A Framework for Evaluating the Compatibility of Occupant Presence Data Sources with Energy Management Strategies

Ben Rosenblum, Lawrence Berkeley National Laboratory

ABSTRACT

Occupant presence data—a record of where, when, and by whom a building is occupied—can be an asset in managing energy consumption in commercial buildings. Commercial buildings could be more energy efficient if occupant presence data are better integrated into energy management practices to ensure that systems are off or throttled back when spaces are unoccupied or have fewer occupants. This project develops a qualitative framework for evaluating sources of occupant presence data for use in energy management and includes a preliminary evaluation chart for assessing the compatibility between occupant presence data sources and energy management strategies.

A system of classifying potential occupant presence data sources (or, more commonly, occupancy sensors) is introduced using characteristics relevant to energy management such as spatial and temporal granularity. This inventory addresses the degree to which data sources might characterize occupants from the low granularity of trend and binary occupied status, to occupant count, to high granularity occupant identity and activity information. Potential occupant data sources are identified and then correlated to particular energy management strategies. In support of this framework, measured occupant presence data from two field studies in Northern California are presented.

Introduction

Buildings are not static entities, but respond in real time to varying conditions. Over the last decade, new technologies have provided us with more detailed data on building conditions at any given time, allowing us to respond to those data to improve conditions and decrease energy consumption. This movement toward continuous performance monitoring, fault detection, diagnostics, and controls offers a means to increase efficiency of heating, cooling, lighting, and plug load systems. Since buildings consume energy to meet the comfort and activity needs of occupants at any given moment, further energy efficiency could be gained by directly responding to occupant presence patterns, including occupant location, identity, preferences, and activities. Automated controls could adjust systems such as heating, cooling, lighting, ventilation, and personal equipment in response to occupant presence data to decrease energy consumption. In one study, the Electric Power Research Institute (EPRI) identified approximately 30% energy savings in an assessment of commercial buildings using occupancy sensors to turn lighting off when spaces were unoccupied (EPRI 1994). Energy simulations could better predict future building energy consumption with the incorporation of more granular and accurate occupant presence data. With better integration of occupant presence data into energy management, energy managers could more easily analyze, detect, and diagnose energy waste, and occupants could be more aware of when and how their activities affect energy use.

This paper is based on the underlying premise that a convergence between energy management and information technology is practically inevitable over the next decade and that the relationship between occupant presence and energy efficiency will evolve as a result of new networked systems and easier access to archived data. Networking convergence will likely not originate solely for energy purposes, but will lead to more easily accessible forms of occupant data that can support new strategies for energy management. A ubiquitous sensing environment may possibly recognize where and what we are doing, predict what we are about to do, and use these data to create low energy, comfortable environments while offering occupants local control over equipment when desired.

Previous research studies have evaluated specific technologies such as CO_2 sensors (Fisk et al. 2010), camera-based occupant detection systems (Kamthe et al. 2009) and (Dhummi et al. 2010), or passive infrared sensors (Tiller et al. 2010). Dhummi et al. (2010), for example, finds that a camera-based system correctly detected occupancy 80% of the time and proposes that occupant presence data could be integrated with demand-controlled ventilation. While there have been numerous past studies of particular occupant data sources, there has not been, to my knowledge, a framework for evaluating numerous occupant presence data source options in relation to different energy management strategies in order to assess the advantages and limitations of each. There have been several thorough past studies surveying, comparing, and contrasting information technology (IT) solutions for gathering occupant presence data, such as Hightower & Borriello (2001) and LaMarca & de Lara (2008), but this research has not defined sources of occupant presence data in relation to energy management. There is a need to further assess the potential advantages of occupant presence data sources within the context of current energy management approaches as well as to speculate on effective future applications of occupant presence data in energy management.

Objective and Scope

The primary objective of this paper is to develop a framework for comparing and contrasting occupant data sources in relation to energy management in order to assess current technology and lay the groundwork for evaluations of future technology solutions. This paper is divided into five phases. In phase one, the different characteristics and qualities of occupant presence data are defined. In phase two, fourteen energy management strategies are described that might benefit from the integration of occupant presence data. In phase three, twenty-three occupant presence data sources are then identified, compared, and contrasted in relation to the characteristics of occupant presence data they provide. In phase four, the characteristics of two occupant data sources are demonstrated based on measured occupant presence data gathered at two sites. In phase five, a preliminary framework for qualitatively assessing the compatibility between particular data sources and energy management strategies is presented.

This paper intends to establish a methodology for assessing the compatibility of occupant data sources and energy management strategies, but does not intend to provide a comprehensive analysis of all potential sources of occupant information. While cost-effectiveness of many sources of occupant presence data remains a limiting factor in the current day, this paper confines scope to those characteristics of occupant presence data fundamental to matching data sources with particular energy management applications. Cost-effectiveness and other factors such as deployment type (existing, network-based or installed, purpose-built), commercial availability, and concerns about occupant privacy are further discussed in Rosenblum (2011).

Phase One: Defining the Characteristics of Occupant Presence Data

It is necessary first to dissect occupant presence into levels of resolution in order to discuss which data are useful to specific energy management applications. It can be costly to try to collect a full picture of occupant presence and at times it is also impractical, since many energy management strategies can be carried out with only a semi-accurate picture of occupant presence. A description of occupant presence data is divided into three categories of resolution: temporal granularity, occupant resolution, and spatial accuracy. In the following section I establish terms to describe occupant presence data, drawing upon terms developed in collaboration with Ryan Melfi and Ken Christensen of the University of South Florida and Bruce Nordman of the Lawrence Berkeley National Lab (Melfi et al. 2011).

Temporal Granularity

Temporal granularity is defined as the level of detail in terms of time. In order to match commonly used energy data resolution, segments from low resolution to high resolution are:

- One month
- One hour
- 30 minutes
- 1 to 15 minutes
- Real-time

Occupant Resolution

Occupant resolution runs from low resolution, where we have only a small amount of information about occupants, to high resolution, where we have a good sense of what occupants are doing. Occupant resolution categories from low resolution to high are:

- Occupant trend: a general pattern of increasing or decreasing occupant presence.
- Occupied status: a binary indication of whether a space is occupied or unoccupied.
- Occupant count: the number of people in a space at any given time.
- Occupant identity: an accounting of who is in a space. If occupant identity is known, then occupant preference information can be established.
- Occupant activity: what individual occupants are doing in the building or zone, such as turning on a computer, pulling down a shade, or opening a window.

Spatial Accuracy

Spatial accuracy, or location accuracy, defines the level of detail of occupant data in terms of where people are located in a building. Spatial accuracy from low resolution to high resolution is:

- Whole building
- Floor
- Zone

- Room
- Personal workstation

Phase Two: Describing Relevant Energy Management Strategies

The following are fourteen energy management strategies that can benefit from further integration with occupant presence data. The strategies were identified based on discussions with experts in the field as well as a review of relevant literature. They are described further in Rosenblum (2011). The survey of energy management strategies is grouped into three categories: "Assessing Energy Performance," "Optimizing Automated Controls," and "Energy Simulation."

Assessing Energy Performance

These are methods of assessing the energy performance of commercial building operations, as discussed in Granderson et al. (2011), in relation to occupant presence data. This includes ways of visualizing occupant data in relation to energy consumption and energy demand data in order to assess current energy consumption and improve energy efficiency.

- Load profiling: check the shape of 24 hours or a week of interval energy data against conjectures about patterns of occupancy to identify energy waste.
- Load shape compared to occupancy: compare an overlay of binary, occupant trend, or count data to interval energy data over a period of time such as a day or week to identify energy waste.
- Simple tracking of energy use per occupant: track weekly or monthly energy consumption normalized as energy use per occupant by dividing energy data by average occupant count.
- Personal energy efficiency tracking: compare daily energy use during unoccupied hours to energy use during occupied hours for systems and equipment used by an occupant.
- Energy use vs. occupancy: assess occupancy as the independent variable and energy data as the dependant variable in a scatter plot.

Optimizing Automated Controls

These are ways of optimizing lighting (EPRI 1994), ventilation (Fisk et al. 2010), heating, cooling, and equipment controls (Roberson et al. 2004) in response to changes in occupant trends, status, count, and identity.

- Heating and cooling (whole building, zone, and room-level): liberalize heating and cooling setpoints in relation to occupant presence data to ensure that heating and cooling supply decreases when a space is unoccupied or has fewer occupants.
- Heating and cooling (personal): adjust heating and cooling supply for personal workspaces based on occupancy.
- Ventilation (whole building, zone, and room-level): regulate airflow rates in shared spaces in proportion to the number of occupants present in a space and adjust in relation to occupant activities such as opening and closing windows.

- Ventilation (personal): regulate airflow rates for personal workspaces, turning off airflow when a space is unoccupied.
- Lighting (room-level and open floor plan): decrease lighting levels, or turn off lighting, when a space is unoccupied and adjust in relation to daylighting levels.
- Lighting (personal): adjust lighting to turn off when a personal workspace is unoccupied. Integrate personal preferences for lighting levels based on occupant identity.

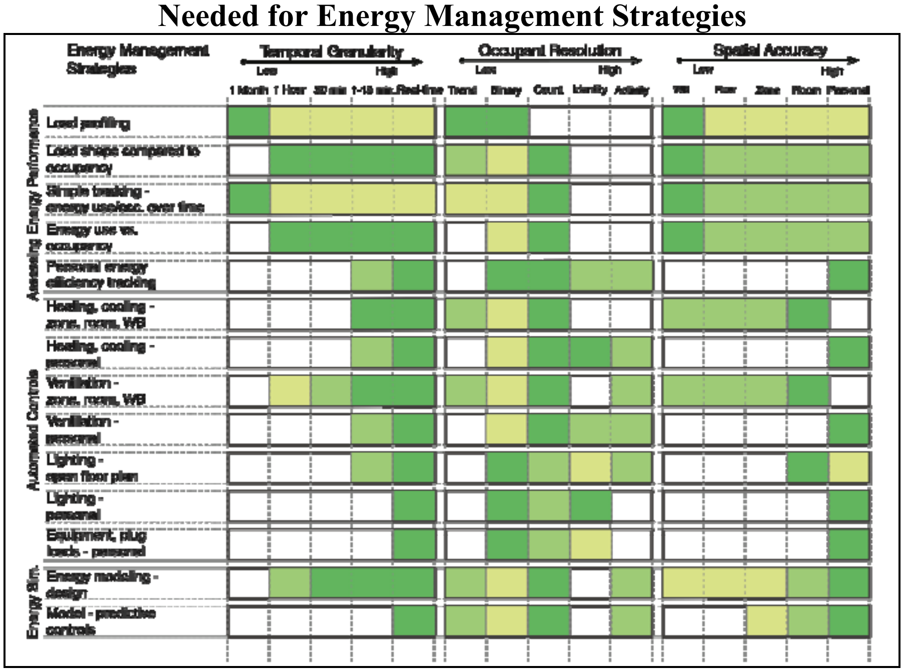
Energy Simulation

These are approaches to using simulation with occupant presence data to improve automated controls and assess the energy performance of current buildings, future retrofits, and new construction. Typically energy models only incorporate whole building binary assumed occupancy. Input with measured high-resolution occupant presence data can improve predictions (Page et al. 2008).

- Energy modeling: a simulation of predicted energy consumption incorporating real-time measured occupant count and location data.
- Model-predictive controls: building systems adjusted based on near real-time energy model predictions incorporating measured occupant presence data.

Figure 1 is a preliminary, qualitative assessment of the characteristics of occupant presence data needed for energy management strategies. Based on a literature review and discussions with experts in the field, each energy management strategy is assessed in terms of the characteristics of occupant presence data presented in phase one: temporal granularity, occupant resolution, and spatial accuracy. Dark green represents the best fit, medium green represents a decent fit, and light green is a slight fit.

Figure 1. Characteristics of Occupant Presence Data Needed for Energy Management Strategies



WB=whole building

Phase Three: Classification and Survey of Occupant Presence Data Sources

The following are twenty-three occupant presence data sources that, based on discussions with experts in the field and a review of literature, are identified as candidates for use in energy management of commercial buildings. This survey is not intended to include every possible occupant data source, but includes a wide spectrum of options with a mix of more conventional installed data sources and data sources based on networks and other infrastructure. Networks and software-based solutions offer the distinct advantage of existing infrastructure for non-energy purposes, therefore minimizing the cost of data gathering. Rosenblum (2011) includes a further review of the qualities of the data sources. The occupant data sources are grouped into six categories: "Basic Proxies," "Direct Presence Detection," "Passive Access Cards," "Wired Network and Software-based Solutions," "Wireless Network-based Solutions," and "Wireless Network-based Solutions with Active Badges." The data sources are grouped based on how they record physical traits of occupants, whether they require occupants to carry a device of some sort, and whether they are installed for energy management purposes or based on existing network infrastructure.

Basic Proxies

Basic proxies are sources of occupant presence data based on general trends of occupancy and involve human-in-the-loop, manual data processing, and guess work (Piette & Khalsa 1998).

- Whole-building conjectures: an educated guess is made about expected hours of occupancy in order to establish system hours of operation.
- Room schedules: an existing log of times of day and week when a particular room, often a conference room or classroom, has been reserved.
- Water meter data: water use throughout the building over a period of time; when occupancy increases, water use in bathrooms, kitchens, and lab activities also increases.

Direct Presence Detection

This category of occupancy data sources involves detecting the physical traits or movement of occupants and does not require occupants to carry additional sensing devices. These are discussed in studies such as Fisk et al. (2010), Kamthe et al. (2009), Dhummi et al. (2010), and Tiller et al. (2010).

- Passive infrared (PIR) detection (wall- or ceiling-mounted): detects changes in non-visible infrared radiation, warmth given off by occupants, within the field of view of a large-aperture Fresnel lens.
- Passive infrared (PIR) detection (workstation or desk-mounted): the same Fresnel lens technology, but installed under a desk or on a cubicle partition.
- Ultrasonic detection: sends a high frequency acoustic signal through a space and then senses the frequency at which the signal returns with changes in frequency interpreted as motion by occupants.

- Microphonic detection: listens for human noise and tunes out other sounds and is usually integrated into dual-technology sensors with either PIR or ultrasonic capabilities.
- Direct-contact detection: measures body heat or body weight through direct contact with occupants and can be deployed in chairs, beds, or other surfaces.
- CO_2 sensors: measures the level of CO_2 in the air in the location where the sensor is deployed. Since people exhale CO_2 in the process of respiration, the concentration of CO_2 in an indoor space suggests the presence of people in the space.
- Basic people counters: sends a horizontal or vertical infrared beam past a door, recording the entering and exiting of people from a space, but typically not the direction of travel.
- Camera-based people counters: captures images of occupants using pre-existing or installed cameras. Assesses location and count based on algorithms.
- Thermal-imaging people counters: tracks the movement of occupant body heat through doorways and other transition boundaries. Tracks multiple people walking through a door simultaneously and records direction of travel.

Passive Access Cards

These systems can provide occupancy information and can be directly integrated with controls, but occupants must carry a card, which is detected when passing by or through fixed access point card readers at building or room entrances.

- Personal access cards: identify individual occupants as they pass from one location to another through a controlled entry point. Technologies include magnetic strips, bar codes, smart cards, and passive radio frequency identification (RFID).
- Key cards: record occupied status when card is inserted in card reader, unlocking door.

Wired Network and Software-based Solutions

These occupant data sources imply occupancy since when an occupant is at her desk she is often using a computer. Reliable records of equipment location can provide higher spatial resolution occupant data. These technologies are further discussed in Melfi et al. (2011).

- Wired network and ARP data: a list of the location and amount of time that desktop computers are connected to the Internet by way of network routers.
- Activity monitors: software installed on a computer that tracks occupant keyboard use and mouse clicks.

Wireless Network-based Solutions

Occupant presence data could be gathered by tracking devices such as laptops, mobile phones, and tablets that are connected to access points (APs) on existing Wi-Fi networks (Cisco 2008). Devices connected to access points are used as proxies for the occupants who use the devices (Melfi et al. 2011).

- Closest access point sensing: records the time that a user's wireless device is connected to an access point, generally the closest, since it has the strongest signal. The range and density of access points in a given building determines spatial accuracy.
- Triangulation: assesses device location based on signal strength data from multiple access points, as opposed to a single access point, increasing spatial accuracy.
- Radio frequency (RF) fingerprinting: compares the actual RF signal of a wireless device to unique predicted RF signals mapped on a floor plan. Unique signals result from reflection, attenuation, and multi-path caused by physical qualities of a space.

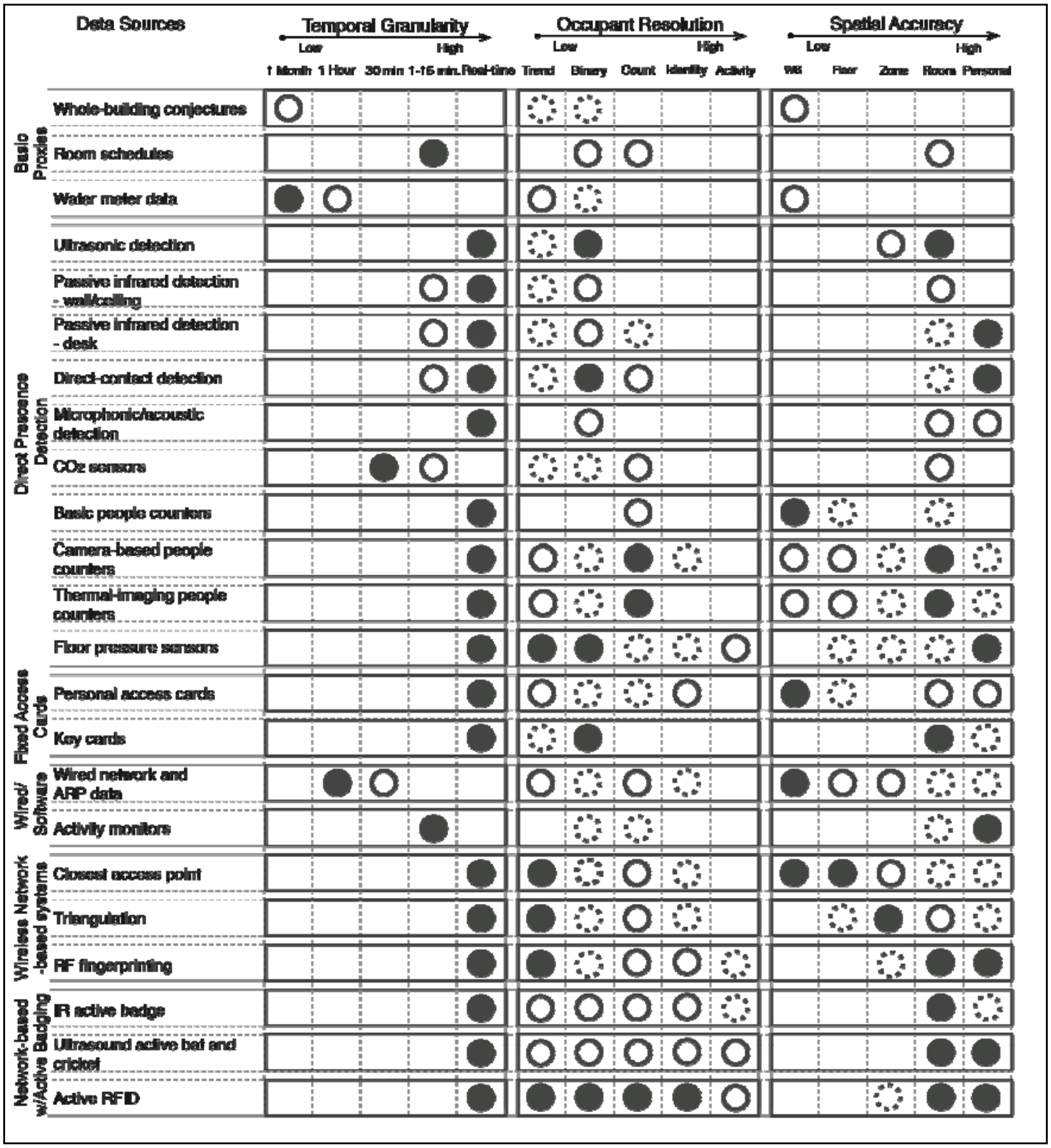
Wireless Network-based Solutions with Active Badges

Active badge systems require occupants to carry a badge or tag that is communicating in real time with a network of sensors. Active RFID tags, for example, are discussed in Li et al. (2011). The signals thus exchanged as a result identify the badge and send location information of the occupant back to a central server.

- IR active badges: an identifier is emitted from a transmitter worn by each occupant to a series of infrared receivers with direct line of sight to the identifiers.
- Ultrasound active badges: a pulse is emitted from a transmitter worn by each occupant and a series of ultrasonic receivers calculates the time taken to receive the pulse.
- Active radio frequency identification tags (RFID): tags worn by each occupant continuously broadcast over radio waves to RFID readers installed throughout a space.

Figure 2 is a preliminary assessment of the characteristics of occupant presence data provided by the occupant data sources. Each occupant data source is evaluated in terms of the qualities of occupant presence data from phase one: temporal granularity, occupant resolution, and spatial accuracy. The circles indicate resolution levels provided, as well as the degree of precision—the percentage of time that a certain resolution is achieved—of occupant information recorded. Filled-in circles represent a high level of precision over 75%, an open circle represents precision from 35% to 75%, and a dotted circle implies precision lower than 35%. Preliminary values in the chart are assigned based on data from prior research studies, further discussed in Rosenblum (2011), and for two data sources—PIR workstation sensors and DHCP closest access point data—values are refined based on field study results presented in phase four of this paper.

**Figure 2. Characteristics of Occupant Presence Data
Provided by Occupant Data Sources**



WB=whole building

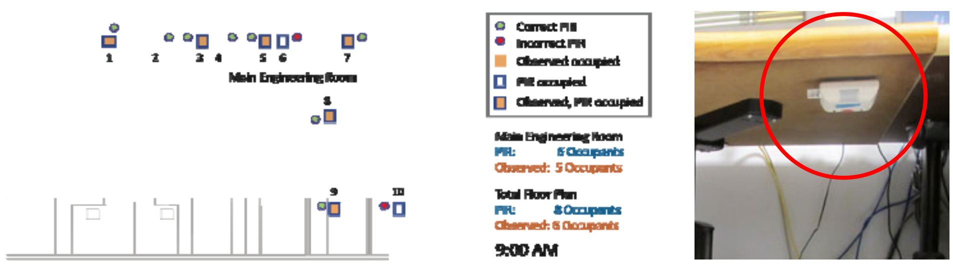
Phase Four: Measured Occupant Presence Data at Two Field Studies

To demonstrate how measured occupant presence data can be translated into the Figure 2 chart, two occupant data sources—PIR sensors installed at workstations and DHCP logs using the wireless closest access point method—are evaluated at two sites in Northern California. Observed occupant patterns are compared to measured data to assess resolution levels and degree of precision.

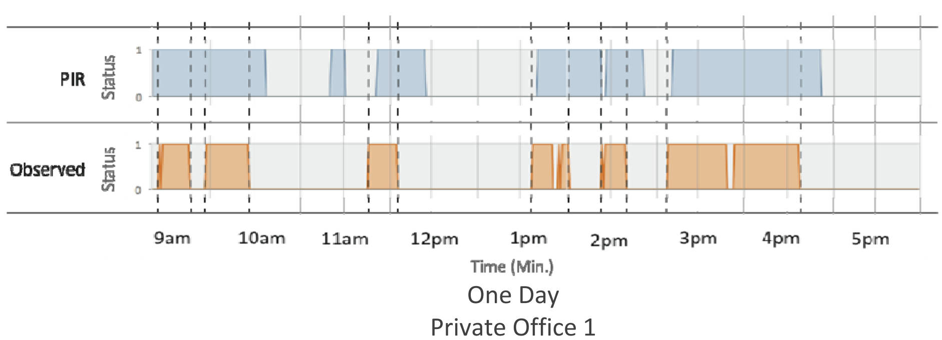
Site one is 2000 ft^2 of private offices and workstations on the 6^{th} floor of the West Tower of the Adobe Systems headquarters building in San Jose, California. Ten passive infrared (PIR) sensors are installed at ten desks (three private offices and seven workstations).

Figure 3 shows a floor plan of the office space (upper left), an image of a PIR sensor (upper right), and precision data for desk 1, one of the private offices, shown in the upper left of the floor plan. The lower image shows observed occupant data, used as a ground truth, compared to PIR data for an entire day. For private office 1, observed status was compared to PIR logged status for nine times of day (on the hour from 9am to 5pm). As shown in Figure 3, the precision, or ratio of correct PIR status to observed status, was 7 out of 9, or 77%. Average precision for all ten desks is 73%. Referring back to qualities provided by PIR sensors in Figure 2, an open circle has been assigned for binary occupied status, since PIR provides a medium level of precision, close to a high level of precision. Trend and count data can be gathered from PIR data, but since PIR does not separate one individual near the sensor from another, count and trend data are of low precision. PIR data provide real time temporal granularity and personal spatial accuracy.

Figure 3. Ratio of PIR Sensor Data to Observed Data at Site One



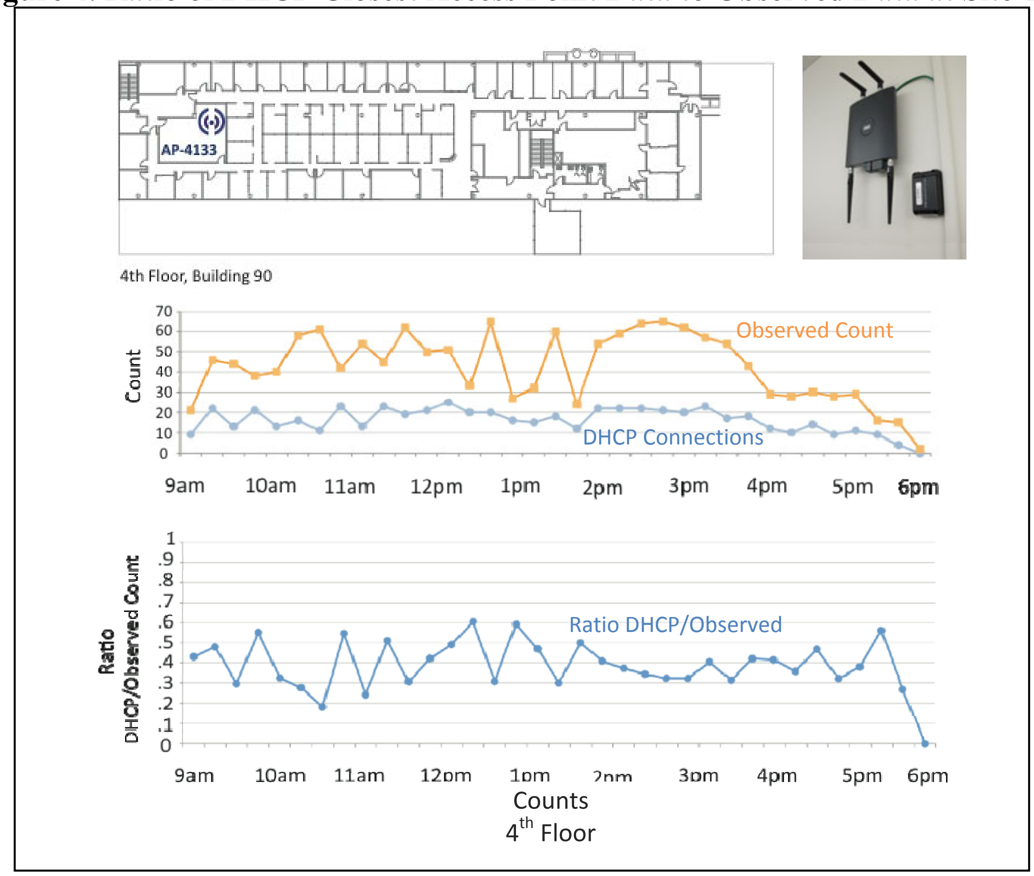
Desk #	Desk Type	Observed Occupied/ Positive	PIR Logged Correct	Positive Status Precision	Observed Unoccupied /Negative	PIR Logged Correct	Negative Status Precision	Overall Precision
1	Private	4	4	100%	5	3	60%	77%



Site two is Building 90 (B90), a four-story multi-purpose office building at the Lawrence Berkeley National Lab in Berkeley, California. Occupant presence data are gathered from the existing wireless DHCP logs, an existing data source, using the closest access point method. The wireless DHCP log has a record of the time that each wireless device in the building connects and disconnects from a particular access point. The data can be aggregated into a count of the number of devices on an access point at any given time and used as a proxy for the number of occupants in a space covered by the access point as discussed in Melfi et al. (2011).

Figure 4 shows a floor plan with the location of an access point, AP-4133, on the 4th floor (upper left) and an image of the access point (upper right). Observed occupant count (orange line) for the 4th floor of B90 was recorded on 34 occasions and then compared to the number of wireless devices (light blue line) connected to the 4th floor access point (AP-4133). The ratio of connected devices to observed count (blue line, lower image) is consistently around .40, where a ratio of 1 would imply one connected device per occupant. Since the ratio of .40 is consistent, a conversion factor of 2.5 (the number of DHCP devices multiplied by 2.5 equals the approximate number of occupants present at any given time) could be used to arrive at a reasonably precise occupant count. As further explored in Rosenblum (2011), the low ratio of connected devices to observed occupant count could result partially from connections to access points one floor down on the third floor, as opposed to the 4th floor access point, as a result of inter-floor signal strength. Referring to the qualities provided by closest access point data in Figure 2, an open circle has been assigned for zone level spatial accuracy and a filled-in circle for floor and whole building level spatial accuracy. Occupant count receives an open circle, occupant trend is assigned a filled-in circle, while temporal resolution is assigned as real time.

Figure 4. Ratio of DHCP Closest Access Point Data to Observed Data at Site Two



Source: Adapted from Melfi et al. 2011

Phase Five: Framework for Assessing Compatibility between Data Sources and Energy Management Strategies

Phases one through four provide the structure for carrying out the fifth and final phase. Phase five establishes a framework for energy managers and other decision makers to assess the compatibility of particular occupant presence data sources with particular energy management strategies. The two summary charts introduced earlier, Figures 1 and 2, are based on the same format and can therefore be used together to visually link occupant data sources to energy management strategies as will be described in this section.

Two Types of Assessment Charts

There are two typical cases where energy managers of commercial buildings would need to consider the compatibility of occupant data sources with energy management strategies:

1) The first case is where an energy manager has a particular energy management strategy in mind and she would like to identify which occupant data source to utilize. She could compare the occupant presence characteristics provided by a whole spectrum of data sources against the characteristics needed to carry out a particular energy management strategy. A Type 1 Assessment, shown in Figure 5, is carried out where one row taken from the Figure 1 energy management chart, the green squares of a particular energy management strategy, is an overlay on top of the circles of the occupant data source chart, Figure 2. As an example, Figure 5 shows the green squares of ventilation controls as an overlay on all of the occupant data sources. The image on the right in Figure 5 is the resulting assessment chart.

2) In the second case, the energy manager has a candidate occupant data source available. He would like to identify the energy management strategies that can be most improved by integrating occupant presence data from that particular data source. A Type 2 Assessment, shown in Figure 6, is carried out where one row taken from Figure 2, the circles of a particular data source, is an overlay on top of all of the green squares of the Figure 1 energy management chart. As an example, wireless DHCP closest access point data, as discussed in the phase four B90 field study, is an overlay on all of the energy management strategies. The image on the right in Figure 6 is the resulting assessment chart.

Any of the fourteen different energy management strategies can be an overlay on the occupant data sources (type 1 assessment) and any of the twenty-three data sources can be an overlay on the energy management strategies (type 2 assessment). By overlaying the two charts, the degree of fit can be assessed between the circles of the occupant data source chart, Figure 2, and the squares of the energy management chart, Figure 1. The overall degree of fit between an energy management strategy and an occupant data source is noted at the right of the chart under the big "degree of fit" arrow. Matches where a filled in circle fits into a dark- or medium-green square for all three types of resolution (temporal, spatial, and occupant) receive a filled-in green circle in the degree of fit column since overall they are highly compatible. A black open circle on a dark-green square or a filled-in black circle on a medium-green square are also reasonably good matches, and receive an open green circle. A black dotted circle on a light-green square is a more tenuous, less than ideal fit, and receives a dotted green circle under the "degree of fit" arrow.

Referring to closest access point data as discussed in the phase four B90 field study, Figure 7 shows DHCP closest access point data as an overlay on energy management strategies.

As was indicated in phase four, the precision of closest access point data at the spatial resolution of a zone is sufficient, but not ideal for zone-level heating, cooling, and ventilation. As seen in Figure 7, both heating and cooling controls and ventilation controls receive an open green circle under the “degree of fit” arrow, as does simple tracking and model-predictive controls. Since closest access point data provide high precision occupant trend data, load shape compared to occupancy and energy use vs. occupancy, as well as energy modeling for design, receive filled-in green circles.

Figure 5. Diagram of Type 1 Assessment of Compatibility Between Ventilation Controls and Occupant Presence Data Sources

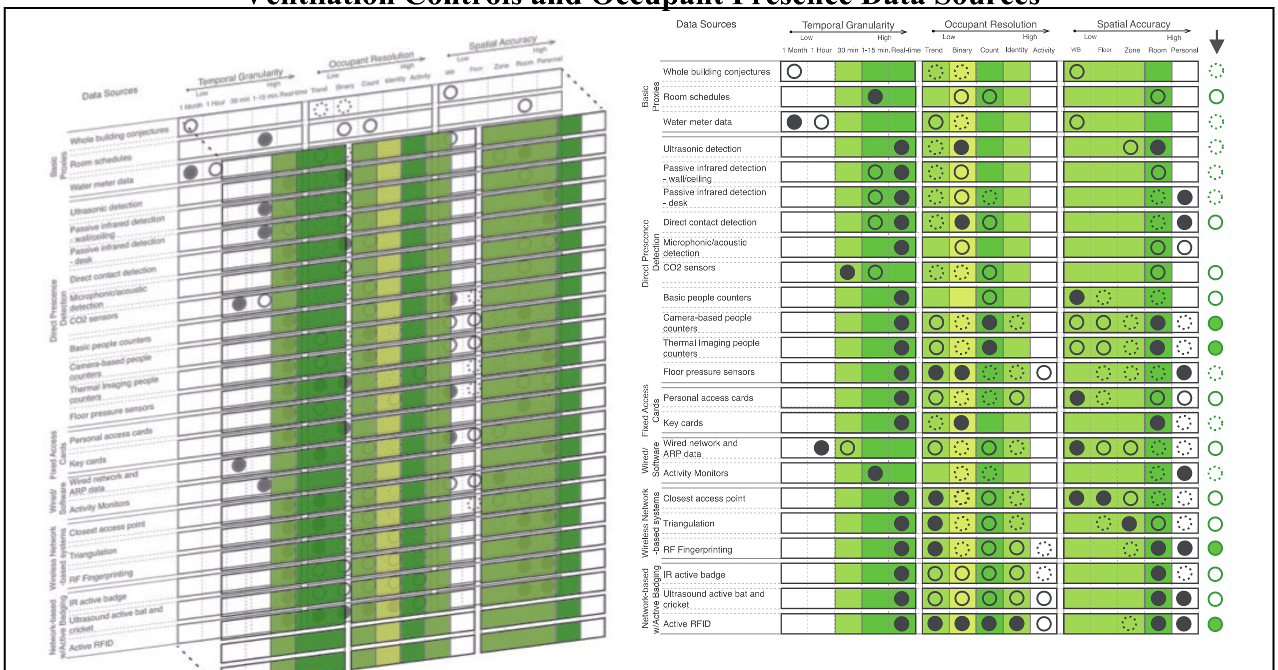


Figure 6. Diagram of Type 2 Assessment of Compatibility Between DHCP Closest Access Point Data and Energy Management Strategies

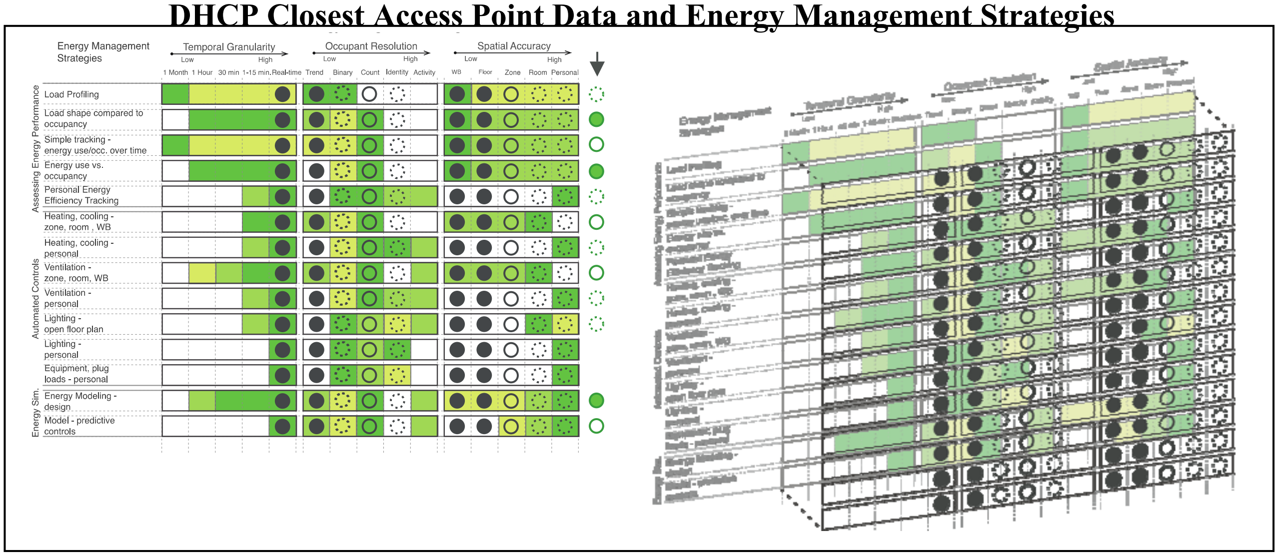
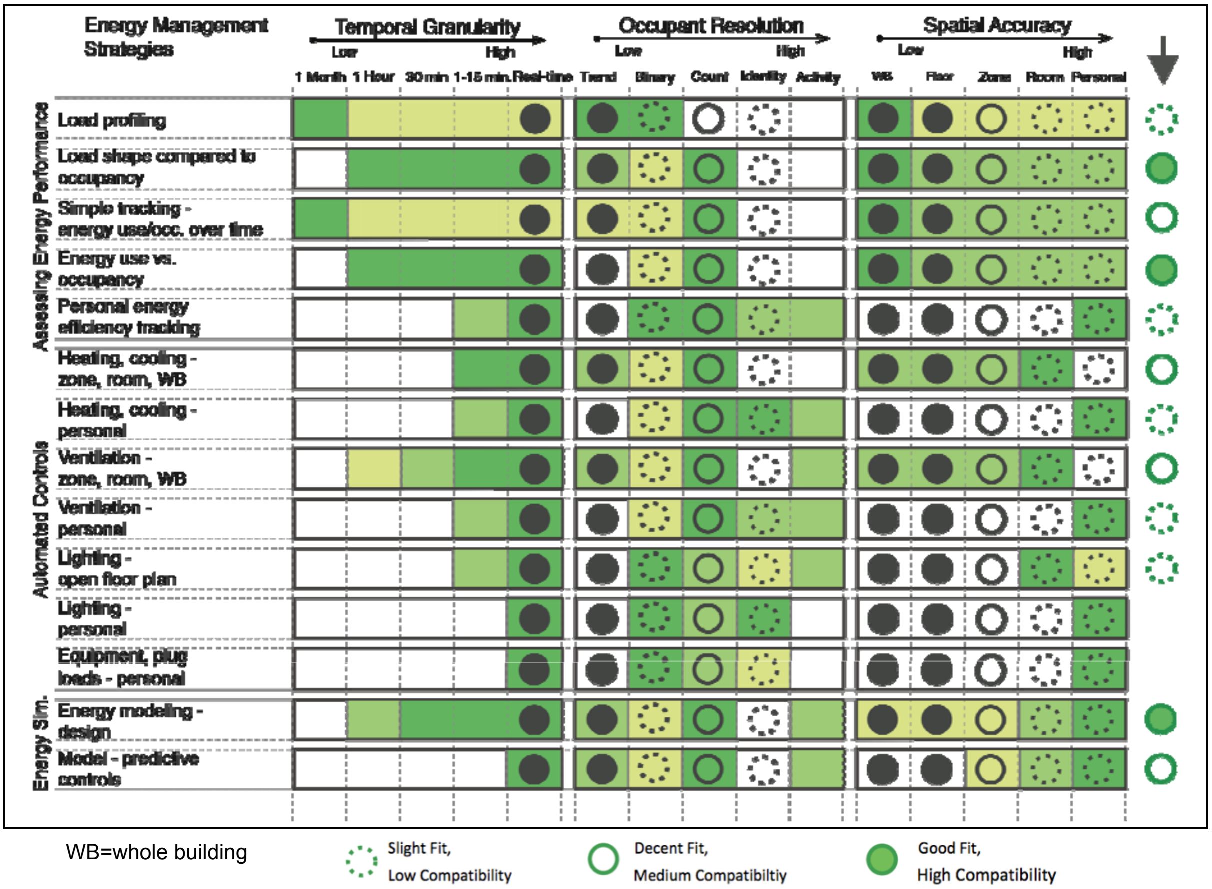


Figure 7. Type 2 Assessment of Compatibility Between
DHCP Closest Access Point Data and Energy Management Strategies



Conclusion

This paper has established a framework for assessing sources of occupant presence data in relation to energy management strategies. This preliminary framework can help energy managers and other decision makers better integrate occupant presence data into energy management in order to decrease energy consumption in commercial buildings through both behavior change and improved system controls. The summary charts presented are intended as a qualitative first attempt to assess, compare, and contrast occupant data sources and relevant energy management strategies. The characteristics of occupant presence data are expected to adjust to new quantitative research and advancements in technology. Future field experiments, similar to those carried out in phase four, could refine the resolution levels of all of the occupant data sources. Wireless network-based and active badging technologies in particular are still in early phases of development and need further analysis.

Beyond further testing particular occupant presence data sources, the process of assessing compatibility between occupant data sources and energy management strategies could be further automated by developing an algorithm that correlates all energy management strategies with all occupant data sources. This potential algorithm, and corresponding database, could be supplemented by a user-friendly Web interface that allows a user to enter any data source or energy management strategy and receive recommendations of matches based on compatibility and particular building conditions.

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