smart objects, the technologies that make those networks possible, and the applications and services that bring those technologies to the market" [27]. In essence, it consists of gathering data from different sensor technologies and using this data to create value. This is why key stakeholders in the buildings industry are scrambling to unveil the latest and greatest smart building, such as The Edge in Amsterdam, while technology companies are developing sensors, applications, and analysis tools in order to create new value and business opportunities for the built environment. It is an exciting time in the smart buildings industry, but significant challenges still remain.

One of those challenges is the inability/difficulty of integrating separate systems into a holistic solution to truly bring value to the key stakeholders in this space. Oftentimes, IoT solutions/platforms are catered to perform very targeted functions, with many products and solutions having semi-overlapping functions that don't necessarily meet all of a stakeholders needs. Owners, developers, property managers, and other key stakeholders are inundated by different vendors attempting to sell them a solution, oftentimes without the technical expertise required to navigate this landscape and ensure that their business goals are actually met. This inevitably requires these stakeholders to have multiple applications, portals, and user interfaces just to access the information, or to spend exorbitant amounts of money to have a software development company integrate all of these systems (assuming the underlying systems are capable of integrating) into a single front-end application. Moreover, most of the applications are intended for use by facility managers, developers, building owners, operators, and property managers, without targeting other key stakeholders, such as the individual businesses within the space or the building occupants. It is for this reason that this research project was initially undertaken, as described in further detail in Section 1.2.

1.2 Motivation

This research project was driven by WSP USA with the intent of creating a framework for building systems projects, specifically emphasizing the human experience in buildings and how data from buildings should be better utilized in order to quantify and track the objectives of the businesses operating within the buildings. Traditionally, data from buildings is generated and consumed by building systems (mechanical, electrical, etc.), with the primary objectives of maintaining thermal comfort conditions, indoor air quality, and decreasing energy costs. This data is likely only available to the owner/operator of the building, not the tenants or occupants within the space, meaning that many tenants and users have little to no insight into the data being collected about their leased space. Additionally, tenants and users don't understand the potential value of this information for operating their businesses more optimally by evaluating operational performance metrics with actual data in a continuous manner. Moreover, it is difficult for real estate developers to understand the value of providing this data to tenants, often decreasing the likelihood that they will require these systems as part of the base building infrastructure. This is seen as a major gap in the way that building data is used and applications are currently deployed in the building space.

The aim of this thesis is to:

(1) Provide insights into what a smart building is and why businesses should care about them.

(2) Describe the difficulties typically encountered in the procurement of a building that limits the ability of operational data to be used by businesses effectively.

(3) Evaluate why information about the occupants of a building is the most valuable data stream traditionally not used by businesses for evaluating and tracking key performance indicators.

(4) Identify metrics going beyond traditional operational metrics (energy use intensity, predictive maintenance, etc.) to provide *business intelligence* around user behavioral patterns, space utilization, user comfort and well-being, etc.

(5) Evaluate a subset of these metrics in an actual commercial office environment.

In order to achieve this, a living laboratory was set up inside the Boulder, CO office of WSP USA to capture operational data by installing sensors and integrating different commercially available systems into a common data platform.

1.3 Thesis Organization

The remainder of the thesis is organized as follows:

Chapter 2 provides an in-depth literature review around the concept of the smart building. In particular, this review is framed to address Motivation Items 1, 2, and 3 above and convey the importance of going beyond the traditional operational requirements of buildings, to providing tenants and occupants access to building data and input to their environment.

Chapter 3 addresses Motivation Item 4 above and develops different key performance indicators (KPIs) that a commercial office tenant or developer could potentially be interested in. Additionally, this chapter defines the metrics that would allow them to objectively evaluate these KPIs.

Chapter 4 describes the different systems installed in the commercial office space and how these systems were integrated together for the purpose of storing building related time-series data. Additionally, this chapter describes the data models used to represent information in the two different database system architectures in order to allow for meaningful and interesting queries of the data.

Chapter 5 selects a subset of the desired KPIs identified in Chapter 3 for evaluation. It then describes the evaluation techniques and calculation methods used and presents the results of these calculations.

Chapter 6 provides a summary, conclusions, and discusses future work.

Chapter 2

Literature Review

2.1 What is a Smart Building?

Attempting to conceptualize and provide coherent boundaries to a smart building is a difficult challenge, which can mainly be attributed to a few key factors:

(1) The possibility of connecting processes to applications is expanding more rapidly than ever before with IoT devices, enabling vendors to blur the lines of what constitutes a smart building on a rolling basis.

(2) Institutions and researchers make a distinction between buildings being smart, intelligent, sentient, etc., which most people in the industry consider synonymous, leading to more confusion as opposed to coherency.

(3) Smart buildings are marketed extravagantly by different corporations spanning many different verticals, almost always with a slight differentiation in definition, making it difficult to understand if there is a smart, smarter, smartest.

In this conversation, it is important to recognize that there are many different dimensions to a smart building, which is why it is often a confusing concept to navigate. In the following review, no differentiation is made between smart, intelligent, sentient, etc. Both smart and intelligent will be used interchangeably for simplification and clarity. This thesis does not attempt to provide a single coherent definition to a smart building, rather, different views are presented below to highlight key factors encompassing a smart building:

> "In a Smart Building, learning will develop over time through the building systems interpreting data from past usage and adapting, allowing the choices of the occupants to be used for the purpose of creating a higher level of comfort and satisfaction." [18]

> "An important component of an intelligent environment is to anticipate actions of a human inhabitant and then automate them." [44]

> "We define a smart environment as one that is able to acquire and apply knowledge about the environment and its inhabitants in order to improve their experience in that environment." [19]

> "A fundamental agenda ... is to develop highly responsive buildings with ... potentials of automatic control and monitoring towards optimizing ambient intelligent environments while balancing this approach with the human values, well-being, health, and quality of life." [24]

In the above quotes, all of the authors agree on the simple fact that intelligence in the built environment revolves around the ability of that environment to cater well to people. Learning and adaptation, anticipation and automation, knowledge application, responding and optimization - all specifically focused on people, namely, the occupants. Now, of course, there are other goals of a smart building, but the traditional applications are mainly geared towards the building owners and operators. This is, of course, a logical first step in the development of a smart environment, but they are still not business or occupant oriented.

There is the initial potential to assume the reason that most of the smart applications and platforms developed tailor to operations teams is because of the financial benefits, correct? The return on investment for energy management strategies must be the greatest value add, hence, why so many of the platforms currently deployed for buildings revolve around energy management. As explored in Section 2.2, energy costs in commercial office environments are orders of magnitude smaller than real estate and employee costs.

2.2 Why Smart Building Investment?

The following three sections align strongly with the 3-30-300 Rule™ developed in a report by the World Green Building Council [33]. The report focuses specifically on the concepts of health, well-being, and productivity in commercial office environments, concluding with the business case for why these factors should be highly considered in selection of a tenant space for rent. While it is by no means an accurate representation of the total cost of ownership (TCO) for all businesses, it provides a solid framework for understanding the magnitude of the annual operating expenses of a typical business, where $3/sf-year is typically spent on utility costs (energy), $30/sf-year on rent (real estate), and $300/sf-year on payroll (people) [33]. Put another way, about 1% of typical operating expenses are spent on energy, 9% are spent on real estate, and the remaining 90% of a business' operating expenses are spent on its people. This of course is highly subject to location, leasing structure, and business type, but it completely shatters the above notion that the highest return on investment is achieved through energy management techniques. A 10% reduction in utility costs only amounts to a 0.1% decrease in overall costs, whereas a 10% reduction in real estate costs equates to a 1% decrease in overall costs. Boosting productivity, while not a reduction in cost but an increase in revenue, has similar scalable attributes. Focusing on decreasing real estate costs and increasing employee productivity through intelligent workspaces is the next frontier for optimizing the operating expenses of a business, and is what a smart building should facilitate.

2.2.1 People

Buildings are human constructs and therefore should be designed, maintained, and operated in a manner that promotes health and comfort [29], thus leading to gains in productivity [33], which is ultimately beneficial to the people and businesses within them.

For instance, air flow rates in commercial office buildings in the U.S. are required to comply with ASHRAE 62.1, which "specifies minimum ventilation rates and other measures for new and existing buildings that are intended to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects" [10]. However, research has shown that doubling ventilation requirements in commercial office buildings from the traditional 20 cfm/person to 40 cfm/person can lead to improved worker performance of up to 8%, equivalent to a $6,500 increase in employee productivity each year, while only increasing annual energy costs by $40/person [35].

Furthermore, it was also identified that an excess of sick building syndrome (SBS) exists in office environments deemed either too hot or too cold [32], providing additional evidence that buildings should be human-centric and promote the well-being of the occupants inside. It is therefore critical that building operations be informed by occupants. This is the crux of a smart building.

Tracking and evaluating human productivity is NOT the focus of this thesis, and the author recognizes the difficulty in actually evaluating human productivity. The studies referenced in the paragraph above, while providing concrete numbers surrounding productivity changes in office workers as indoor environmental paramaters are varied, are not assumed to directly translate to every building or organization. These studies are used to emphasize concepts that seem logical to most people - when people are given more control over their individual environment to customize it to better fit their needs, they are able to do their work more effectively. It is for this reason that the KPIs defined in Tables 3.2 and 3.3 provide analysis metrics around environmental parameters that are known to effect human productivity, without defining how much these parameters are affecting productivity.

2.2.2 Real Estate Efficiency

There are a substantial number of vendor products, solutions, and analysis tools[1] to help companies better understand their real estate portfolios from an objective perspective using occupancy detection. As opposed to survey data recorded on a quarterly, semi-annual, or annual basis, or recorded in preparation for expanding into new real estate, a smart building gives tenants the ability to objectively understand how they use their space at all points in time. This information can then be used to inform and drive their internal real estate strategies. Additionally, building owners can become more informed about how their building is used, providing them with valuable information, such as what areas will likely need capital investments soonest based on high traffic volumes. Focusing on space utilization and real estate efficiency through historical occupancy detection in buildings gives both tenants and the owner/operations team valuable insight into how

[1] Examples include Teem, Condeco, and Enlighted Space

their building is used, allowing them to make well-informed decisions.

For instance, the average desk utilization in the United States is 35%, with peak desk utilization at 61% [13]. According to [39], the average asking rents in Manhattan for February 2018 were $72.74/sf. A business operating in a 10,741 sf space with occupant space requirements of 180 sf/person that is able to increase their desk utilization by 35% has the ability to fit 20 additional employees into the same space, translating to an annual cost savings of $261,864 from avoided real estate expansion costs. This illustrates the importance a smart building plays in the ability of businesses to make well-informed real estate strategy decisions.

2.2.3 Energy

Buildings consume roughly 75% of all electricity produced in the United States, and 50% of all end-use energy [12]. Additionally, nearly 50% of all electricity used in buildings is consumed by HVAC and lighting applications [12]. Commercial energy management systems and residential HVAC systems are often operated according to a static occupancy schedule, regardless of true spatial or temporal utilization patterns, leading to inefficient operation of HVAC and lighting systems. There is significant potential to better automate HVAC and lighting systems, as demonstrated in [14], which achieved 9.54% to 15.73% savings in HVAC electrical energy and 7.59% to 12.85% savings in HVAC thermal energy consumption by switching one of four floors from a static 5:15 am to 10:00 pm HVAC schedule to real-time occupancy scheduling. Beyond automation, upper level building management systems (BMS) have the opportunity to learn from and interpret data to improve building operations.

2.3 What Makes a Smart Building?

Adaptability is at the core of allowing buildings to be able to support people and their activities effectively throughout the building lifespan. Adaptability should be considered within the following categories: physical space, user preferences, and grid requirements.

2.3.1 Adaptation to Changes in Physical Layout

Since the intended lifespan of buildings is often in the range of 50 to 100 years, it is important that buildings designed today are capable of performing well under tenant-improvements and renovations. While the main building may not change substantially, spatial configurations often change (putting up and tearing down of partition walls), leading to exchanging, upgrading, and redesigning of the underlying control components (sensors and their relationships to other subsystems). A smart building should be designed in such a way so that these changes dont hinder the ability of the building to support the people inside. Vendor lock-in is a well-understood concept for clients and building owners, ultimately boiling down to the fact that many current BMS solutions do not provide satisfactory interoperability with other systems, and therefore require only their system components to be used. This can be a major frustration for owners and clients, as the continued successful operation of their building is now dependent on a single vendor, which can lead to exorbitant service costs. Moreover, this has the effects of hampering the ability of the building owner to provide a satisfactory product to his/her tenants, as better products on the market are now incompatible for use in the building. Smart building controls and components should be specified in such a way so that plug and play capabilities are possible, giving operations teams more freedom in product choice to ensure the continued success of their product.

While still early in development and acceptance, efforts such as the IoT Ready Alliance for lighting fixture components, the Open Connectivity Foundation (OCF) for IoT interoperability standards (mainly residential currently), and the BACnet AP Working Group for object oriented representation of BACnet objects are promising initiatives.

2.3.2 Adaptation to User Preferences and Operational Goals

Smart buildings must be able to respond to the preferences of individual users while also considering high-level operational goals. Responding to user preferences is foremost accomplished through the ability of the building to dynamically monitor and control the building subsystems based on the desired control actions of the occupants. Examples of this include smartphone based feedback capabilities[2] , such as changing setpoint temperature, turning on a light with a voice command, lowering the shades, booking a meeting room, or finding a colleague using indoor localization technologies[3] .

Additionally, smart buildings should support high-level operational goals set by owners, tenants, and occupants by learning from, anticipating, and automating specific tasks, such as turning off workstations or lights at the end of the day to meet energy efficiency targets. All stakeholders should be able to monitor their high-level operational goals through standardized access to the building data (energy use, space utilization, etc.) at fine temporal scales, i.e. hours, days, weeks, or months, as opposed to simply monthly or annual access to the data. Access to the data at fine temporal scales allows for tenants and owners to make meaningful strategic adjustments based on initial results, as opposed to waiting a year (or not knowing entirely) to find out that their strategy to decrease overall building energy consumption, in reality, had the opposite effect. Further, as more data becomes available, analytic platforms should be able to monitor the goals set by the individual stakeholders and make suggestions/adjustments without requiring human monitoring of the data.

2.3.3 Adaptation to Grid Requirements

The Buildings-to-Grid Integration initiative [28], [1], from the Department of Energy (DOE) is designed to allow for and promote a transactive, responsive, and resilient energy future. The concept is relatively straightforward: grant grid operators greater situational awareness into the real-time usage and requirements of buildings to allow for demand response, demand side management, load shifting and reshaping, and peak shaving as opposed to conventional resource ramping. Buildings have an especially important role in this strategy, as they consume roughly 75% of all electricity produced in the United States [12]. Using smart buildings as Distributed Energy Resources (DERs)

[2] Pioneering work was done by Comfy

[3] Examples include Infsoft, Senion

or Flexiwatts [20], is simply another form of dynamic monitoring and control of resources within buildings, specifically designed to increase the operational efficiency of utility power generation. This is an increasingly important consideration as greater capacity of renewables come on-line in the global effort to decrease greenhouse gas emissions.

2.4 How are Smart Buildings Procured?

Generally speaking, understanding the why and the what is much simpler than understanding the how of designing, implementing, integrating, and operating a smart building. Many owners/operators are afraid of entering the smart building space due to the complexity of successfully procuring a smart building. The how is difficult due to the high level of coordination required in the design phase, the vast number of technical domains spanned by a building project, the lack of consistent standards and protocols for interoperability and integration, and the lack of semantics for defining the relationships between entities [17]. These are the fundamental issues that must be addressed in the life cycle of the building project, and specifics regarding these domains are explored in the following sections.

2.4.1 Integrated Project Delivery

One of the most critical components in the successful delivery of a smart building project is the coordination of key stakeholders with engineers, architects, and integrators. Understanding the desired key performance indicators (KPI) and associated quantitative metrics to capture the performance of these KPIs, smart building designers and planners can then begin to select the required data endpoints, data granularity, and point level relationships required to achieve these KPIs. They must then consider the individual subsystem architecture (i.e. domain specific systems) and how they will integrate into an overarching system architecture to deliver these KPIs to the individual stakeholders. This requires substantial communication and participation on behalf of the design and integration team. The coordination of MEP, technology, lighting, software applications, integration requirements, and other disciplines is essential for the successful delivery of a smart building.

2.4.2 Integration of Building Subsystems as a Unified Building System

In order to achieve adaptability, building subsystems and services need to communicate with one another, allowing for the building to operate, respond, learn, and anticipate as a single system. This requires substantial coordination of the underlying subsystems, achievable only with the successful interoperability and integration of the following [43]:

- Building automation systems
- Electrical Systems
- HVAC systems
- Lighting systems
- Vertical transportation systems
- Fire protection systems
- Security systems
- Communication systems
- Audio-visual systems
- User applications

While commercially available products such as the JACE-8000 from Tridium [4] and other similar OEM products provide the hardware platform for the integration of different network protocols, and the Niagara Framework [7] enables web-based access and control of end-devices, these are still largely designed for use by building operators and managers for understanding building operation. The system architecture is not designed with occupant-based applications in mind, a fundamental limiting factor in the current development. Recent efforts [21], [42] have sought to provide open source solutions for building operating systems and control platforms, providing a high-level application programming interface (API) to allow for user applications to be built and deployed in a manner more consistent with current software development practices, namely, providing a standardized RESTful interface by which applications can read and write to endpoints. This interface is critical for allowing users to interact with a smart building.

2.4.3 Semantic Consistency

Underlying the successful integration of building subsystems is semantic consistency, allowing for successful machine to machine (M2M) communication and reliable service end points. Standards such as BACnet[4] and Modbus have limited character availability for the description of points, since points can only be described using their names, and names have limited character counts. For that reason, most institutions, vendors, or integrators have their own methodology for capturing and describing point names. Take, for example, the following point name, confRm328Rcpt, taken from an existing building circuit monitor. While it successfully captures a few key features of the point, i.e. spatial (RM328 = Room 328), space type (conf = Conference), and end use (Rcpt = Receptacle), it is still lacking. If this were to be fed up to a portfolio level BMS application, the following features of the data would be unknown: building name, building location, the circuit breaker this point is being monitored from, if this circuit feeds other circuits, etc. Additionally, there could be multiple instances of Room 328 in different buildings, and each point name could also have different units of measurement. For example, the point could be measuring Watts, Kilowatts, VArs, kVArs, kVA, etc., which would require an extension to convey, such as confRm328_W or confRm328_kVA.

This example lends itself well to understanding the importance of semantic consistency, proving how naming conventions such as the above require significant human intervention and do not lend themselves well to large scale projects with thousands or millions of points, nor to successful M2M communication. It is for this reason that multiple attempts at creating metadata schemas, such as Project Haystack [9], Industry Foundation Classes [3], Semantic Sensor Networks [26], BRICK [2], Open Connectivity Foundation [8], and likely other projects have taken shape.

Figure 2.1 shows many of the fundamental relationships that a metadata schema needs in order to allow for a holistic understanding of information. For example, it may be important to know the physical location (where it is located), physical encapsulation (how it relates to other

[4] There is currently a new BACnet working group whose goal is to "develop applications-oriented "interfaces", or "macro objects", to represent various building automation devices such as Chillers, VAVs, RTUs, VFDs, etc." See here for more details.

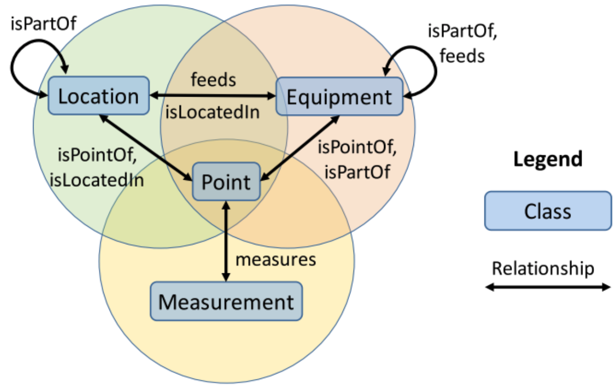


Figure 2.1: Fundamental relationships captured by the BRICK metadata schema [2]

entities, i.e. rooms located on floors), flow between points (electricity flow from meter to circuit, circuit to receptacle, etc.), relationship to other objects (temperature sensor as part of an RTU), relationship to logical constructs (occupancy sensor and daylight sensor used as the control points for lighting level), etc. For a more in depth analysis and explanation, see [9], [15]. While there is currently no single enforced or accepted schema, a smart building requires all disciplines to adhere to an agreed upon schema at the onset of the project and enforce it during the commissioning and integration phase, allowing for vendor-agnostic user applications and analytics engines to be built at the end of the project without substantial manual mapping. This saves additional time and effort when multiple buildings in a real estate portfolio are ported into an application at the end of the project, since the rules engine can be configured to run across specific entity types based on the metadata schema defined.

2.5 The Missing Component: Occupancy Detection

In Section 2.2 the groundwork is laid for why people and businesses should be considered at the core of a smart building design. Moreover, in order to reduce energy consumption, improve real estate efficiency, and increase worker productivity by providing healthier, more comfortable spaces, it is of critical importance to understand the spatial and temporal patterns of occupants within buildings. This section explores occupancy detection, inferencing, and indoor localization, specifically, the nuances of understanding occupancy in buildings and what these nuances mean with respect to the end goal of delivering a smart building.

2.5.1 Dimensionality of Occupancy Detection

As originally proposed in [38], there are three main resolutions to consider when defining and conceptualizing occupancy: temporal, spatial, and occupant. The temporal and spatial resolutions are less nuanced than the occupant resolution, which is explored further in Section 2.6. Figure 2.2 provides a well-formulated visual construct for the different dimensions of occupancy and resolutions within these dimensions.

(1) Temporal resolution: Time span in which the spatial and occupant information is being measured or recorded.

(2) Spatial resolution: Physical granularity of occupancy being measured.

(3) Occupant resolution: To what degree/level is occupancy being measured.

- Occupancy: At least one person
- Count: Exact number of people
- Identity: Who the people are
- Activity: What they are doing

In the majority of buildings with an occupancy detection system, these systems are deployed for lighting controls solutions (PIR sensors) or as security solutions (RFID badges). New applications for indoor wayfinding (Bluetooth beacons) are deployed in very limited contexts, i.e. shopping malls, airports, etc. All of these solutions provide different levels of granularity along each of the occupancy dimensions previously defined, as illustrated in Table 2.1.

Additionally, most commercially deployed solutions focus on explicit occupancy detection solutions as opposed to implicit occupancy detection solutions. Implicit occupancy detection systems

Table 2.1: Sample evaluation of the occupancy resolution of different technologies

Occupancy Dimension	Technology			
	PIR Sensors	RFID Badges	Proximity Sensors	Localization
Occupant	Occupancy	Identity	Identity	Identity
Temporal	Minutes/seconds	Days/hours	Second	Second
Spatial	Room	Building/floor	Room/desk	Coordinate

[38], also referred to as soft sensing [25], [41], or ambient sensing [34] is a novel way to "[extract] occupancy data from systems already in the building [but intended] for other primary purposes" [40]. While a very interesting topic, this thesis doesn't consider implicit occupancy detection systems. The following section is strictly concerned with evaluating explicit occupancy detection systems, i.e. those systems whose primary function is to determine occupancy at some level.

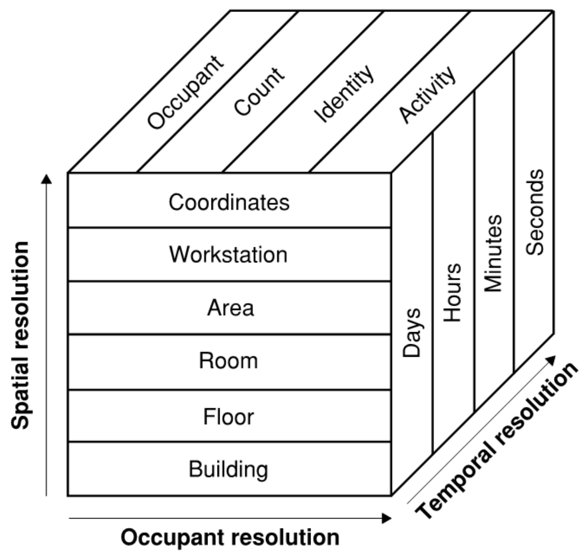


Figure 2.2: Three dimensions of occupancy detection as originally proposed in [38], however, modified to provide higher granularity in the spatial resolution dimension

2.6 Occupancy Detection Technologies

This section is not meant to provide an in-depth exploration of each of the individual technologies, but rather, a higher-level exploration of the potentials of these technologies with respect to the different applications enabled by the varying dimensions of occupancy.

2.6.1 PIR Sensor Evaluation

PIR sensors are typically installed in larger, open office rooms, meaning in many spaces this value is not available. Additionally, while they do monitor at all times, they will often reset a 15-min deadtime counter whenever occupancy is detected. This interval is largely due to the limitations in the technology, which is rather susceptible to false positives or negatives. While they provide average spatial resolution (room) and temporal resolution (minutes), the occupant resolution (occupancy) is simply binary. This is a significant barrier to understanding real-estate efficiencies. For example, if an open office contains desks for 15 workers, and a single worker is there, it is impossible to determine a-posteriori the true number of people that were actually present. Property managers and internal real-estate strategists evaluating space utilization would likely draw false conclusions about the true efficiency of their portfolio using this information. Furthermore, no insight can be obtained as to the utilization characteristics of non-monitored rooms, and PIR sensors dont lend themselves well to providing users with applications for control capabilities, since individual identity and location cannot be reconciled.

2.6.2 RFID Badges Evaluation

RFID badges are often used in access controls solutions, although they can sometimes be deployed in an indoor proximity solution. In the context of access controls solutions, they do provide high occupant resolution (identity). However, this is often only done at the building or floor level, and only upon entrance or exit of a building/floor. Therefore, while the identity of the person is discernible, knowledge of the rooms, desks, or perhaps floors used by the individual is not obtainable, nor for how long the individual resources were used, which lends itself poorly to an understanding of space usage. This data does lend itself well for use by the building owner/operator, for instance, allowing them to adjust mechanical system operations based on arrival/leaving patterns of occupants.

2.6.3 Indoor Proximity Evaluation

The use of indoor proximity sensors is really a byproduct of the difficulty of accurate indoor localization technologies (discussed in the following). Proximity sensors typically measure the Received Signal Strength Indicator (RSSI) strength, or similar radio-frequency measure, between a transceiver (statically placed, such as a WAP) and a receiver (dynamic, typically a mobile device or computer). The system then infers presence/absence, or proximity ranges (i.e. closest, close, far), based on adjustable RSSI cutoff thresholds. This system provides high resolution in the temporal (seconds) and occupant (identity) dimensions. Additionally, since the RSSI cutoff threshold delimiting absence/presence can be selected at different levels for different applications, they can be installed in a dense mesh, leading to desk-level spatial granularity, but could also be distributed on a room or floor basis. Indoor proximity technologies provide opportunities for the development of user applications for feedback and control of spaces. Additionally, they can be used for evaluating real-estate efficiency and for understanding the characteristic usage of space by business groups and even individuals.

2.6.4 Indoor Localization Evaluation

Resolving exact indoor location is an extremely difficult challenge in and of itself and is discussed in great detail in [45]. Key concepts from [45] include the trade-offs that are often made with indoor localization systems. For example, highly accurate systems often rely on a high-density transceiver network and/or battery intensive mobile application, creating high costs of deployment in which the service is under-utilized due to users turning it off in order to retain battery life of their mobile device. On the contrary, less accurate systems are likely equivalent to indoor proximity technologies but could also create a false narrative to real-estate managers if they believe the coordinate information to be accurate. Accurate indoor localization technologies, however, do provide the richest data upon which user applications can be built, and by which real-time feedback is contextually situated in all dimensions of occupancy, allowing for truly autonomous systems to learn from, predict, react to, and automate building operation, expanding the capabilities and opportunities of a truly smart building.

2.7 Literature Review Summary

The above sections provide a logical progression from the reasoning behind why a smart building should be desired, what the fundamental components of a smart building are, and the most important considerations required for the successful implementation of a smart building. Moreover, occupancy detection is explored to provide context for the capabilities and limitations of different occupancy detection technologies with respect to the different dimensions of occupancy illustrated in Figure 2.2. Simple example applications of these technologies for providing information to tenants and occupants were also explored.

In summary, increasing the ability of occupancy detection systems to detect higher resolution data about the building occupants provides the foundation for allowing businesses to evaluate more interesting metrics and users to interact more meaningfully with the building. In the following section, KPIs are developed that may be of interest to businesses, along with the metrics required to evaluate these KPIs.

Chapter 3

Development of Key Performance Indicators

Key Performance Indicators (KPIs) are “a set of quantifiable measures that a company uses to gauge its performance over time. These metrics are used to determine a company’s progress in achieving its strategic and operational goals, and also to compare a company’s finances and performance against other businesses within its industry” [5]. In essence, KPIs are used to measure and track progress in a standardized way to inform an organization of their progress in achieving a desired result.

As an example, say that a campus desires to achieve site Net Zero Energy by 2040, meaning that across its entire portfolio of buildings, the energy consumed on an annual basis is equivalent to the energy produced. The campus would first need to install the metering infrastructure necessary to measure all energy consumption and production, creating a baseline of its portfolio. It now has an annual target net energy reduction goal to track its progress. Then, it would define a strategy or multiple strategies it believes to be most effective in reducing energy consumption and or increasing energy generation and implement these. It is then easy for them to evaluate whether or not they meet their net energy reduction goals on an annual basis, making adjustments as necessary. The KPI would be Net Zero Energy and the metric used to evaluate the success of the campus would be the annual net energy reduction.

KPIs are defined and measured in various ways by different groups within an organization. The director of workplace strategy will have different KPIs than the chief financial officer, additionally different than the KPIs of the director of sustainability. As a start, it is helpful to provide general categories by which to group KPIs. Table 3.1 compares the categories of three popular building standards. Each standard has a differing number of overarching categories, however, they are grouped below to display similarities in the focus of their credits.

Table 3.1: Comparison of WELL v2, LEED v4, and the Living Building Challenge v3.1

WELL v2	**LEED v4**	**Living Building Challenge v3.1**
Materials	Materials	Materials
Water	Water	Water
Community	Sustainable sites Location and transportation Regional impacts	Place Equity
Air Light Movement Thermal comfort Sound Nourishment Mind	Health and human experience	Health and happiness
	Energy	Energy
Innovation	Innovation	
	Integrative thinking Waste	Beauty

While these three standards definitely have different overall goals and ways of adhering to credits[1] , there is a general consensus about what are the most important factors in designing sustainable, healthy, and resilient buildings. While they all recognize the importance of health and experience in some regard, they don't always seem to be well quantified in an operational/ongoing basis to validate the design intents. Moreover, none of them try to directly relate this to the outcomes of a business group. Evaluating the performance of the building is important, but the future of smart buildings lies in the ability to align disparate data streams in order to provide answers to a wide variey of questions. For instance, what if we were able to answer some of the following, more interesting questions:

- What percent of the time are occupied spaces at or above a certain daylight level threshold?

[1] See here for a more in depth comparison of the standards

CO2 level threshold? Temperature threshold? Do certain spaces/space types meet this threshold more often than others?

- Are certain business groups more energy intensive than others? Are certain space types more energy intensive than others?
- We are hiring 20 additional staff over the next 3 years. Do we need to lease more space, what types of spaces do we need, or could we reconfigure our existing space to meet this challenge?
- How do the planned space requirements per person align with the actual utilization?
- Are the sustainability measures that my company has put in place resulting in reduced energy costs? How can I streamline building certifications (LEED, WELL, etc.) with this data?
- What are optimal space conditions for each employee?
- What is the area and energy normalized revenue for my business ($/kWh-sf)? Why are there differences in this number across business groups?
- What is the occupancy normalized energy use intensity?
- Based on last week's/month's energy consumption, what is our predicted EUI and how does this align with our sustainability goals?

With these high level questions in mind, Tables 3.2 and 3.3 provide a list of KPIs and definitions for those KPIs, additionally posing potential business intelligence questions that these metrics could be used to answer. These tables do not present an exhaustive list of KPIs, definitions, and business intelligence questions. They are the result of many conversations over the course of this project with different key stakeholders. The data group categories are generally grouped and targeted to a specific audience of stakeholders and their prescribed goals, summarized in Table 3.4.

Table 3.2: List of key performance indicators focused on understanding spatial performance, employee engagement, and employee satisfaction

Data Group	KPI	Definition	Business Intelligence Questions
Spatial Performance	Collisions and Interactions	The event of two people within 3 ft of each other (1) Level 1: 3 seconds - 5 minutes (2) Level 2: 5 minutes - 20 minutes (3) Level 3: $>$ 20 minutes (4) Collision: $\leq$ 3 seconds	(1) Can we reorganize the space to increase/decrease collisions? (2) Which areas have the highest traffic levels? (3) Which employees are social or non-social? (4) How much time do managers spend with their business groups? (5) Which employees have a proven record of inter-office networking? (6) Which employees should be considered for a managerial role? (7) Which employees enjoy working together? (8) Where do employees spend most of their time interacting with others?
	Adjacencies	(1) Spacial location of internal departments	(1) What departments have a high level of interaction? (2) Should two separate departments with high levels of interaction be moved closer together to increase efficiency?
	Space Utilization	(1) The amount of time a room/area/space is used and by whom	(1) Should floor space be redistributed for different functions? (2) Which business groups use specific space types? (3) What space types are most utilized? (4) What space types are underutilized?
	Desk Utilization	(1) The amount of time a specific desk is occupied	(1) What is the desk utilization rate? (2) Do employees use the same desk or do they switch? (3) Do employees typically sit or stand?
Employee Engagement	Platform Adoption	(1) Number of application downloads	(1) Have employees registered for the application?
	Platform Engagement	(1) Number of times an employee interacts with an application and/or provides user feedback	(1) Are employees using the application? (2) Do certain business groups use the application more than others?
Employee Satisfaction	Employee Satisfaction	(1) Thermal comfort (hot, cold, just right) (2) Acoustical Comfort (loud, quiet, just right) (3) Air Comfort (stuffy, fresh, just right) (4) Light Preference (Natural, artificial) (5) Light Levels (bright, dim, average) (6) Distraction level (high, low, none) (7) Work style preference (private, open office) (8) Overall satisfaction (weighted metric)	(1) What are the optimal space conditions for each employee? (2) Are users becoming more or less satisfied with space? (3) How does employee satisfaction relate to absenteeism? (4) How does employee satisfaction relate to staff turnover? (5) Who should we hotdesk where?

Table 3.3: List of key performance indicators focused on understanding building operations and business metrics

Data Group	**KPI**	**Definition**	**Business Intelligence Questions**
Building Operations	Maintenance Efficiency	(1) The average amount of time required for facilities management to complete a maintenance request with regards to lights, HVAC, circuit breakers, AV equipment, etc.	(1) How quickly is the maintenance department able to fix requests? (2) Are building occupants having their requests filled? (3) Can we streamline maintenance using an analytics engine?
	Indoor Environmental Quality	(1) VOC concentration (2) CO2 concentration (3) Zone temperatures (4) Relative humidity (5) Particulates concentration (6) Lux Levels	(1) Are VOC concentrations too high? (2) How often are space temperatures in the ASHRAE 55comfort zone? (3) Are we complying to RESET/WELL/LEED? (4) Is the building at a risk for mold growth?
	Energy Use Intensity (EUI)	Source or site: (1) kBtu/sf (2) kWh/m2	(1) Are smart buildings less energy intensive than traditional buildings? (2) How does our building energy performance compare to national averages and other standards? (3) Based on the previous weeks energy usage, what is the predicted annual EUI?
	Occupancy Normalized EUI	Source or site: (1) kBtu/sf-%occupancy	(1) How can I relate the energy intensity of my building to the actual occupancy status?
	Water Usage	(1) Water volume	(1) Is this building more water intensive than others in my portfolio? (2) Do certain floors consume more water than others? Why?
	Emissions	(1) Marginal emissions factor (2) Emissions	(1) Are intelligent buildings less carbon intensive than non-intelligent buildings?
Business Metrics	Absenteeism	(1) Number of days of absence due to illness on a weekly, monthly, or annual basis	(1) Are employees healthy? (2) Are employees in a smart building less likely to be sick than employees in other buildings?
	Staff Turnover	(1) Percentage of regular, full time employees leaving employment for a given month, quarter, year	(1) Are employees less likely to leave if working in a smart building than other buildings?
	Area and Energy Normalized Revenue	Revenue per energy consumption per area: (1) $ Revenue/kBtu-sf (2) $ Revenue/kWh-m2	(1) How can we reduce energy intensity without decreasing revenue?
	Employee Normalized Revenue	(1) $ Revenue/employee (2) $ Revenue/business group	(1) What is our revenue/employee trend?

Table 3.4: Characterization of the main stakeholders interested in the different data groups and the overall

Data Group	Stakeholders	Goals
Spatial Performance	Director of real estate strategy Office manager	To understand how real estate is used and strategize on how to use space most effectively.
Employee Engagement	Chief financial officer Director of workplace strategy Chief operations officer	To understand whether employees are using their application and strategize how to increase uptake in order to better understand employees (employee satisfaction).
Employee Satisfaction	Human resources Director of workplace strategy Recruiter Wellness Director	To understand whether employees are satisfied and comfortable, identify the issues directly, and strategize on how to make employees happier and healthier.
Building Operations	Facilities manager Property manager Owner Sustainability director	To understand how the building is performing, identify faults and energy savings opportunities, streamline maintenance, and improve equipment longevity and performance.
Business Metrics	Human resources Business director Chief financial officer Chief executive officer Chief operations officer	To characterize the overall performance of the business and correlate this with the engagement and satisfaction of employees and performance of the building, and identify opportunities to increase overall revenue through cost reduction strategies (i.e. save on real estate or building operations) and/or increase profit (by increasing employee productivity and satisfaction).

These KPIs were written assuming the following key pieces of information would be available:

- Detailed floor plan and space breakdown
- Indoor localization occupancy recorded at the highest spatial and temporal resolutions, with identity level occupancy
- Circuit or receptacle level sub-metering
- Fine spatial distribution of indoor air quality sensors, namely, temperature, relative humidity, CO2, VOC, and particulate matter sensors
- User application with feedback capabilities for each of the Employee Satisfaction metrics

It is important to note that many of the questions in Tables 3.2 and 3.3 can be answered using information available from base building systems, financial statements, and feedback generated by users. Increasing the overall number of data points using a high density multi-sensor mesh grants us the ability to answer the questions with increasing specificity, however, this is not always practical using sensor technology available today. As wireless sensors become increasingly available, however, installing these systems becomes substantially less labor intensive and much more practical to implement. Furthermore, many of these metrics could be calculated with lower resolution data, however, the highly detailed nature of these questions illustrates the power of having extremely rich data sets and the types of questions that become possible to answer.

3.1 A General Framework

Over the past twelve months, we have had the privilege of engaging with a significant number of different stakeholders, ranging from architects to developers to systems integrators. We often come across two main types of people:

(1) Those that want a smart building but do not really understand what that means or why they would want it, other than the fact that they can market it as such.

(2) Those that are wary of the smart building industry because they are currently struggling to design, operate, or manage traditional buildings without the additional complexity.

Asking them what types of questions they would like to be able to answer with a smart building often doesn't lead far. They don't fully understand what a smart building can achieve. However, if we then present them with some visualizations showing space utilization from our office space, for example, they begin to generate questions. Then, explaining to them how the solution works helps demystify the entire IoT and smart building concept. We then often have a lively discussion, exchanging ideas and generating new and interesting questions and potential use cases.

For this reason, it is essential to have a general framework for the procurement of a smart building. A smart building is not a building full of shiny objects, blinking lights, and bit streams. The goal of each project should be to use the available technology in order to measure, quantify, track, report, and adjust the operation of the building to better suit the needs of the tenants and users, as outlined in Section 2.2. Each owner will have a unique set of goals that they are hoping to achieve with a building and issues that they would like to address in this newest iteration that they experienced with their last project. Furthermore, while many of the above KPIs were defined in the context of a commercial office building, different project types and clients will have substantially different goals. Key factors regarding the necessary components for the successful implementation of a smart building project are discussed in Sections 2.4 and 2.5. But the most critical aspect is to develop a strategy by defining the goals, KPIs and associated metrics, systems, and data points required to evaluate the metrics, along with their associated resolution. Figure 3.1 was developed to further illustrate this process.

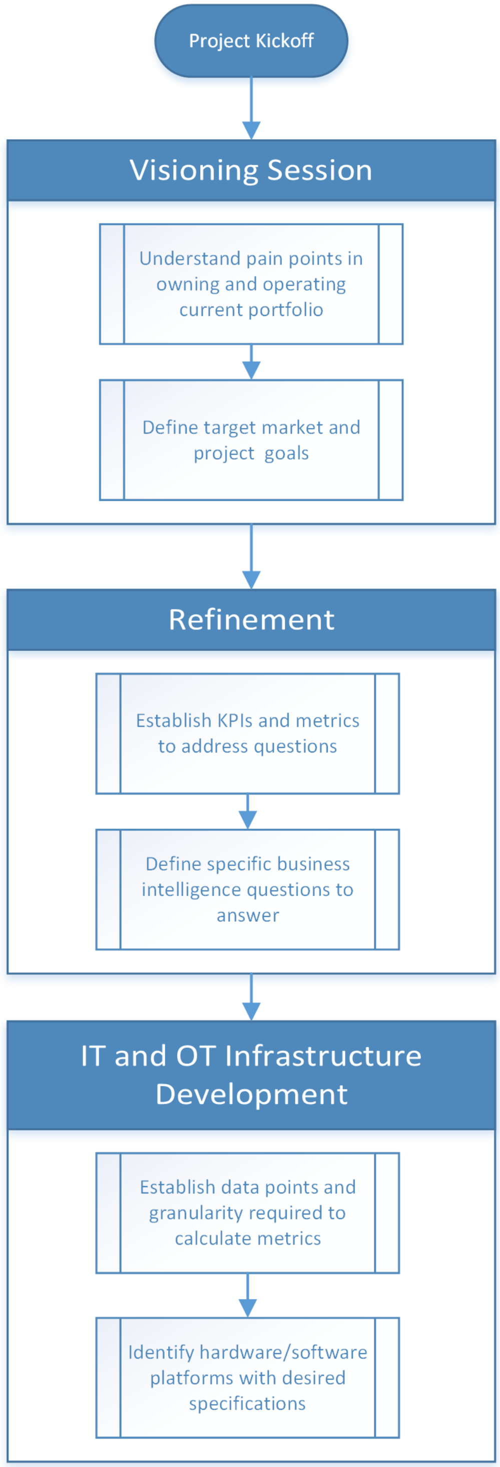
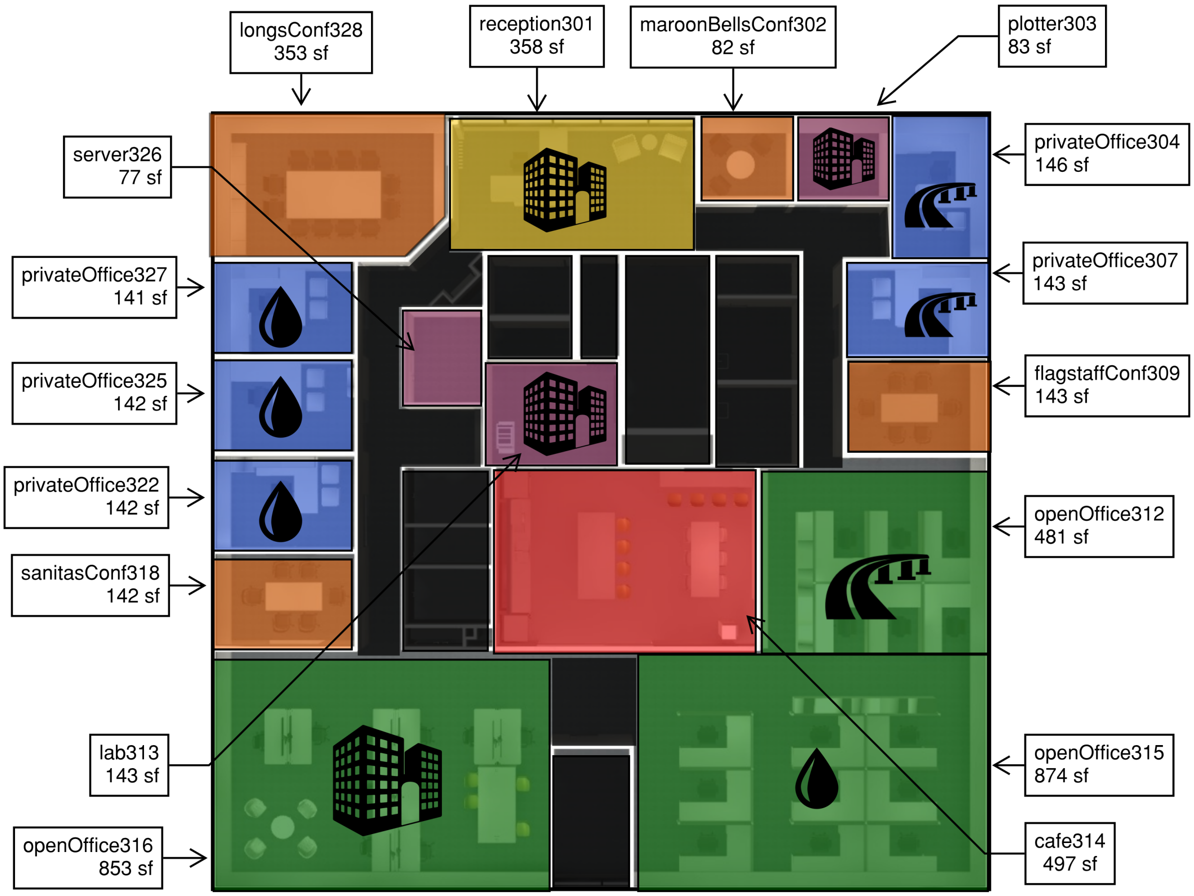


Figure 3.1: Initial visioning process for a smart building project

Chapter 4

Living Laboratory Setup

The WSP USA office space in Boulder, CO has been outfitted with different systems for detecting occupancy, monitoring power consumption, and monitoring indoor environmental conditions. Some of the systems installed in the office space were installed as part of the tenant improvement plan when WSP USA moved into the space in Fall 2016, while others were installed in an ad-hoc fashion for testing purposes. Furthermore, while most systems have their own data model, backend storage, and graphical user interface for data trending and visualization, all of the different systems were integrated and stored in a centralized database to provide a single point for data access. This was originally done in an ad-hoc fashion using many different means for collecting and storing the data in a SQL Server Express database, however, a commercial software platform was eventually deployed. The office space is leased and resides on the third floor of a commercial office building. Figure 4.1 provides a floor plan of the space, broken out by each of the individual spaces, their space type and square footage, and the main business groups residing in each of the spaces.



Space Types	Total Area (sf)
Reception	358
Lab/Server/Plotter	303
Cafe	497
Private Office	714
Open Office	2208
Conference	886
Not Considered	1367
Gross Square Footage	**6333**

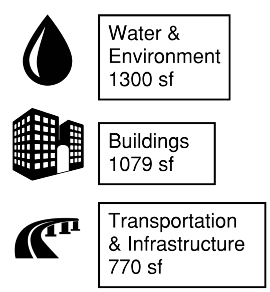


Figure 4.1: Floor plan of the WSP USA office broken out by spaces, space types, area, and business groups

4.1 Sensing Systems

The following sections describe each of the different sensors and systems used for data collection. Table 4.1 is provided at the end as a summary of the different data points collected by each of the systems, and Figure 4.2 provides the layout of the sensor systems in the space.

4.1.1 System A: A Multi-sensor Mesh

System A is typically deployed as part of the lighting control system, where the sensor is mounted into individual lighting fixtures. The sensor is a multi-sensor that measures passive infrared (PIR) occupancy, temperature, ambient light level, and power consumption of the attached lighting fixture (when mounted into individual light fixtures as part of the lighting control system). The standard design is to deploy the sensors on an approximate 10 foot by 10 foot grid, providing occupancy detection at approximately 100 square-foot intervals. For our deployment, the sensors were not installed as part of the lighting control system, but simply as an add-on platform to gather information about the space. 48 sensors were deployed across the approximately 6,400 square-foot office space, with binary level occupancy being recorded at 1 minute intervals.

This system consists of three main components:

(1) Multi-sensors

(2) Gateways

(3) Central server

The multi-sensors are the actual data collection points. When installed as part of the lighting controls solution, power is provided to the sensors via an LED driver connected to the fixture. For our setup, power was provided to the sensors via a 120VAC-12VDC transformer. A gateway is then used to communicate with up to 250 sensors using an IEEE 802.15.4 wireless communication protocol. Although only 48 sensors were used, two gateways were installed in the office space. Power to the gateways is provided over the Ethernet connection (PoE), which is also used to communicate back to the central server. The central server stores data from sensors for up to 36 months, and additionally provides a BACnet/IP interface to the underlying sensors. Additionally, the server provides a RESTful API for data access, however, data can only be accessed for the previous hour using the RESTful interface.

4.1.2 System B: A Digital Access Controls System

System B is a digital access controls system that uses Bluetooth technology for authentication. The system consists of four main components:

(1) Network door controller

(2) Network readers

(3) Electric strikes

(4) Mobile application

The network door controller is a PoE based device that can support up to two network readers per controller. The network readers are connected to the controller via a shielded multi-conductor cable, which is also used to provide/release power to the electric strikes upon proper authentication, enabling the door to open. Users are required to download the mobile application and create an account, which is then used as the access device into the building. While not traditionally used as an occupancy detection system, the Bluetooth readers record multiple different event-types (verify, trigger, range-enter, range-exit) for each mobile device. These events are recorded in a cloud hosted database, and can be accessed via the system's API, which can then be processed to estimate the number of people in the space. For our deployment, a single network controller was installed with two network readers. One of the network readers was installed at the entrance to the floor in the stairwell, while the other was installed at the entrance to the lab space.

4.1.3 System C: A DALI Lighting Control System

System C is a digital addressable lighting interface (DALI) lighting controls system, which assigns a unique static address to each device in the system. The lighting control system was installed during the tenant improvement phase in Fall 2016. The DALI protocol is more commonly found in the European market, but was chosen as a more flexible lighting control solution and to better understand the technology.

The system consists of:

(1) DALI field relay

(2) DALI digital to analog converter (DAC)

(3) DALI LED drivers

(4) DALI dimming modules

(5) DALI wallstations

(6) DALI multi-sensors (daylight and occupancy sensing)

(7) DALI vacancy sensors

(8) DALI powerpack

(9) Fixtures

(10) Lighting control panel (LCP)

(11) Lighting server and management software

The lighting control solution is centrally managed via the lighting server and management software through a web-based interface. The server stores historical data, logs, and configuration files of all downstream devices, providing a central portal to configure the lighting control strategy of the entire system. Additionally, the lighting server provides a BACnet/IP interface to the underlying DALI components to allow for integration with other systems. The LCP provides a network interface from the lighting server to the underlying DALI end devices and is used to control and operate all lighting devices via the DALI protocol. The specifics of the control strategy and the function of each of the devices is not critical to the description of this system. It is important to note, however, that the occupancy sensors for this system are installed on a room level basis and have a wider viewing lens than the more granular occupancy sensors of System A described previously.

4.1.4 System D: A Branch Circuit Monitoring System

System D is an integrated electrical panel and branch circuit monitoring device, which was also installed as part of the tenant improvement phase in Fall 2016. Two electrical panels and branch circuit monitoring devices were installed on the third floor. The meters are able to measure current, real power, apparent power, voltage, frequency, and power factor. The meters provide an embedded web server for configuration of the circuits and display real-time measured values. Moreover, the device provides external communication capabilities via the Modbus TCP/IP communication protocol. It is important to note that these panels only provide power to the third floor lighting, receptacles, hot water unit, and server CRAC unit, but do not feed the base building mechanical equipment.

4.1.5 System E: An Indoor Environmental Quality Monitoring System

System E is typically installed as part of the mechanical system infrastructure. The base building mechanical system consists of two rooftop units and zone thermostats, but did not provide any means by which to collect data about the operations. Therefore, System E was installed in order to collect data about the indoor air quality of the office.

The system consists of the following:

(1) Five temperature and relative humidity sensors

(2) One outdoor temperature and relative humidity sensor

(3) Seven temperature, relative humidity, and CO_2 sensors

(4) One CO_2 and VOC sensor

(5) One controller

(6) Two I/O expansion modules

The two expansion modules are connected to the controller and provide additional I/O capabilities. All indoor sensors are wired back to the controller and provide an analog 0-10V signal, while the outdoor sensor communicates via a 4-20 mA analog signal. The points come online via BACnet/IP through the controller, allowing for external communication to other systems. A software program installed on a virtual machine (VM) on the same subnet as the controller allows for configuration of the points.

4.1.6 Systems Summary

Sections 4.1.1 through 4.1.5 provide a description of each of the individual systems. Table 4.1 provides a summary of each of the different systems installed with respect to the data capture characteristics. Additionally, Figure 4.2 shows each of the individual sensors mapped on top of the floor plan. Note that for System D, the branch circuit meters are inside the electrical closet, which doesn't illustrate the individual circuits. Appendix B includes an electrical plan (Figure B.1) along with Table B.1 to define how the individual circuits were mapped to the spaces. Based on the receptacle placement, circuits are not always cleanly mapped to a single space, and these circuits were included in an "all" section. For the most part, however, receptacle placement and circuits map well to individual spaces.

Table 4.1: Summary table of the individual systems and data points recorded from each

System	**Data Points Recorded**	**Frequency of Data Capture**	**Number of Data Point Groups**[1]
System A	Occupancy Ambient light Temperature	1min	48
System B	Verify event Trigger event Range enter event Range exit event	Each occurrence	2
System C	Occupancy Lighting group power Ambient light	1min	21
System D	Power Energy	1min	79
System E	Temperature Relative humidity CO_2 VOC	5min	14

[1] A data point group is either a physical sensor with multiple points (Systems A, B, E), or a digital abstraction of a group of points (Systems C, D)

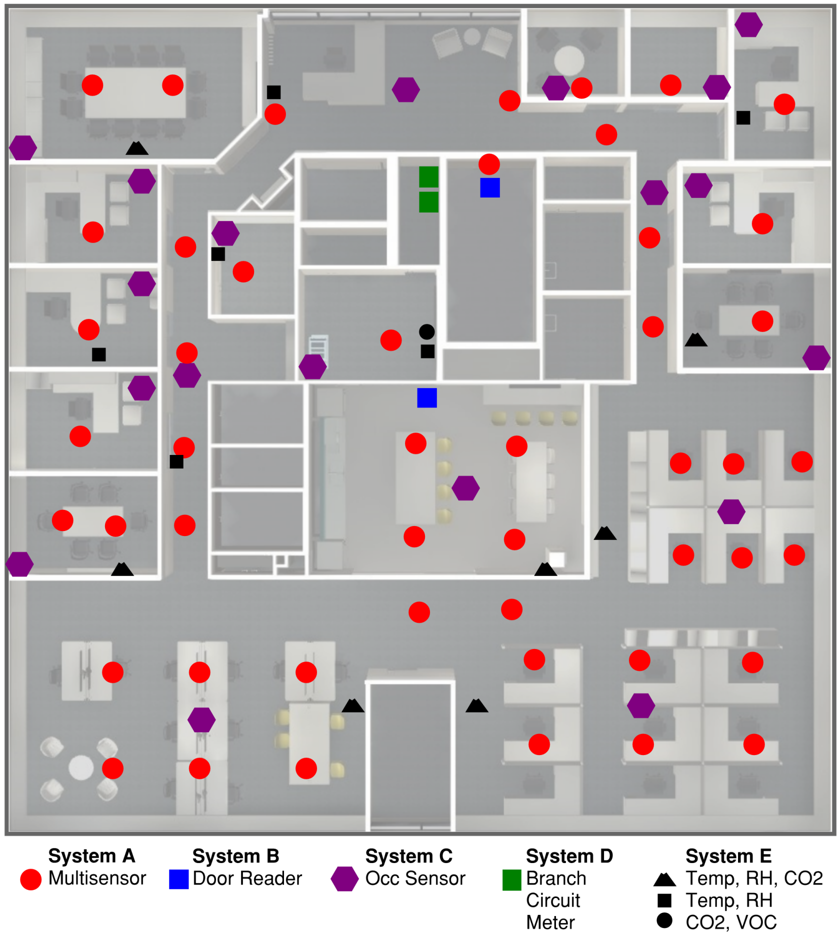


Figure 4.2: Location of sensors in the WSP USA office space

4.2 System Architecture

The installation and commissioning of each of the individual systems was just the initial phase in the creation of the lab. The significantly more difficult part was determining how each of these systems would communicate with a higher level application to record data in a centralized manner, and determining how this data should be represented. This step took the majority of the time and consisted of many numerous iterations. In the end, only one of the architectures proved useful, which is described in the following sections.

4.2.1 Initial Architecture

4.2.1.1 Data Model

A relational data model was initially used in order to capture rich meta-data about the building, its components, and the relationships between them. One of the difficult aspects of a relational model is to define it in such a way as to allow future extensibility without causing data inconsistencies. Making changes to a database schema after information is already stored can be difficult and requires proper planning and migration procedures, a task reserved for professional database administrators. For this project, the relational model was created using a SQL Server Express 2014 database. The model was built in order to capture the different spatial hierarchies of a building project, similar to the spatial resolutions defined in Figure 2.2. Moreover, the hierarchy was conceptually designed to model the `site/equip/point` concept used by Project-Haystack, defined as follows:

- **Site:** single building with its own street address
- **Equip:** physical or logical piece of equipment within a site
- **Point:** sensor, actuator, or setpoint value for an equip

Project-Haystack originally developed from the perspective of the mechanical equipment of the site, in which case the total number of points and granularity required to describe an entire site can be contained within that model. From the mechanical equipment perspective, the model performs rather well. However, as more sensors and data points are introduced into a space, such as capturing occupancy information at a desk level, or tracking location of mobile devices throughout a building, this simple three tier hierarchy breaks down, further explored in [16]. Regardless, an attempt was made to utilize this framework with some modifications. While not all the specific information is included for each table, Figure 4.3 defines the main tables, type groupings, and one-to-many relationships for the initial data model.

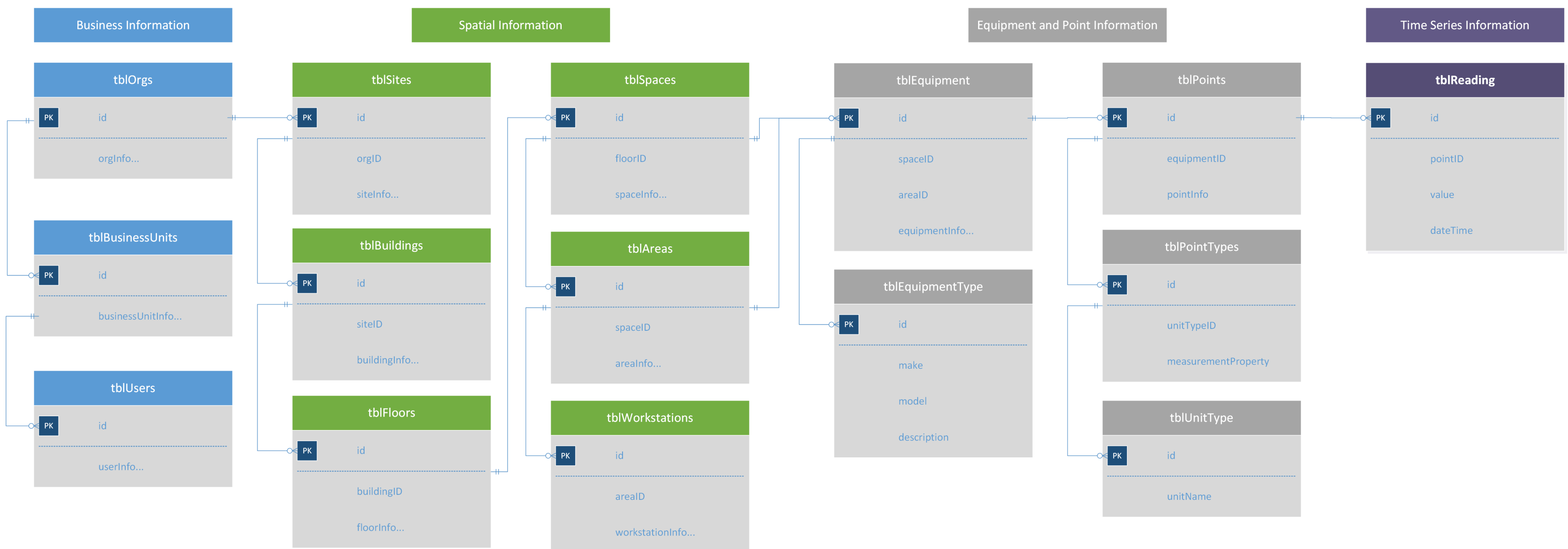


Figure 4.3: Initial data model architecture

The crows foot notation is used in the above data model definition to illustrate one-to-many relationships. An example reading of the above notation, for the building to floors table is as follow: Each building can have many floors, but a floor can only belong to a single building. Equipment is related to a spatial element at an area and floor level. While this allows for granular mapping of equipment to spaces, what if a piece of equipment needs to be related at a building level, or site level? What do we do in the case of mobile equipment? Adding additional foreign key columns in a relational table, while providing more flexibility, requires all potential spatial mappings to exist. Additionally, while we know that a relationship does exist, the relationship type is not made apparent. Is that piece of equipment physically located in the space, is it providing power to that space, is it controlled by a sensor in that space? All of these relationships are very difficult to capture in a relational model, and lend themselves better to a resource description framework (RDF) or graphical model, as used in the Brick Schema.

Similar to the Project-Haystack definition, each piece of equipment is a physical or logical grouping of points, and each point has a specific history associated with it. The equipment will have meta-data associated with it, such as the type, make, model, year installed, etc. Additionally, the point will have meta-data associated with it, such as the property being measured, the units, etc. The readings table basically acts as a time series store, including the date and time of data capture, the value, and the point it is associated with. One of the most limiting aspects of this data model is the fact that all time series information is stored in a single table, which resulted in extremely slow query times.

While the data model did indeed have some limitations, it could have still proved useful. However, ensuring the consistency of this data model with the external systems throughout the data importing and mapping process is what ultimately led to this model being disregarded, as described in the following section.

4.2.1.2 Data Importing

Storing history data from the different systems described in Section 4.1 requires different importing methodologies. In order to store data from a BACnet or Modbus device, a middleware engine needs to be used that has a BACnet or Modbus client, which allows for the data to be captured on a standard time interval. However, an additional step is required in order to map the data from the BACnet or Modbus client into the database. An open source BACnet and Modbus client were used from IoT-DSA in conjunction with a commercially available middleware engine.

In order to capture and store data through a RESTful API, custom scripts need to be written to extract this data, map it to its correct point in the database, and write the history. While this process is a standard skill for software developers creating web applications, this was a substantial road block for the author to collect data.

System A has both a BACnet interface and a RESTful API, however, the BACnet interface does not provide temperature information. Additionally, occupancy information through the API is not available at the individual sensor level, but at what is defined as the area level, which is a spatial grouping of sensors. All data for System B is available through their API. Data for Systems C and E is only available through BACnet, and data for System D is only available through Modbus.

The data import routines for each of the different systems is summarized in Figure 4.4. The items below describe some of the difficulties encountered in maintaining correct, consistent, and reliable data mapping. Each of these difficulties were experienced multiple times throughout the course of the project, and is the reason that Section 2.4 is so important for getting it right the first time and why having standardized data semantics, ontologies, and interfaces in the IoT world is vital for the success of higher level applications. The difficulty encountered in maintaining all of these separate routines is what ultimately led to the abandonment of this system architecture.

(1) Any configuration change at the application level of System A or B would lead to inconsistent data mapping. For instance, a software upgrade on System A required some of the sensors to be recommissioned. Upon recommissioning, some of the IDs changed and

therefore the data mapping did not work.

(2) Systems C, D, and E rely on the Modbus/BACnet client to capture points at specified intervals. If the network goes down or the server goes down at any point, this data is lost and cannot be retrieved.

(3) Since systems C, D, and E are Modbus/BACnet interfaces, these points are initially only described with their point names, which are used to identify them when the data is written to a temporary CSV file. The import script relies on these naming conventions to then map the data to the SQL model. If any of these point names are changed, say by a subcontractor or building operator, the data mapping doesn't work.

(4) Initial configuration of the Modbus/BACnet client to the underlying data points requires significant human intervention, and is prone to fault.

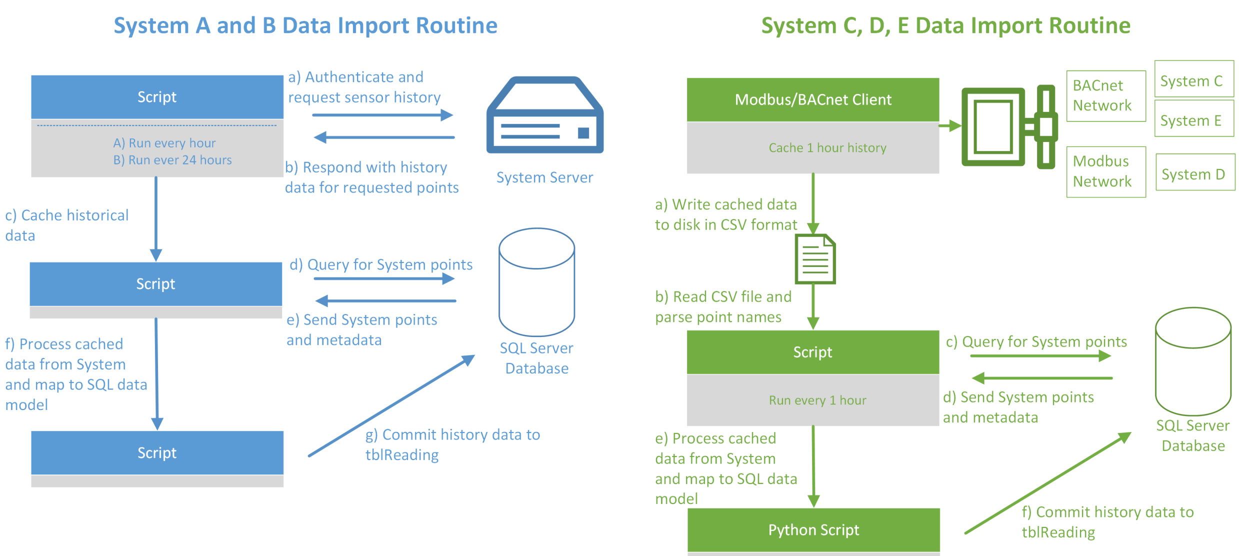


Figure 4.4: Data import routines

4.2.2 Final Architecture

4.2.2.1 Data Model

The final architecture uses a commercial software platform that has built-in drivers for connecting to open source building automation protocols, uses the Project-Haystack data model, has a built in graph oriented and time series database model, and additionally has a built-in query engine with visualization capabilities. Although the standard `site/equip/point` hierarchy is the default setting, this was modified to be `site/floor/[space]/equip/point`, where the `[space]` is an optional parameter in the hierarchy, meaning that an `equip` could be directly assigned to a `floor` or additionally to a `space`. Moreover, this graphical model allows for nested equipment and spaces. For instance, it is much easier to define six sub-spaces of openOffice316 in which to allocate the System A multisensors, without having to define anything more granular than space, i.e. without having to define the `tblAreas` in Figure 4.3. This prevents having to be increasingly more specific to capture more granular spatial relationships. Readers are referred to the Project-Haystack website for a more thorough breakdown of the data model.

4.2.2.2 Data Importing

Having built-in drivers for connecting to BACnet and Modbus that also handle historizing the data at specified time intervals to a self-contained database greatly simplifies the data import and mapping processes. Rather than having to manage multiple import and manipulation scripts, a BACnet and Modbus client, and a database, all of these modules are built in to this single software platform. It is important to note, however, that significant configuration/commissioning effort is still required and that a thorough understanding of the Project-Haystack tagging model is also necessary. Additionally, all applications that provide data access through an API still require a custom import script for this procedure. For instance, all points of System A are available through the BACnet interface except for the temperature point. While the software platform does have an open source HTTP client, attempts to use it have been unsuccessful. Custom extensions, similar to the above HTTP client, can be written, compiled from a lower level programming language, and enabled in the software, although there is also a significant learning curve to this as well (for those coming from a non computer science background). At this point in time, all points listed in Table 4.1 except for System A Temperature and the System B events have been successfully integrated into this single software application.

4.2.3 System Architecture Summary

Initially, a relational data model was created and used in conjunction with multiple scripts and an external Modbus/BACnet client to record and historize data from the described systems. In theory, this approach has merit and likely would be a good project for a software developer. However, maintaining all of the separate components and ensuring reliable, consistent, and correct mapping of the underlying data points was a significant challenge. This challenge was exacerbated in the living laboratory environment, where both network configuration changes and software application settings were often being modified and manipulated to test out new systems and integrations. Although significant work was put into the initial system architecture, the underlying data was untrustworthy and therefore provided little value. For this reason, a commercial software application was eventually deployed, which uses the Project-Haystack data model, and has a built-in time series database, query engine, and visualization capabilities, greatly simplifying the end-to-end data management and analytics process.

Chapter 5

Evaluation and Discussion

Data was collected from June 18th to June 29th, 2018 inside the Boulder office. Employees were asked to use the digital access controls system (System B) upon entering and exiting the office space in order to simulate the ability of the system to collect data if it were deployed as a true solution (instead of as a test system). The rest of the data points don't require human intervention for recording purposes and were simply recorded using the data collection features of the commercial software platform. The following paragraph provides descriptions for some commonly used terminology in this chapter.

In the following metrics, the word space is used to define a room, i.e. longsConf328, whereas space type is used to reference a grouping of spaces by functional category, i.e. conference room. This is in accordance with Figure 4.1. Additionally, daily profile is used to define a "typical day", i.e. the average magnitude of a specific measurement characteristic at a specific point in time in a 24-hour period. An example of this would be the average energy consumption at 8 am over all of the observed days. When dealing with time series data and a good time series analysis library, it is relatively straightforward to take data available at high granularity (i.e. every minute), to averaging or summing it to less granular time intervals (hourly/daily/weekly/etc.). This is referred to as "rolling up" in the following sections. Most of the calculations performed in this chapter are simple calculations, but classified in more interesting ways.

Data collected over the defined period was used to evaluate the following KPIs and questions from Tables 3.2 and 3.3. Further, when occupancy information is involved, these metrics are calculated using information available through the different systems providing occupancy related information (Systems A and B) to compare the ability of the systems to evaluate the metrics. Information from System C did not provide much useful data during the collection period.

The following sections are formatted to present figures that allow for analysis of the questions at the beginning of each section. The analysis of the figures is then presented in line.

5.1 Space Utilization Metrics

- What is the average space utilization by space, space type, or business group? This is useful for understanding how well each specific room is being used, as well as how functionally equivalent spaces are used as a whole, and for understanding whether different business groups use spaces in different ways.
- What is the space utilization by space, space type, or business group at an hourly or daily level? This is more useful as a drill-down graphic if trying to analyze utilization of a specific hour or day.
- What is the overall building space utilization? This is a useful metric for understanding space utilization based on overall square footage.

Each of the above questions requires a space utilization calculation. When this calculation is performed for a multi-day period, it is based on a daily defined time span over which the calculation is made. For example, space utilization can be evaluated for a typical working day (8 am - 5 pm), for afternoons (12 pm - 5 pm), or over an entire 24-hour period (12 am - 12 am). Space utilization calculations assume that, if multiple sensors exist within a single space (System A), these sensors are evenly distributed throughout the space, i.e. the area prescribed to each sensor within a given space is equivalent. This is generally true in this scenario. They are made at hourly intervals by calculating the number of minutes that each occupancy sensor reads “occupied” as a percentage of the entire hour, which can then be rolled up to higher intervals as well. For all space utilization metrics where a grouping is performed (i.e. space utilization by business group), an area normalized approach is used. For example, the Sustainability and Energy group consists of a large open office (874 sf) and three smaller private offices (142 sf each). The space utilization of the large office is weighted by $\frac{874}{874+3*142}$ when the actual calculation is made. This is referred to as the area normalized space utilization (ANSU). Most of the space utilization metrics can be very informative for real estate planning and office space management.

Pseudocode for calculation of the ANSU metric at an hourly interval is as follows:

---

for all Groups **do**

  for all Spaces in group **do**

    for all Sensors in space **do**

$$sensorOcc = \sum_{m=1}^{60} \frac{sensor == occupied}{60min} 100\%$$

    end for

$$spUtil = \sum_{allSensors} (sensorOcc\ spaceArea) \frac{1}{numSensors\ groupArea}$$

  end for

$$ANSU_{group} = \sum_{groupSpaces} spUtil$$

end for

where the ANSU is measured as a percentage.

For calculation of the above metric, hallways, restrooms, and storage areas are not considered since they are not truly usable spaces. The following figures allow for the analysis of the above defined questions.

One of the first things to notice from Figure 5.1 is that the System B sensors in Open Office 315, Lab 313, Private Office 322, and Server 326 do not appear to be working correctly, as these

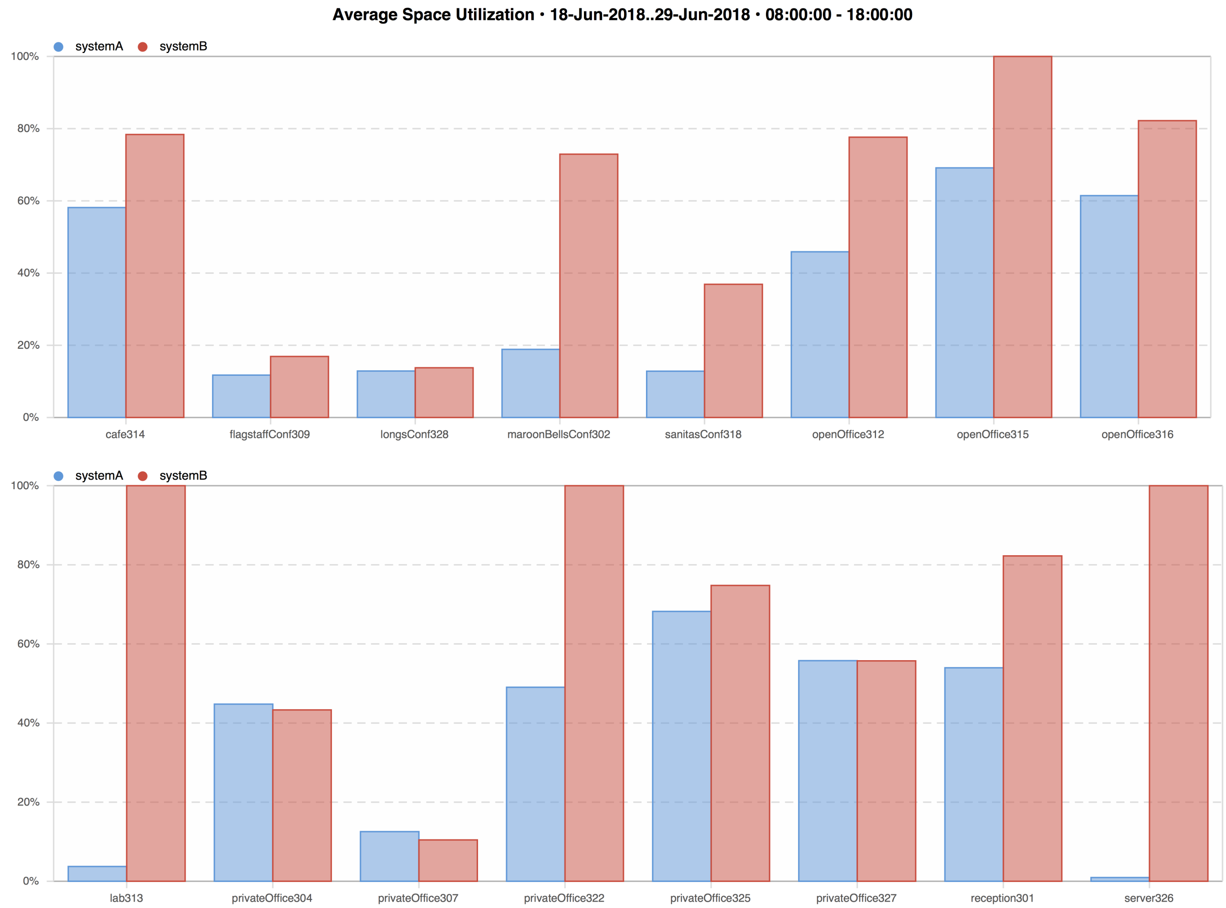


Figure 5.1: Space utilization grouped by space for June 18th - June 29th, 2018

rooms were not occupied 100% of the time during the two week period. Both the Lab 313 and Server 326 spaces have server equipment (high heat loads and blinking lights), which could contribute to the false positive readings for these two rooms. The exact cause of the low data quality, however, is not known. It is important to recognize, however, that faulty sensors are a common occurrence, and if not recognized and fixed in a timely fashion, can lead to poor data quality and eventually ruin any high level insights that were expected from an occupancy detection system.

What is also apparent in Figures 5.1 and 5.2 is that the space utilization calculated for System B, in nearly all cases (except for Private Office 304 and 307), is well above the space utilization calculated using the sensors from System A (more than twice for Sanitas Conference 318!). This

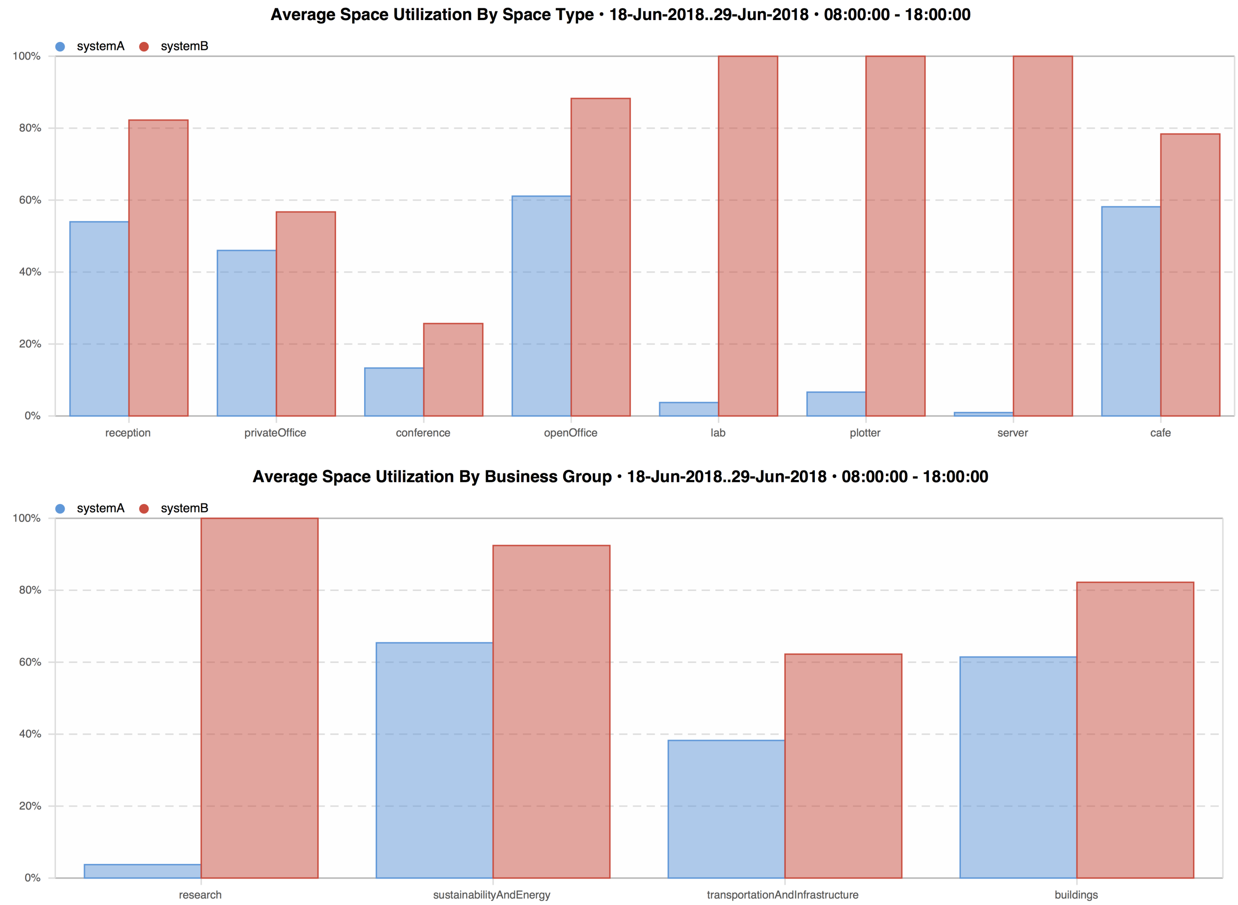


Figure 5.2: Space utilization grouped by space type and business group for June 18th - June 29th, 2018

could be attributed to a few factors:

(1) The sensors of System B have fallen out of calibration. The sensors were installed approximately 3 years ago, whereas the sensors of System A were installed only a year ago.

(2) The update period of the sensors from System A are potentially faster than from System B, changing from occupied to unoccupied more accurately.

(3) The increased spatial density of the System A sensors allow for a more accurate understanding of the true space utilization.

The similarity in the space utilization calculated for Private Offices 304, 307, 325, and 327, where only a single sensor is installed for both Systems A and B, is an argument against Item 1 above. If these sensors are out of calibration, we would expect to see disparate results in the calculation between these two systems. However, the fact that the utilization is always higher for System B in spaces where a single sensor is installed for System B and multiple sensors are installed for System A provides a better argument for Item 3 above. As discussed extensively in Section 2.5, the quality and accuracy of spatial utilization metrics reported is highly dependent on the underlying occupancy detection system.

Consider an internal real estate strategist making decisions for conference rooms and open offices based on the information presented in Figure 5.2. Open office space utilization appears at approximately 90% based on the data available from System B, whereas System A is approximately 61%. They would likely conclude from System B results that open office spaces are very well utilized, and they potentially need more open office space, whereas the conclusion from System A would be that they could use open offices more efficiently and they should focus on increasing the space utilization in open offices. These are very different conclusions, and if performed at scale, could lead to decisions with large monetary differences. The same argument could be made for conference spaces as well. Figure 5.4 shows the maximum daily utilization for conference rooms occurs on June 26th, reaching approximately 38%, but for most other days, the utilization is between 10% and 20%. Apportioning 14% of the office gross square footage to spaces used on average 13% of the time does not seem like the best use of resources. Flagstaff or Mt. Sanitas could be utilized for a different purpose, allowing the real-estate team to reapportion space instead of leasing more space in the case of expanding.

Additionally, Figure 5.2 shows the increased magnitude in space utilization of open offices compared to private offices. Figure 5.1, however, shows this is mainly attributed to low utilization of Private Offices 304 and 307, which both have lower utilization rates than the others. Potentially it makes sense to reconfigure these two private offices to different space types, or reassign employees who are typically at their desk more often (and not travelling or out on site) from an open office environment (where utilization is high) to a private office. Open offices can be more distracting,

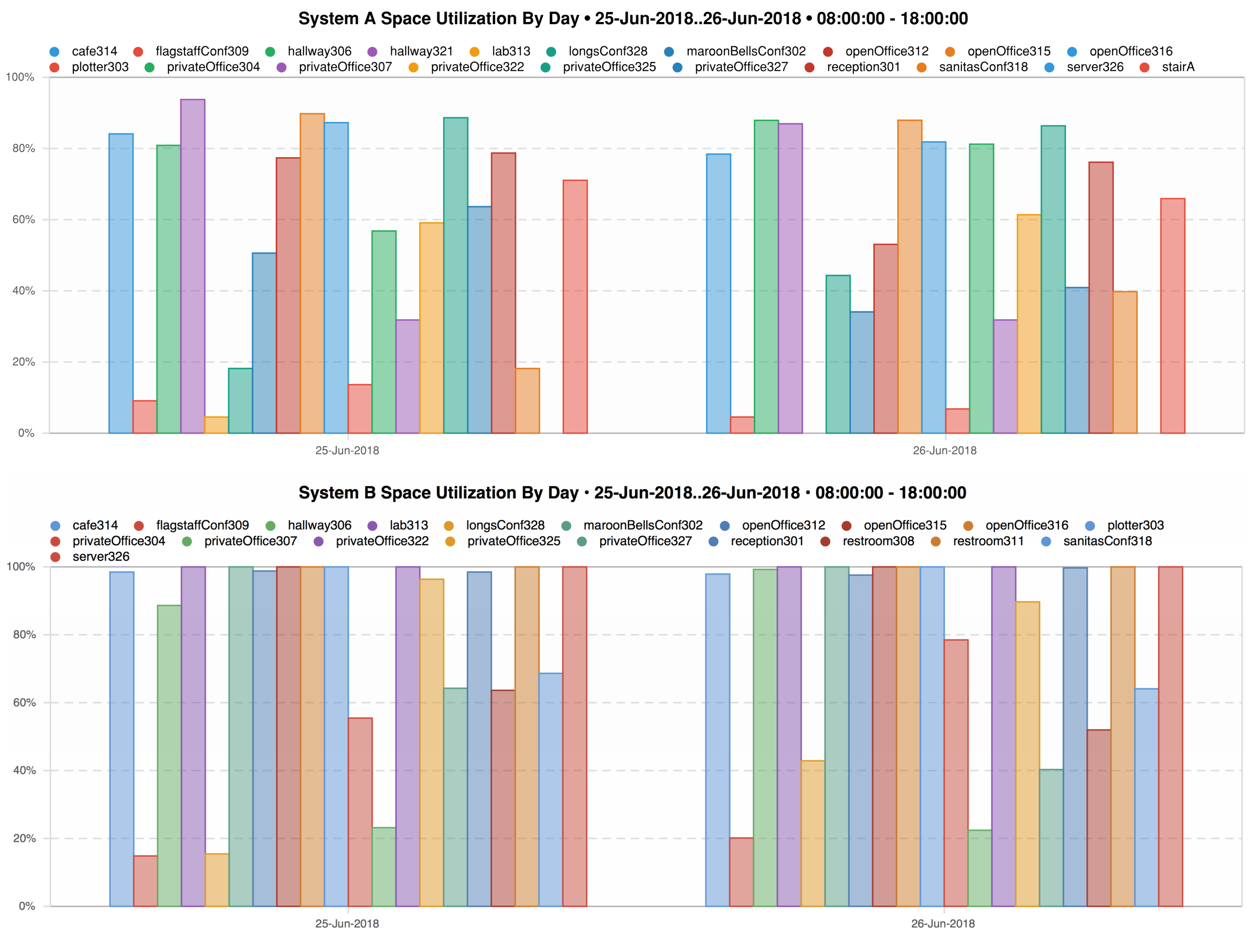


Figure 5.3: Daily space utilization by space for a two day period

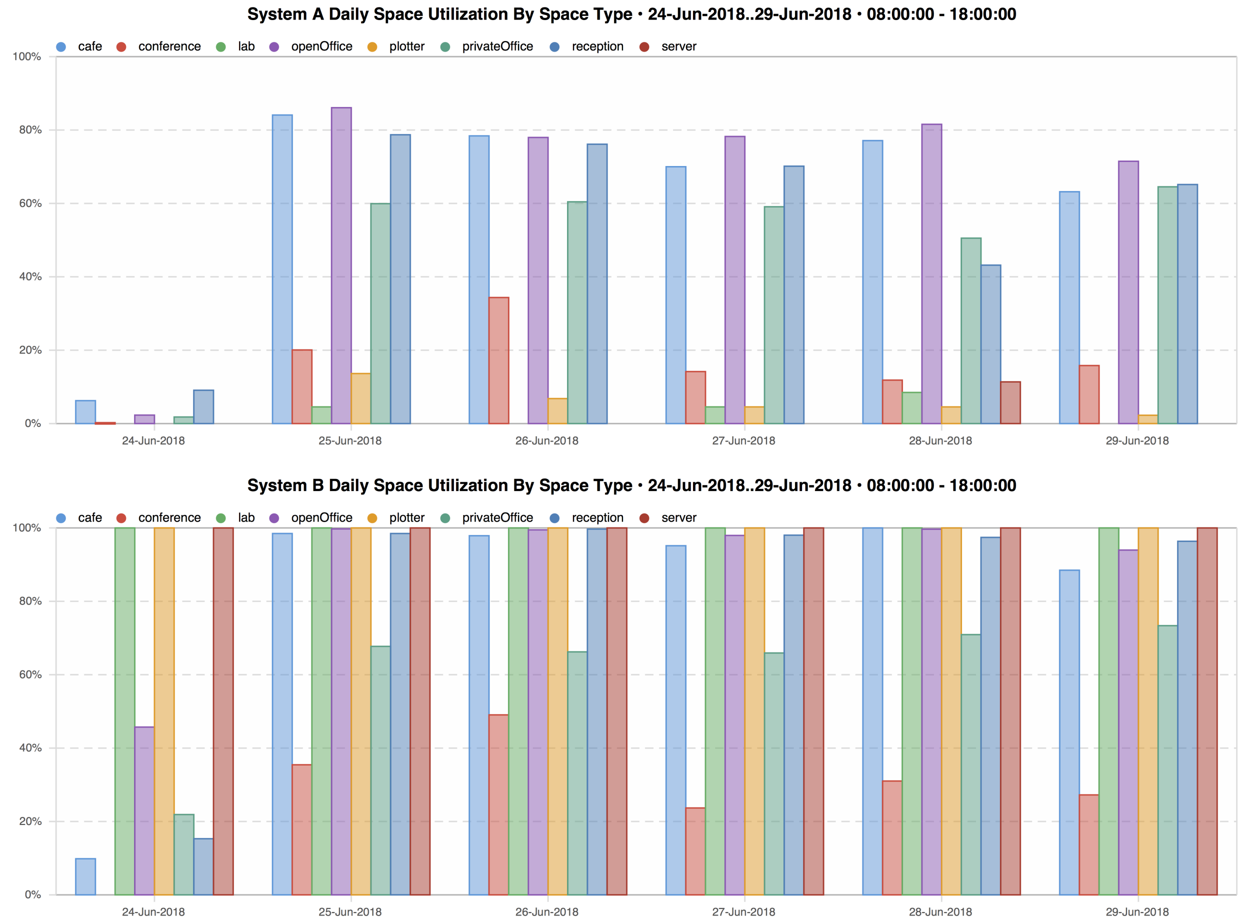


Figure 5.4: Daily space utilization grouped by space type for June 18th - June 29th, 2018

and granting employees the opportunity to book a private office on days when the space is not being used could be beneficial to the company. Further, it is important to recognize that this could be atypical utilization for this two week period since job requirements vary temporally. looking at more than two weeks worth of data may also be fruitful.

Evaluating the utilization by business group in Figure 5.5 shows the 20% difference in utilization between the Transportation and Infrastructure group compared to the Sustainability and Energy and Buildings groups. This lends itself to evaluating the question of whether all business groups should have the same occupant density design ratios. Does the Transportation and Infrastructure group inherently need less space per person? Is it just the nature of the employees in this

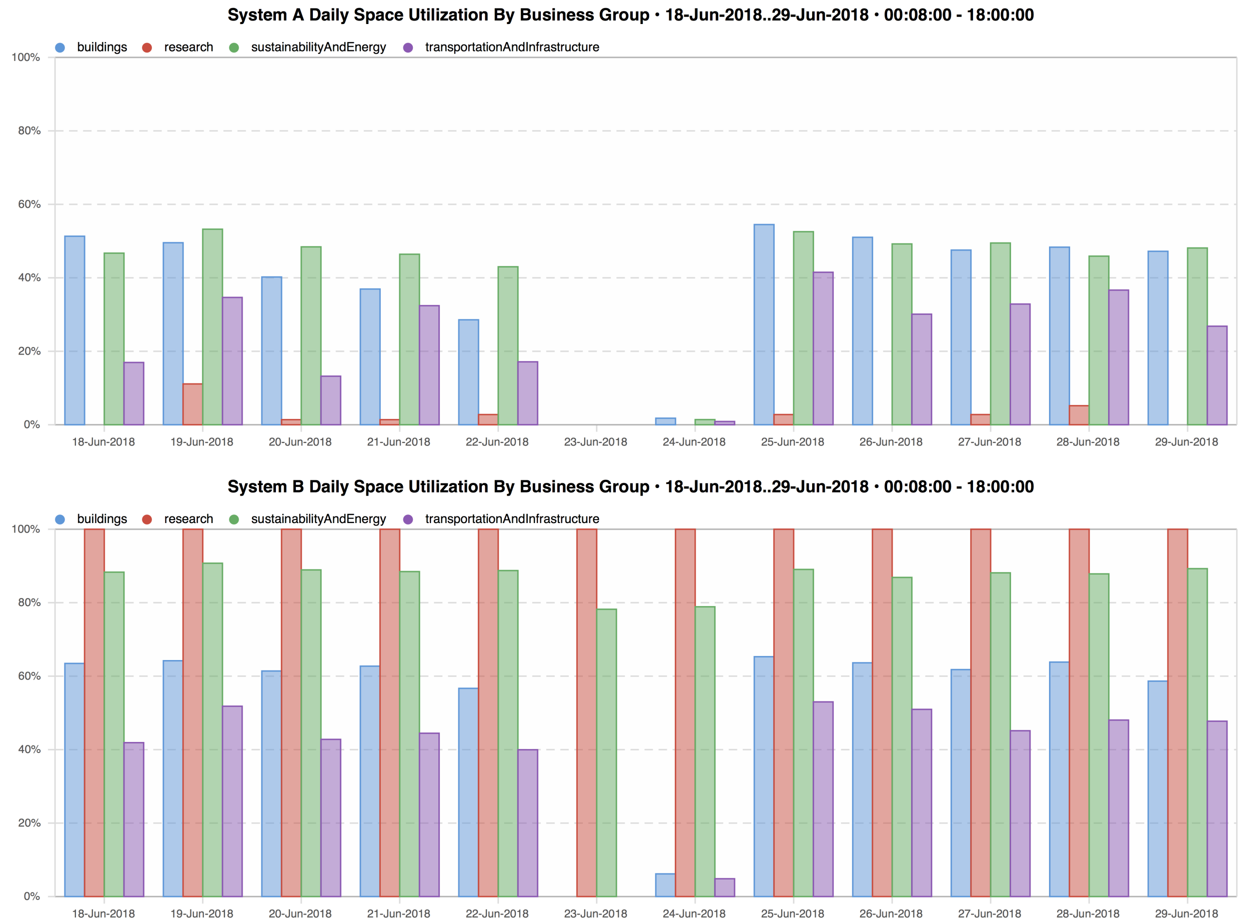


Figure 5.5: Daily space utilization grouped by business for June 18th - June 29th, 2018

office space and their specific job types? Attempting to evaluate these questions when information from only a single office is available is difficult, however, these questions can be evaluated when a larger percentage of the real-estate portfolio is included in these calculations.

5.2 Energy and Power Metrics

- What is the average daily energy profile by space, space type, or business group? This is useful for understanding what the energy consumption of a typical day looks like over a 24 hour period.

- What is the energy consumption by space, space type, or business group? This is useful as a drill down graphic to analyze specific hours or days if desired.

- What is the maximum hourly power usage by space, space type, or business group? This uses the maximum power draw for a space, space type, or business group for each hour as a representative value for that hourly interval. This is useful for determining which hours of the day is peak draw occurring. Additionally, it can help identify which spaces, space types, or business groups have the highest power draw.

- What is the maximum hourly power intensity (W/sf) by space, space type, or business group? This is the area normalized version of the above metric, allowing for a more fair comparison of power draw characteristics based on area.

- What is the predicted annual EUI of the space? This is useful in a measurement and verification context when trying to determine whether or not your company (or building) is on track to meet its long term sustainability targets.

The following figures allow for the analysis of the above defined questions.

Energy saving opportunities arise when observing the steady load profile of the server room. As this is a small room with lots of equipment, the power intensity is well above that of the other spaces. The steady profile, however, shows that no server side energy saving techniques are being used in this office. With a daily energy consumption of approximately 29 kWh, a 10% reduction in daily energy consumption would lead to a reduction of 87 kWh per month. However, it really is not cost effective to consider energy saving strategies for this, since with an approximate $0.10 per kWh cost of electricity in Colorado, this yields only an annual savings of $106.

One of the first things to notice in Figure 5.7 is that the base load for the Buildings group is about 0.5 kW higher on average than the Transportation and Infrastructure group, while the Sustainability and Energy group has an approximate 0.2 kW higher base load than the Transportation and Infrastructure group. All of the groups have similar work equipment (a computer and two monitors), and there should not be a significant difference in the base load of any of these groups.

Figure 5.6: Energy and power consumption characteristics grouped by space type June 18th - June 29th, 2018

We expect there to be little to no load outside of scheduled hours for these groups, since computers and monitors should be sleeping or shut down at the end of the day, however, this is not the case.

The top graphic presented in the drill down of Figure 5.8 shows the difference in energy profiles in the private and open office environments. The profiles are rather consistent, but off-schedule drops and surges in power are noticeable in the private offices, and high off-schedule base load is observable in the open offices. This can also be seen in Figures 5.7 and 5.6. Drilling down by business group and then by space type allows us to isolate the surge problem to one of the circuits supplying power to Private Office 322, 325, or 327, which turns out to be either A39, CT_B, or A13, CT_O (see Table B.1 for circuit references). A further refined drill down displayed in the middle graphic of Figure 5.8 shows that power cycling is occurring on A39 (CT_B). Performing a drill down of the circuits which have a high off-schedule consumption in the bottom graphic of

Figure 5.7: Energy and power consumption characteristics grouped by business group June 18th - June 29th, 2018

Figure 5.8, narrows the base load to one of five circuits. Four of these circuits are located in Open Office 316, which is consistent with the high base load observed earlier of the Buildings group in Figure 5.7. While the exact sources of the power cycling and high base load in Open Office 316 has not been found, the ability to narrow down sources in a logical, progressive fashion, shows the promise of these types of tools.

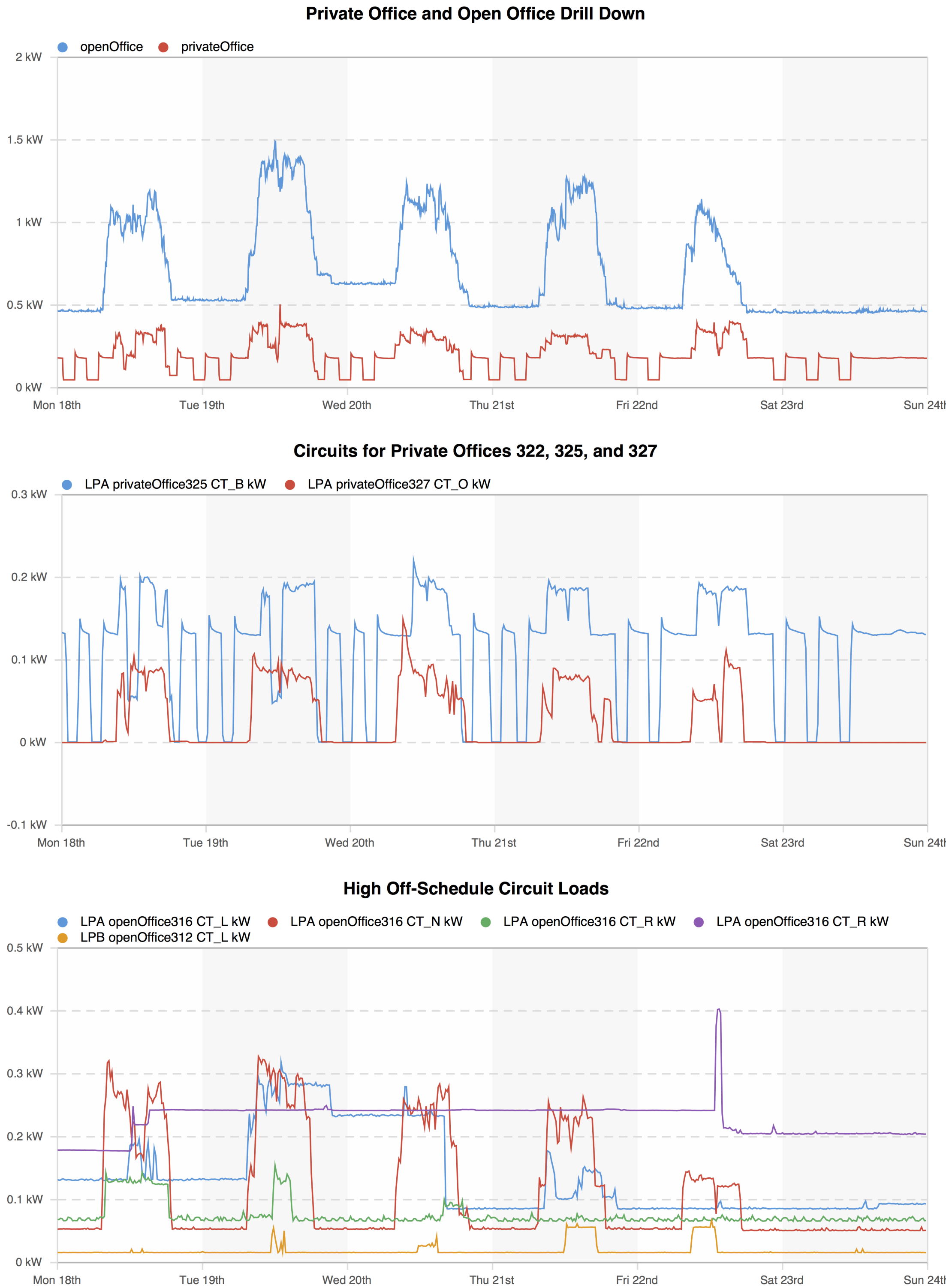


Figure 5.8: Drill down of power intensity for open and private offices

5.3 Occupancy Normalized Metrics

- What is the occupancy normalized energy consumption (onE)?
- What is the predicted occupancy normalized EUI (onEUI) of the space?

The above items reference an occupancy normalized energy calculation metric, which is really some of the more fruitful and interesting work performed in this thesis. The need for evaluating the energy consumption of a building based on the operational hours has already been identified by the Energy Star Score. While this score accounts for differences in operational hours, it doesn't take into account how the building is actually utilized during those operational hours. As an example, let's evaluate two identical 8,000 square foot office buildings operating for 50 hours per week. Building A has a planned occupant density of 125 sf/person, resulting in a total of 64 people, while Building B has a planned occupant density of 250 sf/person, resulting in a total of 32 people. It is easy to subjectively state that the space within Building A is used more effectively than Building B. However, evaluating both buildings from an energy usage perspective, we would expect Building B to consume less energy than Building A, albeit it is unlikely to have a 50% reduction in energy consumption. From an EUI comparison, Building B would appear to be more efficient, however, the EUI/person would be significantly better for Building A. Moreover, in order to fit 32 more people in a space designed at an occupant density of 250 sf/person, an additional Building B would be required, resulting in significantly more operational energy consumption than a single Building A.

The goal of the following two sections is to explore methods of evaluating the building energy consumption while simultaneously considering spatial utilization.

5.3.1 Approach 1: Occupancy Normalized Energy

The onE metric is calculated using the following algorithm:

---

(1) Calculate the hourly building energy consumption (BEC)

(2) Calculate the hourly ANSU

(3) $onE = BEC(1 - \frac{ANSU}{x})$

(4) $onEUI = \frac{\sum_{allHours} onE}{buildingArea}$

where x is a normalizing constant and ANSU is evaluated as a percentage.

Using $x = 100\%$ equates to normal energy consumption when the building has an ANSU of 0%, zero energy consumption when the building has an ANSU of 100%, and linearly interpolated at ANSU values inbetween. It is not desirable for the onE to drop to 0, so a normalization constant of 150% and 200% are also explored. The concept behind normalizing by 200% is the following: if the BEC doubles as the building becomes 100% occupied, the onE profile would appear constant. While the units of the onE metric work out to be typical energy units, the interpretation of the metric will inevitably need to be different than looking only at energy consumption. Finally, depending on the granularity of the occupancy detection system installed in the building, the metric could vary drastically. A standard would need to be developed around the calculation of this metric, defining how the metric would be evaluated depending on the granularity of occupancy detection system installed and how the single metric would be compared across a portfolio of buildings with different granularities of occupancy detection systems installed. This is discussed further in Chapter 6.

Figure 5.9 displays hourly and daily rollups of the onE metric calculation for both Systems A and B using different normalization constants of 100%, 150%, and 200%. The daily energy profile and ANSU profile is typical of a commercial office space - both ramp up around 7 am and ramp down around 6 pm during weekdays. Analyzing the 200% onE metric, we notice a much

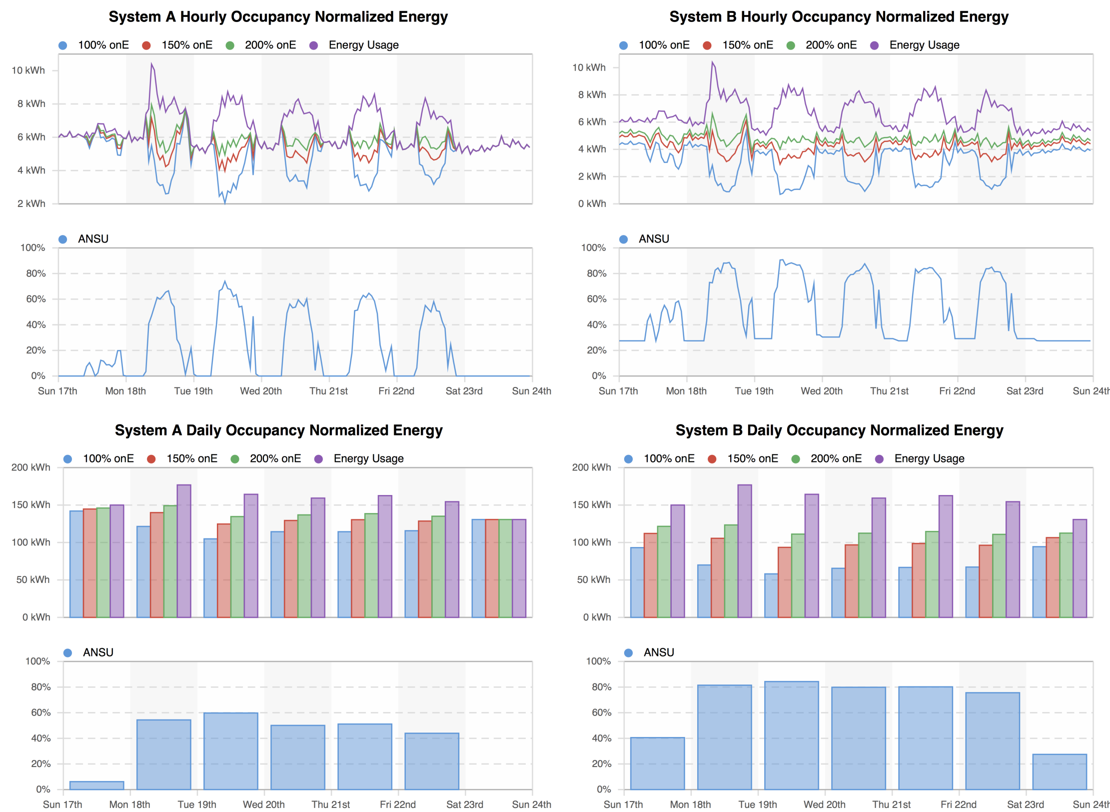


Figure 5.9: Energy normalized by occupancy with ANSU for June 17th - June 24th, 2018

steadier profile throughout the day. The entering of employees corresponds to an increase in energy consumption, but because the ANSU also increases, there is no ramp up in the 100% onE profile. Both the 50% and 75% onE profiles behave as expected as well, ramping down during the day when the ANSU increases.

The difference in magnitude of the onE calculation based on the difference in the occupancy information available from Systems A and B is also apparent in Figures 5.10. With higher ANSU values (and ANSU values calculated with three faulty sensors)

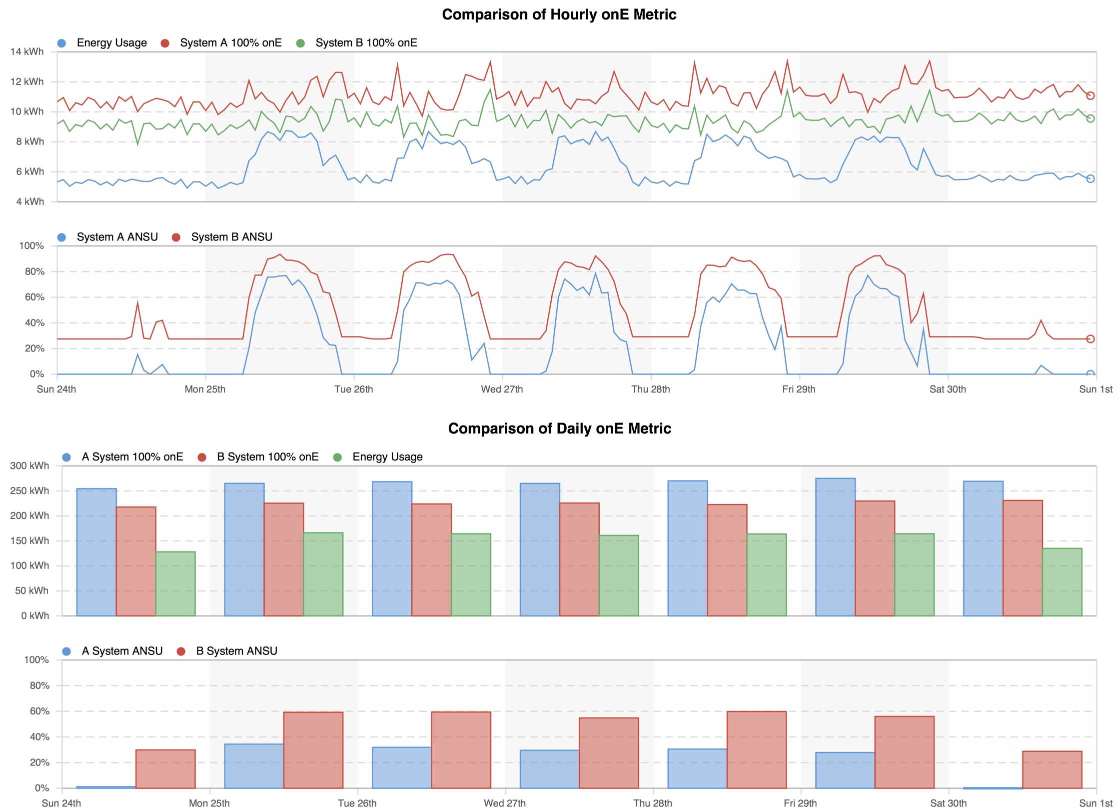


Figure 5.10: Comparison of onE metric by system for June 24th - July 1st

5.3.2 Approach 2: Occupancy Normalized Energy with Regression

Another approach that is less arbitrary than the previous approach is to correlate the BEC to the ANSU using an Ordinary Least Squares (OLS) regression model. An OLS model is created with the BEC as the independent variable and the ANSU as the dependent variable.

$$BEC_{fit} \;=\; \beta_0 + \beta_1 \; ANSU$$

Data is not separated into training and testing datasets. Data from the two week evaluation period is used to perform the regression and the predictions[1] are overlaid with the data used to perform the regression in Figure 5.11.

The regression performed results in a coefficient of determination ("R-squared") value of

[1] These are simply referred to as predictions, although they are not true predictions

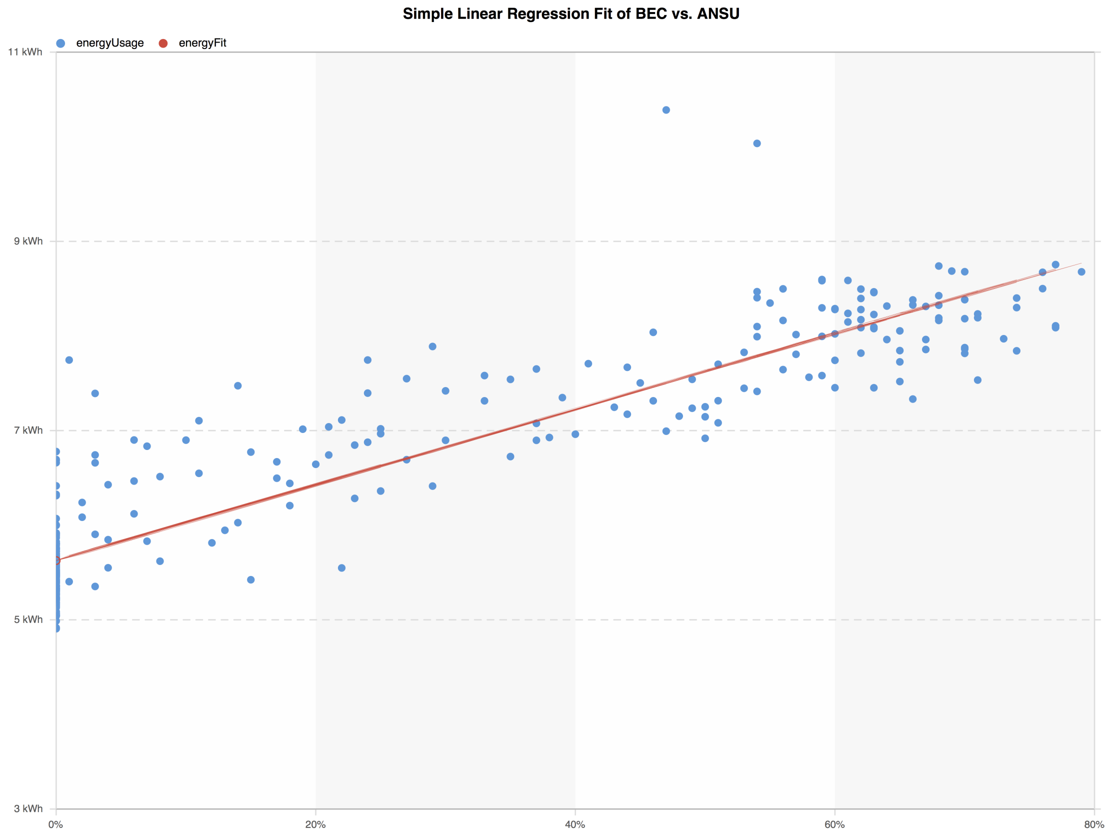


Figure 5.11: Ordinary Least Squares Simple Linear Regression of BEC vs. ANSU

$R^2 = 0.8394$ and the following regression equation:

$$BEC_{fit} = 5.6228kWh + (0.03997)ANSU$$

A BEC modification factor, defined as $BEC_{mod} = \frac{BEC_{true}}{BEC_{fit}}$, is also used as an evaluation metric for the performance of the regression model. This modification factor, however, could be used in an automatic fault detection and diagnostics (AFDD) application given a high enough confidence in the underlying regression model. Results of the BEC_{fit} are overlaid with the original dataset along with the BEC_{mod} and ANSU are displayed in Figure 5.12.

The results displayed in Figure 5.12 show that the regression model follows the general trend of the BEC rather well. Limitations in the accuracy of the model can be seen as the model bottoms out at the bias term of $\beta_0 = 5.6228kWh$, which is also when the space utilization is at 0%. This

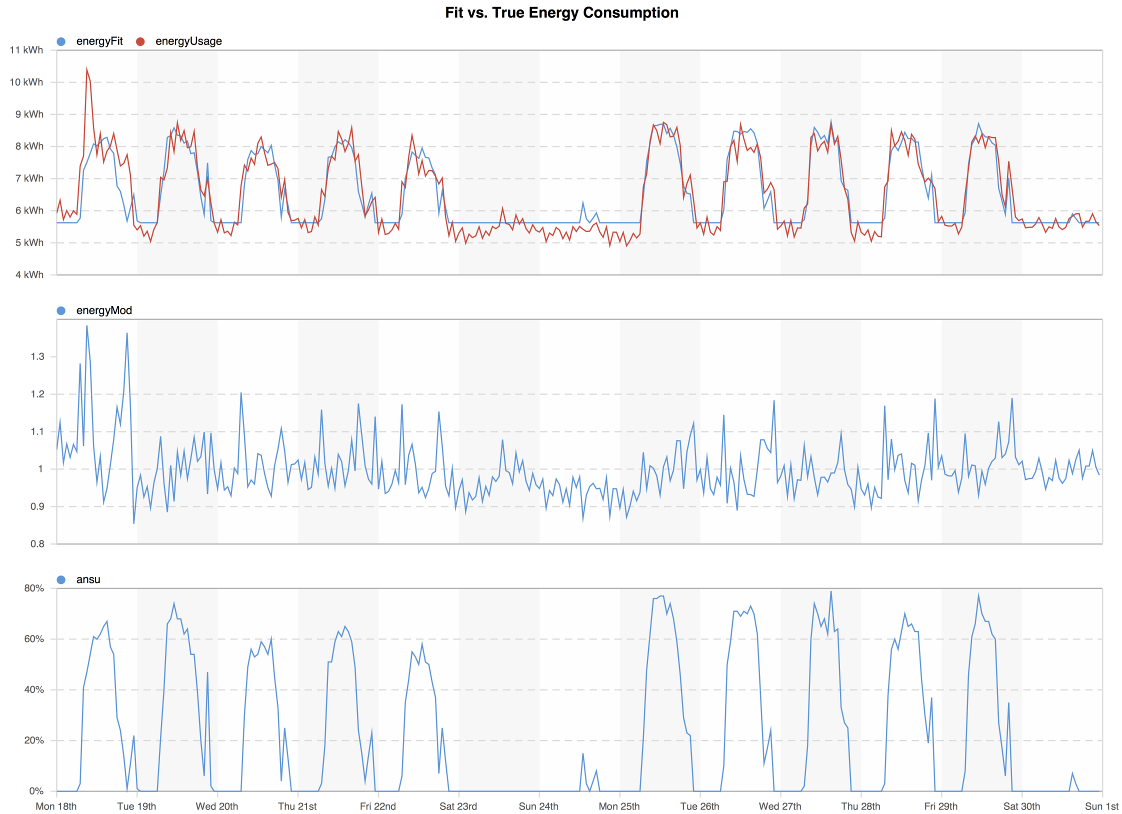


Figure 5.12: True BEC overlaid with the predicted BEC and the BEC modification factor

could be attributed to external conditions not being captured in the regression model, such as temperature, solar radiation, etc. The plot of the BEC_{mod} at the bottom of Figure 5.12 shows the temporal variation in the predicted vs true BEC profiles, which could be used in the context of AFDD. For instance, using a margin of 0.95 - 1.05 and reporting instances when the BEC_{mod} falls outside of this range would be one potential application.

Chapter 6

Conclusions and Future Work

This thesis presented an in-depth literature review surrounding the concept of a smart building, characterizing the value proposition in accordance with the 3-30-300™ Framework. Furthermore, occupancy detection systems are identified as the most underutilized data source available to building owners and operators to allow for more intelligent building operations, which would also allow them to provide more Information as a Service type services to be utilized by businesses, tenants, and individuals within their buildings. Potential KPIs were identified that extend beyond the traditional operational metrics typically evaluated for buildings, and are summarized in Tables 3.2 and 3.3. Then, different commercially available sensing and software systems are described along with their implementation in a living laboratory office environment. These systems are used to collect data from June 18th to June 29th, which is then analyzed using a subset of the previously defined KPIs and business intelligence questions, which are analyzed through a series of figures.

One of the more important contributions of this work is to establish two new potential approaches for understanding building performance, which uses the true space utilization characteristics of a building and correlates this with the energy consumption. The first method (onE1) takes a semi-arbitrary approach at normalizing energy consumption by the area normalized space utilization (ANSU). The second method (onE2) uses the ANSU as the regressor in an OLS simple linear regression model to fit the building energy consumption (BEC). The true BEC is then divided by BEC_{fit} as a normalization factor, and the proportion is returned (BEC_{mod}), which could be useful in generating more accurate load predictions for demand response and load forecasting applications.

In Chapter 2, the argument is made that designing buildings to be more human-centric is at the core of a smart building. This involves generating feedback data from users and allowing them to interact with the building in more meaningful ways. The metrics evaluated in this thesis focused mainly on more interesting ways to evaluate space utilization and energy consumption characteristics. At this point in the development of the living laboratory, there is no opportunity for users to effect change on their indoor environment. A logical next step is to create or implement an application to provide users with a means to generate feedback regarding their individual experience. A bonus feature of this type of software would allow for user feedback to influence the base building systems (mechanical, electrical, lighting, etc.). More importantly, however, would be the ability to capture data generated through this application and correlate it with the actual building operational characteristics. Moreover, the importance of highly granular occupant detection systems is stressed early on, however, System A, which provides higher spatial resolution data than System B, does not provide count or identity level occupant resolution data (Figure 2.2). It would be much more interesting to attempt to evaluate these metrics using this higher resolution data. Therefore, another next step is to install an occupancy detection system that provides higher resolution occupancy data and compare that data with the results presented in this thesis.

As discussed previously in Chapter 5, additional work needs to be performed in standardizing an algorithm by which to calculate occupancy normalized energy consumption metrics. The standardization process should consider the spatial and occupant granularity of the underlying occupancy detection systems installed in the building, as well as providing a means by which these metrics would be compared across a portfolio of buildings (or across portfolios) regardless of the underlying occupancy detection systems installed in the different buildings. Additionally, while a method for calculating the ANSU, and two methods for calculating the onE were proposed, the standard would need to formalize the algorithm used to calculate these metrics. For example, in the ANSU calculation for this evaluation, hallways, restrooms, closets, and stairwells were not considered since they don't provide typical usable space. A standard would have to formally and explicitly define what these space types would be, or whether all space types should be considered in this calculation.

Furthermore, the linear regression equation used to evaluate onE2 uses simply the ANSU metric as the basis for the regression. While the model fits the training data relatively well, a more formal approach should be taken in evaluating the goodness of fit of the regression model by using a training and testing dataset. Additionally, future BEC could be forecasted using predicted values of ANSU along with other regressor variables, including forecasted temperature, solar radiation, and humidity. This could then be used in a demand response type application, as explored in [37], for example.

Another interesting concept to explore would be to incorporate the planned space density into a space utilization performance metric. For example, the open office spaces are planned with an occupant density of approximately 93.5 sf/person, whereas the private office spaces are planned with an occupant density of approximately 142 sf/person. The goal of this new metric would be to evaluate the true occupant density against the planned density as a means of understanding how space plans align with reality. This would be an informative metric for architects and space planners at the onset of a project, who could then use this metric for right sizing space more efficiently.

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Appendix A

Glossary

ANSU: Area Normalized Space Utilization

API: Application Programming Interface

BACnet: Building Automation and Controls Network

BACnet AP: BACnet Applications

BEC: Building Energy Consumption

BMS: Building Management System

DALI: Digital Addressable Lighting Interface

HVAC: Heating, Ventilation, and Air Conditioning

IoT: Internet of Things

IT: Information Technology

KPI: Key Performance Indicator

LEED: Leadership in Energy and Environmental Design

OCF: Open Connectivity Foundation

OLS: Ordinary Least Squares

OT: Operational Technology

PIR: Passive Infrared

PoE: Power Over Ethernet

REST: Representative State Transfer

RFID: Radio Frequency Identification

RSSI: Received Signal Strength Indicator

SBS: Sick Building Syndrome

TCO: Total Cost of Ownership

VM: Virtual Machine

WAP: Wireless Access Point

WELL: WELL Building Standard

Appendix B

Electrical Plan and Circuit Mapping

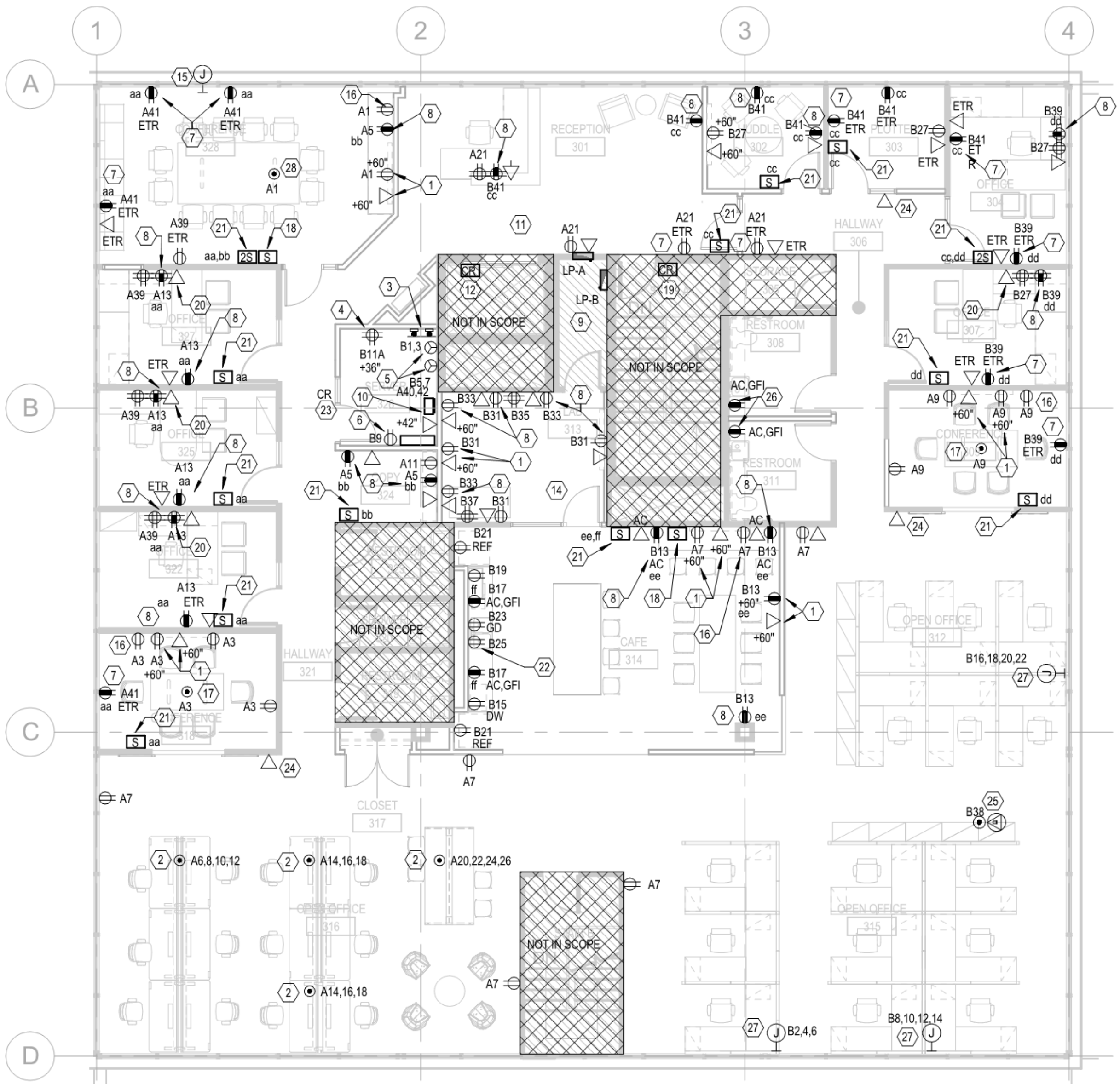

Figure B.1: WSP USA Boulder office electrical plan

Table B.1: Mapping of circuits to their individual space types

Space	Space Type	Meter	Circuit Number	Circuit Letter	Description
cafe314	Cafe	LPB	B13	CT_O	Kitchen Receptacle Switched
			B15	CT_N	Kitchen Dishwasher
			B17	CT_M	Kitchen Receptacle Switched
			B19	CT_L	Kitchen Microwave
			B21	CT_K	Kitchen Refrigerator
			B23	CT_J	Garbage Disposal
			B25	CT_I	Microwave
copy324	Copy	LPA	A11	CT_P	Copier
flagstaffConf309	Conference	LPA	A9	CT_Q	Conference Room 309 (Flagstaff) Receptacle
lab313	Lab	LPB	B31	CT_C	Lab Receptacle 1
			B33	CT_D	Lab Receptacle 2
			B35	CT_E	Lab Dedicated Receptacle 1
			B37	CT_F	Lab Dedicated Receptacle 2
longsConf328	Conference		A1	CT_U	Conference Room 328 Receptacle
			A5	CT_S	Reception & Copy Receptacle Switched

Table B.1 continued from previous page

Space	**Space Type**	**Meter**	**Circuit Number**	**Circuit Letter**	**Description**
			A41	CT_A	West Receptacle Switched Pre
openOffice312	Open Office	LPB	B16	CT_N	Environment Furniture Feed 6
			B18	CT_M	Environment Furniture Feed 7
			B20	CT_L	Environment Furniture Feed 8
			B22	CT_K	Environment Furniture Feed Switched 3
openOffice315	Open Office	LPB	B2	CT_U	Environment Furniture Feed 1
			B4	CT_T	Environment Furniture Feed 2
			B6	CT_S	Environment Furniture Feed Switched 1
			B8	CT_R	Environment Furniture Feed 3
			B10	CT_Q	Environment Furniture Feed 4
			B12	CT_P	Environment Furniture Feed 5
			B14	CT_O	Environment Furniture Feed Switched 2

Table B.1 continued from previous page

Space	**Space Type**	**Meter**	**Circuit Number**	**Circuit Letter**	**Description**
openOffice316	Open Office	LPA	A6	CT_S	Buildings Furniture Feed 1
			A8	CT_R	Buildings Furniture Feed 2
			A10	CT_Q	Buildings Furniture Feed 3
			A12	CT_P	Buildings Furniture Feed Switched 1
			A14	CT_O	Buildings Furniture Feed 4
			A16	CT_N	Buildings Furniture Feed 5
			A18	CT_M	Buildings Furniture Feed Switched 2
			A20	CT_L	Buildings Furniture Feed 6
			A22	CT_K	Buildings Furniture Feed 7
			A24	CT_J	Buildings Furniture Feed 8
			A26	CT_I	Buildings Furnitur Feed Switched 3
			A7	CT_R	Open Office General Receptacle

Table B.1 continued from previous page

Space	Space Type	Meter	Circuit Number	Circuit Letter	Description
plotter303	Plotter	LPB	B36	CT_D	Plotter Receptacle 1
			B38	CT_C	Plotter Receptacle 2
			B41	CT_A	North Office Receptacle Switched
privateOffice304	Private Office	LPB	B27	CT_H	East Office Receptacle
privateOffice307	Private Office	LPB	B39	CT_B	East Office Receptacle Switched
privateOffice322	Private Office				
privateOffice325	Private Office	LPA	A39	CT_B	West Office Receptacle Pre
privateOffice327	Private Office	LPA	A13	CT_O	West Office Receptacle Switched
reception301	Reception	LPA	A21	CT_K	Reception Hall New Receptacle
sanitasConf318	Conference	LPA	A3	CT_T	Conference Room 318 Receptacle
server326	Server	LPB	B40	CT_B	Split System Conditioner 1
			B42	CT_A	Split System Conditioner 2
			B1	CT_U	Server Room Receptacle 1
			B3	CT_T	Server Room Receptacle 1
			B5	CT_S	Server Room Receptacle 2
			B7	CT_R	Server Room Receptacle 2
			B9	CT_Q	Server Room Dedicated Receptacle 2

Table B.1 continued from previous page

Space	**Space Type**	**Meter**	**Circuit Number**	**Circuit Letter**	**Description**
			B11	CT_P	Server Room Dedicated Receptacle 2
all	Multiple	LPA	A2	CT_U	South Office Lighting
			A41	CT_T	North Office Lighting
			A38	CT_C	Lighting Panel B Phase A
			A40	CT_B	Lighting Panel B Phase B
			A42	CT_A	Lighting Panel B Phase C
			A15	CT_N	Spare 1
			A17	CT_M	Spare 2
			A19	CT_L	Spare 3
			A23	CT_J	Electric Room Receptacle Pre
			A25	CT_I	West Bath Lighting Pre
			A27	CT_H	Water Heater Pre
			A29	CT_G	Water Heater Pre
			A31	CT_F	Bath Lighting Pre
			A33	CT_E	East Bath GFI Receptacle Pre
			A35	CT_D	Water Heater Pre
			A37	CT_C	West Bath GFI Report Pre