Annex 66: Definition and Simulation of Occupant Behavior in Buildings

Technical Report: Studying Occupant Behavior in Buildings: Methods and Challenges

November 2017

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Table of Content

Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 29 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the Energy in Buildings and Communities (EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)

Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy & CO2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building & Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling
Annex 63: Implementation of Energy Strategies in Communities
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behavior in Buildings
Annex 67: Energy Flexible Buildings
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - Survey on HVAC Energy Calculation Methodologies for Non-residential Buildings

Introduction to Annex 66

Energy-related occupant behavior in buildings is a key issue for building design optimization, energy diagnosis, performance evaluation, and building energy simulation. Actions such as adjusting the thermostat for comfort, switching lights, opening/closing windows, pulling up/down window blinds, and moving between spaces, can have a significant impact on the real energy use and indoor environmental quality in buildings. Having a deeper understanding of occupant behavior, and quantifying their impact on the use of building technologies and building performance with modeling and simulation tools is crucial to the design and operation of low energy buildings where human-building interactions are the key. However, the influence of occupant behavior is under-recognized or over-simplified in the design, construction, operation, and retrofit of buildings.

Occupant behavior is complex and requires a multi-disciplinary approach if it is ever to be fully understood (Figure 1). On one hand, occupant behavior is influenced by external factors such as culture, economy and climate, as well as internal factors such as individual comfort preference, physiology, and psychology; On the other hand, occupant behavior drives occupants' interactions with building systems which strongly influence the building operations and thus energy use/cost and indoor comfort, which in-turn influences occupant behavior thus forming a closed loop.

There are over 20 groups all over the world studying occupant behavior individually. However, existing studies on occupant behavior, mainly from the perspective of sociology, lack in-depth quantitative analysis. Furthermore, the occupant behavior models developed by different researchers are often inconsistent, with a lack of consensus in common language, in good experimental design and in modeling methodologies. Therefore, there is a strong need for researchers to work together on a consistent and standard framework of occupant behavior definition and simulation methodology.

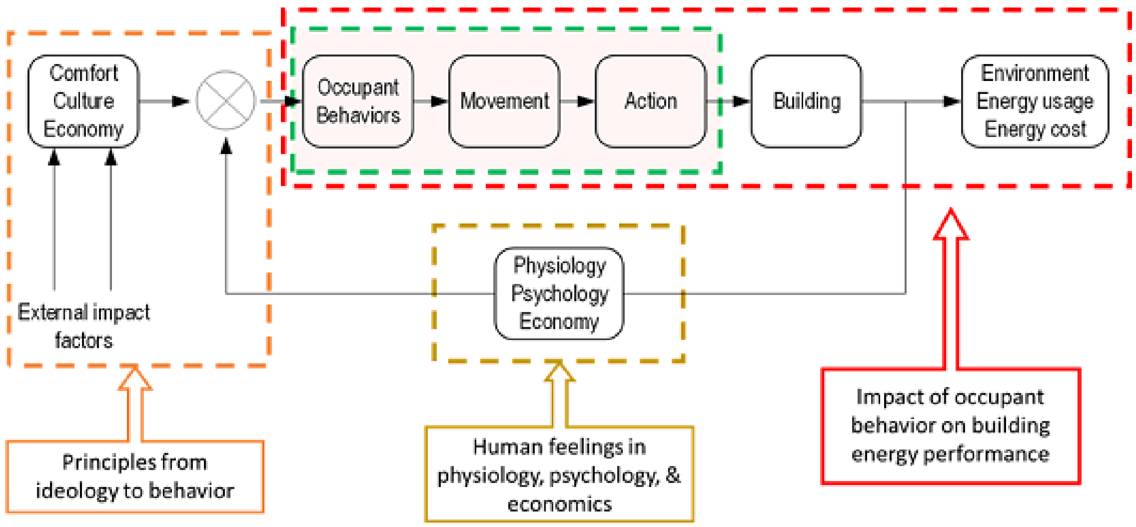

Figure 1: Relationship between occupants and buildings

The Annex 66 project was approved unanimously at the 74th Executive Committee Meeting of the International Energy Agency's Energy in Buildings and Communities Programme, held on 14th November 2013 in Dublin, Ireland. Operating Agents are Dr. Da Yan of Tsinghua University and Dr. Tianzhen Hong of Lawrence Berkeley National Laboratory. The Annex aims to (1) set up a standard occupant behavior definition platform, (2) establish a quantitative simulation methodology to model occupant behavior in buildings, and (3) understand the influence of occupant behavior on building energy use and the indoor environment. The project has five subtasks:

Subtask A – Occupant movement and presence models. Simulating occupant movement and presence is fundamental to occupant behavior research. The main objective of the subtask is to provide a standard definition and simulation methodology to represent how an occupant presents in his/her office and moves between spaces.

Subtask B – Occupant action models in residential buildings. Occupant action behavior in residential buildings affects building performance significantly. This subtask aims to provide a standard description for occupant action behavior simulation, systematic measurement approach, and modeling and validation methodology for residential buildings.

Subtask C – Occupant action models in commercial buildings. Some specific challenges of occupant behavior modeling exist in commercial buildings, where occupant behavior is of high spatial and functionality diversity. This subtask aims to provide a standard description for occupant action behavior simulation, systematic measurement approach, and modeling and validation methodology for commercial buildings.

Subtask D – Development of new occupant behavior definition and modeling tools, and integrating them with current building performance simulation programs. This subtask will enable applications by researchers, practitioners, and policy makers and promote third-party software development and integration. A framework for an XML schema and a software module of occupant behavior models are the main outcomes.

Subtask E – Applications in building design and operations. This subtask will provide case studies to demonstrate applications of the new occupant behavior modeling tools. The occupant behavior modeling tools can be used by building designers, energy saving evaluators, building operators, and energy policy makers. Case studies will verify the applicability of the developed modeling tools by comparing the measured and simulated results.

17 countries and 123 participants from universities, research institutes, software companies, design consultant companies, operation managers, and system control companies participated in this Annex. All parties expressed an interest in developing a robust understanding of energy-related occupant behavior in buildings, via international collaboration on developing research methodologies and simulation tools that can bridge the gap between occupant behavior and the built environment. The Preparation Phase started in November 2013 and continued through November 2014. The Working Phase started in December 2014 and lasted for two and a half years. The Reporting Phase took place from July 2017 to May 2018.

1. Introduction

According to IEA, buildings are the largest energy-consuming sector in the world, and account for over one-third of total final energy consumption[1]. This consumption not only differs widely due to available technologies providing comfort and fulfilling individual requests, or due to climatic, societal, cultural and social backgrounds in different parts of the world, but also – to a significant extent – due to occupant behavior in buildings. With tightening requirements for building energy performance and sustainability, researchers, and increasingly also architects, planners, and building managers, have begun to recognize the importance of occupants' behavioral and presence patterns. Numerous studies have found that occupants can significantly influence energy consumption, even in buildings with identical structures[2]. However, researchers have only started to understand, let alone accurately predict this phenomenon. Occupant actions such as adjusting a thermostat or opening a window can be related to a whole variety of different drivers, including physical, physiological, psychological, and social factors. As buildings should be designed and operated to meet a whole set of ambitious performance objectives, the uncertainty of occupant behavior poses a major challenge. Given the great progress that has been made predicting the energy performance of a building with regards to physics-based phenomena, it is most desirable to also unlock the untapped potential of behavioral energy savings.

An essential step forward to meet this challenge is the collection of representative data. These could be derived either from real-life buildings (in-situ measurements, surveys) or laboratory experiments. Resolution, accuracy and explanatory power of the data strongly depend on the chosen methodology. Regardless from the approach, monitoring occupant behavior mostly requires a substantial sensor infrastructure and other investments; and privacy and ethical issues make data collection difficult. Hence, there is a lack of consistent data from real-life building operation to be overcome.

What can then be done with occupant data? The answer is plenty. Most applications for occupant data, such as developing models to support design and improving controls and operations, have been vastly underexploited. One major focus is on using occupant data to better predict occupancy and occupants' behavior in building performance simulation. In order to help design comfortable and energy efficient spaces, and not greatly oversize equipment due to the uncertainty of occupants, a more accurate (model) representation of occupants about

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[1] OECD/IEA (2013), Transition to Sustainable Buildings - Strategies and Opportunities to 2050. http://www.iea.org/Textbase/npsum/building2013SUM.pdf

[2] e.g. S. Chen et. al., Definition of occupant behavior in residential buildings and its application to behavior analysis in case studies Energy Build, 104 (2015), pp. 1-13. D. Calì et. al., Energy performance gap in refurbished German dwellings: lesson learned from a field test, Energy Build, 127 (2016), pp. 1146-1158

which designers are confident will be invaluable. The same model could later be used for performance optimization within the building management system. Furthermore, an equally important pursuit is to use occupant data to make inferences about the relationship between a building and its occupants so that future building designs are superior with regards to energy and comfort performance. For instance, if reoccurring patterns of occupants are observed – like closed blinds on west-facing windows during every afternoon, this could result in alternative design solutions with regard to zoning, façade design or choice of shading device. For existing buildings, data collected about occupants can be applied to controls, operations, and renovations. As an example, knowledge of the distribution of arrival times for occupants can help inform a more efficient operating schedule.

While the strong surge of interest has spurred considerable research, there is a definite lack of a consistent research framework about which to tackle the complexities of the field of building occupancy and occupants' behavior. The freshness of the field has resulted in a hodgepodge of research approaches and results. Oftentimes, the studies are so inconsistent that external validation is totally impossible. To further complicate matters, the study of building occupants spans multiple fields of research including engineering, architecture, information technologies and social sciences to name the most relevant. Thus, individual traditional researchers are rarely equipped with the tools and knowledge to comprehensively approach new research projects in the field. It was only with the implementation of a multi-disciplinary and international group of researchers who were brought together under the umbrella of the International Energy Agency – Energy in Buildings and Communities Programme project Annex 66 on "Definition and simulation of occupant behavior in buildings", that this concerted work was made possible.

High Quality occupant studies are challenging, costly, and time-consuming due to the aforementioned interdisciplinary knowledge and resources. Beyond this other technical and design challenges exist, sensors may malfunction, certain behaviors may be difficult to measure, numbers of participants for an experiment may not be sufficient for statistical evaluation, results may be counterintuitive and inexplicable, and participants may cause a host of problems.

The objective of this report is to guide researchers who are about to embark on a building occupant research campaign so that they can avoid some of the major pitfalls associated with occupant studies. It is targeted at graduate students and other researchers who have decided to plunge into the exciting world of occupant research. The structure follows a chronological order to guide researchers through occupant studies: from conception and design, through the study and validation phases; this report also addresses the critical issues of data management and ethics. Given of the multi-disciplinary nature of this research, a broad roster of expert authors from around the world has contributed to this work. Undoubtedly, the diligent researcher will read beyond this report as needed. A book on 'Exploring Occupant Behavior in Buildings - Methods and Challenges' which has been published by Springer in parallel to Annex 66, may serve for this purpose. This deliverable is designed to serve as a comprehensive overview of the research methods used in the context of building occupant research.

2. Occupancy and Occupants' Actions

Understanding occupants' presence and actions within the built environment is a crucial aspect to begin to characterize and quantify variations in the energy use. The main purpose of this section is to introduce readers to the diverse occupancy and occupant behavior-related phenomena that should be considered prior to conducting experimental, modeling, or simulation-based research studies. It serves as a basis for the following chapters of this report. Within this section, first, a nomenclature for the field of research dealing with occupants in buildings is defined. This nomenclature distinguishes between occupants' presence and behavior, states and actions, adaptive triggers, non-adaptive triggers, and contextual factors. Secondly, an extensive list of occupant behaviors is provided and categorizations of occupants' actions are introduced. The list includes most of the possible phenomena that researchers may wish to study, measure, and ultimately model. The categories are physiological, individual, environmental, and spatial adjustments. Third, a list of adaptive and non-adaptive triggers together with contextual factors that could influence occupant behavior is presented. Individual elements are further grouped into physical environmental, physiological, psychological, and social aspects. Finally, a comprehensive literature review was performed in order to assess some of major patterns, trends and weaknesses of the past and current occupant research (the detailed literature review is not included in this report). The conclusions highlight the importance to publish future occupant monitoring campaigns with significant details to inform future researchers and save redundant effort. Such details are necessary related to the methodology including for example a clear description of the type of variables monitored, and related to the results, where both the influencing factors that were found to be significant and insignificant should be documented.

All occupant-related phenomena that impact building energy performance, comfort, and occupant satisfaction are presented and defined in this section (see Figure 2.1). Occupants can impact buildings in two ways: through the direct impact of their presence (heat production, carbon dioxide emission, moisture generation, etc.) and through their interactions with the building. In most buildings with traditional technologies, presence of occupants is the prerequisite for any behavior, since occupants can only interact with the controls and the building envelope if they are present in the building. This assumption does not hold true for controls that can be adjusted remotely by occupants (e.g., smart WiFi-enabled thermostats).

Occupants' presence and behavior can be modeled as *states* and *actions* using different modeling approaches. In general, the action changes the state and the state remains constant until a new action is taken (e.g., the state of the window will remain closed until an occupant opens it). State changes can be triggered by either *adaptive triggers* (those which are rooted in occupant discomfort or expectations of discomfort) or *non-adaptive triggers* (those which are part of occupant tasks, like using a computer). These triggers as well as the resulting *action* or *non-action* are moderated by *contextual factors*. The adaptive triggers activate adaptive behaviors such as opening windows due to increasing carbon dioxide or closing blinds due to glare. Non-adaptive triggers activate behavior that is not performed with the goal of adapting to the indoor environment.

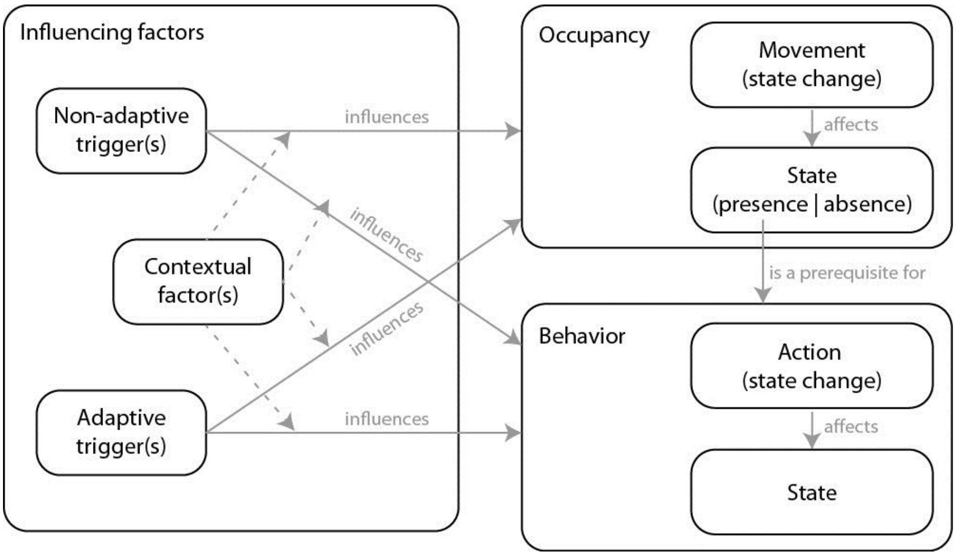

Figure 2.1: Ontology of occupant-related phenomena

An overview of those triggers and contextual factors that have been studied in the past or based on discussion between the authors that can influence occupancy and/or occupants' behavioral patterns is given in Figure 2.2.

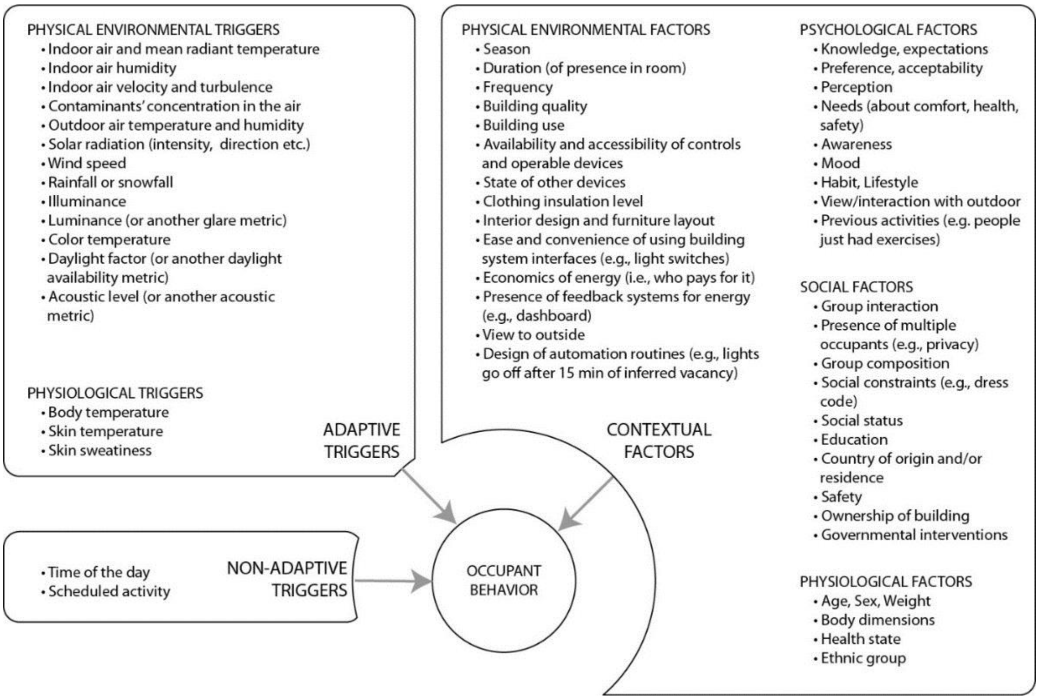

Figure 2.2: Potential influencing factors driving occupants' behavior in a building

In an ideal world, a monitoring campaign with respect to occupancy and occupants' actions would include all potential influencing factors described in the previous section. In reality, however, financial resources and therewith the number of observed factors are limited. Before starting a monitoring campaign it is thus important to balance the cost of potentially necessary devices (data points) and the results potentially obtained by their implementation. The decision to include or exclude a certain variable is best made based on results from previous studies.

Among the occupant action domains explored in the literature, some have benefitted from decades of research in diverse contexts, while others have been seldom studied. The predominant actions that have been researched more extensively include: window opening in both commercial and residential buildings; occupant control of heating and cooling in homes; and window blind and lighting control in office buildings. However, many domains require much more research, including: occupant posture, occupant repositioning in response to discomfort, and lighting use in residential buildings, and many others.

Occupant behavior is influenced by a large number of complex variables that extend well beyond physical phenomena to include social and psychological factors. Researchers should take considerable care and rigor in both measuring and documenting these phenomena. Model users must be made aware of the contexts upon which observational studies and models were built upon, otherwise, models may be applied in entirely different and inappropriate building contexts.

One of the conclusions of the current review of the literature is that it is crucial for future occupant monitoring campaigns to be published with sufficient detail to inform future researchers and avoid redundant effort. Contrary to common practice, both the influencing factors that were found to be significant and those found to be insignificant should be documented. If several comprehensive studies indicate that a given variable is not a significant predictor in a particular domain, future studies can avoid diverting limited resources towards that variable. Moreover, the statistical significance of predictive variables should be determined and reported, as currently there is a large degree of variability in the literature in this regard. It is likewise critical to have consistent reporting of other technical terms. For instance, the literature reveals that numerous papers did not specify whether “interior temperature” refers to indoor air temperature, operative temperature, mean radiant temperature, or even internal body temperature. Precision and consistency in the usage of terms is essential for the field of occupant research to move forward.

3. Research Design

The aim of this section is to set out a process that researchers can follow to design a robust study for quantitative research on occupant behavior in buildings. The material is introductory, and is intended to provide an overarching framework for thinking about the research design process.

It is important to note that this section takes a broadly quantitative social and physical 'realist' approach to researching occupant influences on energy demand in buildings. This arises from the annex's origin which is to improve the representation of building occupants and their influences on energy demand within building energy simulation models which are themselves quantitative and realist in their representation of the world. The aim is therefore to establish relationships (ideally causative ones) between the external environment, the building and its internal environment, occupant behavior, and building energy consumption.

Taking a 'realist' approach means that there are occupants' actions that directly affect energy demand in buildings, and that these actions can in part be explained through the use of concepts that are independent of the researcher and the individual occupants themselves. A realist approach takes the view that while these concepts can never be measured perfectly (i.e. without any error), – they can be measured and used to (imperfectly) predict occupant behavior. The section therefore does not take a purely social constructivist approach of saying that occupant influences on energy use in buildings are purely a construct of human social processes with no meaning or existence outside of the individual occupants engaged in them. It thus places this work more in the context of such academic disciplines as physics, psychology, quantitative social science and behavioral economics – than such academic disciplines as qualitative sociology, anthropology and ethnography.

Occupant behavior in buildings research must be fit for purpose. To be fit for purpose, the purpose must be known and the findings of the research must fall within acceptable margins of error for that purpose. Therefore, to be useful, research must not only produce findings, but also quantify the uncertainty in those findings to show they lie within the acceptable margins of error for that purpose. To achieve this requires both quantifying uncertainty, but more importantly designing-out enough uncertainty to fall within required error margins. Accepting that things cannot be measured perfectly, mapping the theoretical model, choosing an appropriate research design, and selecting and applying appropriate methods all help in reducing uncertainty.

Central to the approach taken here is an emphasis on intellectual clarity around what is being measured and why, and literally drawing this out in the form of a theoretical model of the cause and effect relationships between occupant motivations and energy use in the form of a concept map. Making this explicit through concept mapping requires representing the concepts being explored as nodes, and the relationships between those concepts as links (see Figure 3.1). Having captured diagrammatically how the system is thought to work, the next step is to formulate research questions and hypotheses capturing the relationship between variables in the theoretical model, and to start to augment the diagram with the measurands (things that can actually be measured) that are good proxies for each concept. Once these are identified, the diagram can be further augmented with one or more methods of measuring each measurand. This approach also provides a framework for the writing of pre-analysis plans, which help researchers clearly articulate their proposed methods of analysis prior to collecting their data, thus helping to guard against malpractice, such as searching for statistically significant relationships between variables that were not the original intent of the study.

Having established the theoretical model, the next step is to delineate the scope of its applicability. This will require a clear statement of population of interest, i.e., the population of units of analysis the theoretical model is supposed to represent. This also goes in line with the choice between descriptive and inferential statistics which will fundamentally shape the research and the conclusions that can be drawn.

In research adopting a realist approach, be it qualitative or quantitative, it is necessary to carefully define concepts and their presumed relationships, and to clearly state research questions and what the researcher intends to measure before starting data collection. Some higher forms of analysis are only applicable to quantitative research approaches, such quantifying reliability; however, an awareness of the idea of reliability, validity, and uncertainty is essential for any researcher. Further, it is typical for one research question to give rise to many hypotheses, as hypotheses need to be sufficiently specific to be measurable without ambiguity. This usually takes the form of a measure of *statistical confidence* between the data gathered and the theoretical model being explored. For research on the influences of occupant behavior on energy demand in buildings it is important to realize which levels of statistical confidence may or may not be appropriate. Similarly, it is important to determine the statistical confidence required of the findings which will vary with context.

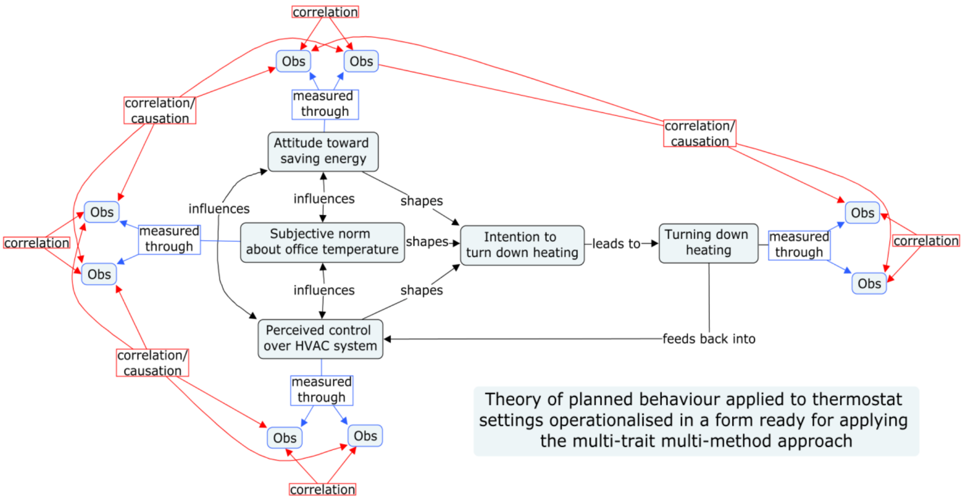

Figure 3.1 Example of a concept map. Black boxes and links represent the established theory. Blue boxes and links represent measurable properties. Red boxes and links represent analytical relationships for testing validity

As discussed above, each study should specify the population to which the findings are thought to apply. Once this is specified, then if generalization from a sample to a population (inferential statistics) is to be used, a *sample frame* is needed from which to draw a sample. Factors identified in the theoretical model as influencing the outcome variable(s) of interest will need to be addressed (exemplified or nullified) in the construction of a sample frame. The sample frame is (ideally) a list of all units of analysis in the population. Sampling strategies broadly divide into probability-based methods, which are needed for generalizing from the sample to the population, and non-probability sampling methods, which are often used for pragmatic and costs reasons. Of the probability-based methods, the "gold standard" is pure *random sampling*. Because pure random sampling is often both very difficult and very expensive, a range of alternative methods have been developed that are still statistically generalizable.

The process of determining how best to measure constructs is called operationalisation. Sometimes they can be measured directly with a single instrument, for example, air temperature. Frequently, however, it is necessary to combine outputs from a range of instruments to measure the construct of interest. When multiple instruments are needed to measure a construct the term latent variables or hidden variables are frequently used to describe them.

Once having identified concepts, turned them into constructs, and operationalized them into things that can be measured, the challenge remains of determining the nature of the relationship between the concepts in the research question. There are essentially three types of relationships that could exist between the concepts measured: there could be a *causal* relationship, the concepts could be *correlated*, or they could be entirely *independent*. It is the role of research design to determine the nature of the relationship between the concepts. Research design is the process of devising a process that directly satisfies a brief, in this case, the research question or research aim. Broadly speaking there are two forms of research design: descriptive (or correlational) research designs, and experimental (or causative) research designs (see Figure 3.2).

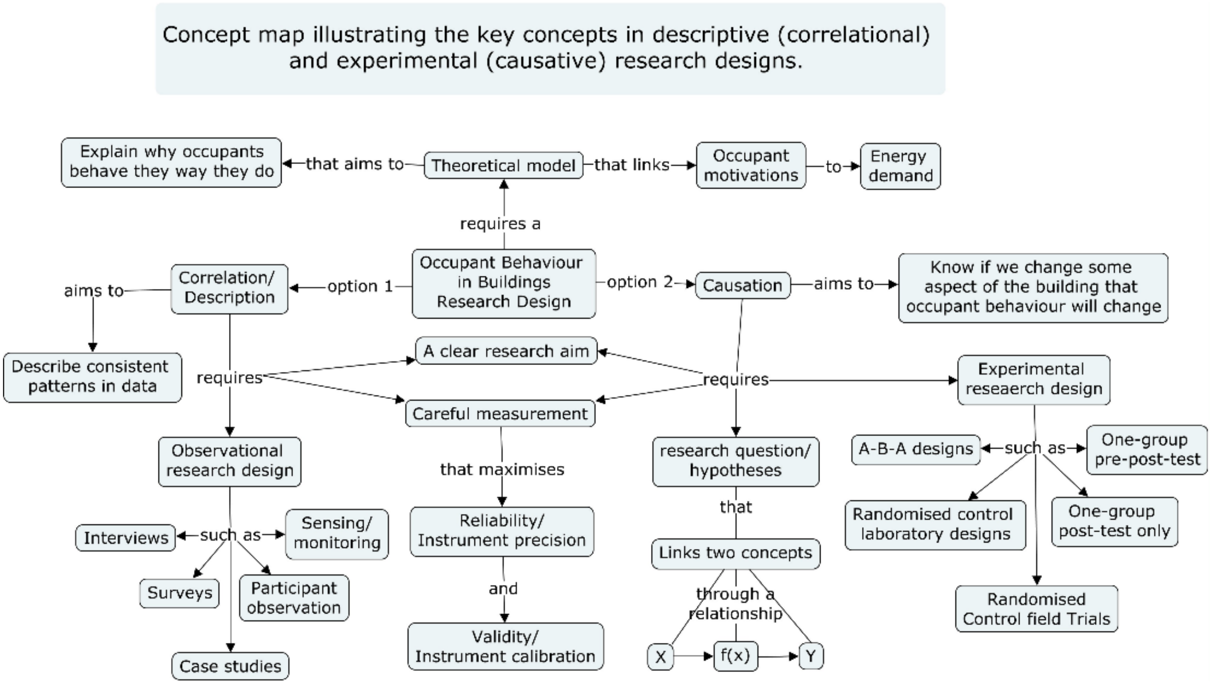

Figure 3.2 Concept map illustrating some of the key concepts in both descriptive (correlational) and experimental (causative) research designs

Descriptions of research and model building approaches are used in both the physical and social sciences. Both the social and the physical sciences have developed much the same intellectual architecture of concepts to describe issues around research design. They have, however, called them different things. In the social sciences, how consistently an instrument (say a set of questions) measures something is called 'reliability' - in the physical sciences the same concept is called 'precision'. Typically, the social sciences are much more concerned about intellectual clarity on defining and operationalizing concepts than the physical sciences, whereas the physical sciences are more concerned about measurement device calibration. Conceptually, social research methods (participant observation, social surveys, interviews, focus groups) are also instruments in that they are designed to measure specific things that are subject to the same forms of uncertainties (imprecision, inaccuracy, etc.) as their physical counterparts (e.g., sensors). Thinking of physical, physiological, psychological, and social instruments in the same way is useful in supporting cross-disciplinary collaboration and establishment of a common vocabulary of measurement in this highly interdisciplinary and socio-technical area of study.

4. Occupant Sensing and Data Acquisition

Occupant sensing and data acquisition are an essential element for occupant behavior research. A wide range of different types of sensors has been implemented in fields to collect rich information on occupants and their interactions with the built environment such as presence, actions, and power consumption. This information establishes a foundation to study physiological, psychological and social aspects of occupant behavior. This section summarizes existing occupancy and occupant behavior sensing and data acquisition technologies in terms of field applications and develops nine performance metrics for evaluation.

Upon a comprehensive literature review, we conclude that there are six listed categories of sensing technologies: image-based, threshold and mechanical, motion sensing, radio-based, human-in-the-loop, and consumption sensing. The applications of those technologies in occupant behavior research include: occupant presence, people counting, human building interactions such as turn on/off lights, thermostats and window blinds adjustment, energy consumption impacts of miscellaneous loads, and tracking movement. In addition, nine performance metrics were developed and defined to evaluate existing sensing technologies. An overview of the surveyed sensing technologies and their performance metrics is given in Table 4.1. Such metrics provide a guideline for future occupant behavior researchers when field data collection is needed.

Future occupant sensing should be "peel and stick" with minimum maintenance[3]; however, the challenges of such self-configured and long-lasting deployment of occupant sensing remain. Those challenges can be discussed in terms of four categories: (1) sensing element, (2) power consumption, (3) processing, and (4) communication. First, current sensing elements still cannot satisfy certain building system requirements, for example, HVAC controls. The detection of the number of occupants is not accurate enough—even to detect if there is a human or not—for temperature setback or ventilation controls. Secondly, most sensors depend on an external power source for a long-term experiment. This creates cost and wiring challenges for large-scale deployment, such as in a whole building. Thirdly, the current data processing unit is either on-board or cloud-based. An on-board processing unit consumes power and a cloud-based requires high data security. Fourthly and finally, communication determines how frequent the data should be sent out for storage. Communication typically consumes the most power (>60%) of the whole sensor unit.

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[3] Department of Energy. (2015). DOE Peer Review for Building Technologies Office (BTO) Sensors and Controls Technologies and Emerging Technologies R&D Program.

Table 4.1 Overview of sensing technologies and their performance metrics

		Cost	Power Type		Data Storage		Deployment Type		Sensing Range		Data Sensed					Collection Style	Accuracy	Demonstrated Control Applications			
	Specific Sensing Technologies		Battery	Wired	Internal	Network	Industry / Comm./ Public	Residential	Distance from Sensor	Angle from Sensor	Presence	Count	People-Tracking	Actions	State			Product on the Market	Lighting	HVAC	Security
Image-Based	Video	$$$	Y	Y	Y	Y	Y	N	Infinite	90-180°	Y	Y	Y	Y	Y	Periodic / Events	High	Y	N	N	Y
	IR Camera	$$$$	Y	Y	Y	Y	Y	N	Infinite	90-180°	Y	Y	Y	Y	Y	Periodic / Events	High	Y	N	N	Y
Threshold and Mechanical	IR Beam	$	N	Y	N	Y	Y	N	20m	N/A	N	N	N	N	N	Events	Low	Y	Y	N	Y
	Piezoelectric Mat	$$	N	Y	N	Y	Y	N	N/A	N/A	Y	N	N	N	N	Events	Low	Y	N	N	N
	Reed Switch	$	N	Y	N	Y	Y	Y	N/A	N/A	N	N	N	Y	Y	Events	Low	Y	Y	Y	Y
	Door Badges	$$$	N	Y	N	Y	Y	N	N/A	N/A	Y	Y	Y	Y	Y	Events	Medium	Y	Y	Y	Y
Motion Sensing	PIR	$$	Y	Y	Y	Y	Y	Y	10m	110°	Y	Y	N	N	N	Events	Medium	Y	Y	Y	Y
	Ultrasonic Doppler	$$	Y	Y	Y	Y	Y	Y	20m	360°	Y	N	N	N	N	Events	Medium	Y	Y	N	Y
	Microwave Doppler	$$	Y	Y	Y	Y	Y	Y	20m	360°	Y	N	N	N	N	Events	Medium	Y	Y	N	Y
	Ultrasonic Ranging	$$	Y	Y	Y	Y	Y	Y	4m	90°	Y	Y	N	N	N	Events	Medium	N	N	N	N
Radio-Based	RFID	$$$	Y	N	N	Y	Y	Y	3m to 200m+	N/A	Y	Y	Y	N	N	Periodic	Medium	Y	N	N	N
	UWB	$$$	Y	N	N	Y	Y	N	3m to 200m+	N/A	Y	Y	Y	N	N	Periodic	Medium	Y	N	N	N
	GPS	$$$	Y	N	N	Y	Y	N	Infinite	N/A	Y	Y	Y	N	N	Periodic	Medium	Y	N	N	N
	WiFi / Bluetooth	$$$	Y	N	N	Y	Y	Y	32m	N/A	Y	Y	Y	N	N	Periodic	Medium	Y	N	N	N
Environmental	Air properties	$$	Y	Y	Y	Y	Y	Y	Per space	N/A	Y	Y	N	N	N	Periodic	Low	Y	N	Y	Y
	Acoustic	$$	Y	Y	Y	Y	Y	Y	Per space	360°	Y	Y	N	Y	Y	Periodic	Medium	Y	Y	Y	Y
Human-in-the-Loop	Observation	$$$$	N/A	N/A	N/A	N/A	Y	Y	N/A	N/A	Y	Y	Y	Y	Y	Periodic / Events	High	N/A	N	N	Y
	Occupant data	$$	N/A	N/A	N/A	N/A	Y	Y	N/A	N/A	Y	Y	Y	N	N	Events	Low	Y	N	Y	Y
	Building data	$$	Y	Y	Y	Y	Y	Y	N/A	N/A	Y	N	N	Y	Y	Events	Medium	Y	Y	Y	Y
Consumption Sensing	Energy	$$	Y	Y	Y	Y	Y	Y	N/A	N/A	Y	Y	N	Y	Y	Periodic	Medium	Y	N	Y	Y
	Water	$$	Y	Y	Y	Y	Y	Y	N/A	N/A	Y	Y	N	Y	Y	Periodic	Medium	Y	N	Y	Y

Note: “$” represents a low-cost sensor (<$10) and “$$$$” represent an expensive sensor (>$1,000), N/A Not applicable, Y used, N not

5. Introduction to Occupant Measurement Methods

There are numerous methods to collect occupant-related data for the purpose of researching occupants – each with its own strengths and weaknesses. Researchers who are about to embark on a new occupant data collection campaign might have the following questions:

- Which research methods are most suitable for understanding the current occupant-related phenomena of interest?
- What research strategies and technologies have been used in the past and which have been successful?
- What is established best practice for applying the research and data collection methods?
- What practical challenges are sure to arise and how can they be surpassed?
- How should the research methods be documented and communicated to the audience?

This section tries to give some answers by shortly introducing into four major methods (see Figure 5.1) for occupant research: in-situ, laboratory, survey, and virtual reality. The next three chapters provide more detail on best practice, research strategies, available technologies, and challenges associated with in situ, laboratory, and survey methods. Further, hybrid methods, whereby multiple complementary approaches are exploited, are briefly discussed. With regard to in situ methods the literature suggests that they yield greater external validity and the potential for long-term studies, but are constrained by sample size, the characteristics of the building at hand, and sensor location. In contrast, laboratory studies provide greater flexibility with regards to sensing equipment, better control over indoor environment, and more straightforward experiments, but are costly in terms of human resources and may suffer from biases stemming from placing occupants in unfamiliar environments and performing unnatural activities. Survey approaches yield insights into occupant behaviors and allow phenomena to be measured that sensors may be incapable of measuring, but they rely on self-reporting, which may be subject to significant bias. Lastly, virtual reality is an emerging method to study occupants, but for now is limited to the visual and acoustic domains (i.e., not thermal comfort or indoor air quality).

In situ

Laboratory

Survey

Virtual reality

Figure 5.1: Occupant measuring methods. Clockwise from top-left: In situ, laboratory, virtual reality, and survey.

Oftentimes, it may be appropriate or necessary to exploit the benefits of several of the above methods to achieve research goals. For instance, one method may have insurmountable obstacles that can be solved effectively using a second method. Or, multiple methods may be used in the same study for triangulation purposes, i.e., to form greater confidence and approach a problem from several directions. While any research design requires careful thought and planning, mixed methods designs demand additional consideration to ensure methods are compatible and do not interfere with each other.

The term “mixed methods” is used here in a way that might be referred to elsewhere as “combined methods” or “multiple methods”, whereby multiple approaches to data collection and analysis—whether qualitative, quantitative, or both—are used in a single research study. In other words, “mixed methods” here is a question of methods (data collection and analysis), and not one of methodology (ontology, epistemology, axiology—i.e., the “worldview” that underpins research design).

Mixed methods studies can be designed in a number of ways, all with the common feature of combining multiple methods (qualitative, quantitative, or both) in a single study. If qualitative (“qual”) and quantitative (“quan”) methods are combined, the combination can have greater weight on one or the other. Alternatively, both parts might have equal weight in the final results.

For example, a quantitative survey might be followed by qualitative interviews that provide additional insight into survey results, but ultimately the research question demands a quantitative result (a "what" question, not a "how" question). In this case, the survey results would be featured more prominently than the interview results and study would be considered quantitative-dominant—or QUAN-qual. If the same study were conducted with a qualitative research question, however, it would be considered a quan-QUAL design, where the order of phases remains the same, but the emphasis is on the qualitative element (e.g., interviews). Recognizing that mixed methods is adaptable to a variety of research questions and needs makes it a potentially very fruitful choice.

A common classification system for mixed methods is: convergent parallel, exploratory sequential, explanatory sequential, and embedded[4]. Briefly, a convergent parallel design involves quantitative data collection and analysis and qualitative data collection and analysis to be performed in parallel, and then compared and interpreted together. An exploratory sequential design involves using qualitative methods (first phase) to help inform quantitative methods (second phase). An explanatory sequential design starts with quantitative data methods (first phase) followed by qualitative methods (second phase) that help explain the quantitative data. Finally, an embedded design involves applying a quantitative or qualitative method, but embedding a lesser amount of the opposite (e.g., a quantitative survey with a few qualitative questions within in). In contrast to convergent parallel studies, embedded studies involve analyzing the qualitative and quantitative data together, rather than performing separate analyses. Beyond the four basic mixed methods designs, there is also the more advanced multiphase design, which involves a combination of qualitative and quantitative methods performed either in series or in parallel, with each phase informing the next one.

[4] Creswell JW, Clark VLP (2007) Designing and conducting mixed methods research.

6. In-situ Approaches to Studying Occupants

This section provides a brief overview of in-situ approaches to studying occupant behavior and presence. It aims to provide researchers with a systematic approach to in-situ occupant monitoring studies. The section begins with a recommended systematic method for designing, conducting, and publishing in-situ occupant studies. Following that in-situ specific sensor technologies and sensing strategies are discussed. Because of the practical nuances of in-situ studies, this explores such issues as: sensor placement, validation, access to studied spaces, monitoring spaces with multiple occupants, biases, participant recruitment, and ethical considerations. Next, recommendations are provided for the level of documentation that should be provided when publishing in-situ studies – with particular attention to detail regarding the contextual factors that could influence the results. Finally, the use of surveys to complement in situ sensor-based methods is discussed.

In-situ monitoring of occupants and indoor environments offers an opportunity to obtain realistic data about building occupants at a relatively low cost. They do not require laboratories because they use existing buildings as living laboratories. Occupancy, occupant actions, and their predictors can be estimated using a combination of built-in sensors and additional sensors with central or distributed data-logging capabilities. Sensors can be a relatively nonintrusive approach to monitor occupants, though privacy, security, and ethics are important considerations. Longitudinal occupant monitoring campaigns require robust sensors to be positioned such that they do not interfere with occupant activities – and similarly that occupants do not interfere with them.

In-situ monitoring campaigns are not without drawbacks and challenges. Deploying, checking, and retrieving sensors can be very labor-intensive – particularly for large sample sizes and studies involving multiple distributed buildings. Sensors for in-situ monitoring are constrained by location availability, cost, privacy, and, aesthetics. Unlike in laboratory studies, researchers may have limited access to sensors and other equipment used for in-situ monitoring. Adjustment or replacement of monitoring equipment can be invasive and time-consuming. Secondarily, but notably, frequent visits may remind occupants that they are being monitored. This section addresses this concern and explores Hawthorne effect mitigation measures.

The four major phases of in-situ monitoring studies are: (1) investigation and design of experiment; (2) participant recruitment and equipment installation; (3) study; and (4) publishing. The recommended procedure is presented below, and then certain steps are expanded in the sections that follow. Note that the exact order of steps will vary greatly from study to study. For instance, the researcher can likely not enter occupants' private spaces (e.g., private offices or homes) prior to obtaining their informed consent. Thus, an iterative approach involving several visits to assess the space, install sensors, and interview the occupants may be required.

At the heart of in-situ occupant monitoring studies are the sensors that detect occupancy, occupant actions, and the predictors for occupant actions. Sensor technologies are discussed at length in Section 4; the current section is focused on in-situ specific matters. Often, the most practical and economical method to detect occupant actions, presence, and environmental conditions is to use electronic sensors that are connected to a central building automation system (BAS). Once such systems are configured to record and store data, minimal maintenance is required and faults or unexpected readings can be detected and possibly resolved remotely without intruding on occupant spaces. Furthermore, data storage is virtually limitless with regards to cost—except perhaps for video or audio storage, which is significantly more memory-intensive.

In the frequent event that existing sensing capabilities in a space are inadequate for the extent of the desired monitoring, a viable option is to add additional sensors. The preferable option is to integrate wired or wireless commercial sensors into the BAS such that data can be reliably collected and stored with minimal impact on occupants. Modern building automation systems often integrate with wireless sensor networks or can be expanded to do so. For post-construction upgrades, wireless sensors are preferable for occupant monitoring because of the ease of integration, lack of requirement for wiring, and minimal disruption to occupants. Suitable BAS-integrated sensors may not exist off-the-shelf, particularly for unique applications related to occupant action sensing (e.g., Venetian blind slat angle adjustment). Furthermore, BAS-grade sensors may be more expensive due to their packaging, communication protocol, electrical safety rating, and design for long-term reliability. Finally, existing BAS infrastructure may not easily allow for expansion. For instance, a building may still have pneumatic controls or decentralized digital controls. Thus, two major options remain: the addition of sensors with centralized data acquisition or packaged systems with decentralized logging. As discussed previously in Section 4, centralized data acquisition is preferable for detecting sensing faults and obtaining data unobtrusively.

Numerous new and anticipated technologies will substantially broaden the types of occupant actions that can be sensed. Given the relatively small field of occupant research, researchers should look to other domains for research methods and technologies. Notable examples include:

- accelerometers and furniture-integrated sensors can be used to estimate occupant posture, orientation and adaptation to daylight glare, and occupant presence
- Wearable sensors can be used to measure occupant metabolic rate and interaction with building systems
- Computer keyboard and mouse data can be used to assess productivity
- Wireless computer networks can be used to estimate the number of personal wireless devices as a proxy for occupancy

Many practical issues are frequently encountered during the design and study phases of in-situ occupant monitoring studies. In brief, these include:

- In-situ studies often prevent placement of sensors in optimal locations because of practical constraints. When measuring indoor environmental conditions, the ideal situation is to sense them at the location of the occupant, as this is most representative of the environment that the occupant is immersed in.

- Whether in-situ studies use sensors, polling, or other methods to measure occupant-related quantities, an important step is to validate the collected data.
- In contrast to laboratory-based studies, researchers normally have limited access to spaces to use for in-situ studies. Moreover, study participants may have limited patience for invasive and frequent researcher visits. Moreover, frequent visits increase occupants' cognizance that they are being studied and the associated Hawthorne effect. Thus, it is critical to plan visits carefully to maximize efficiency.
- A largely unresolved issue, which extends to the occupant modelling domain, is monitoring multiple occupants using in-situ methods. For multi-occupant spaces (e.g., homes, classrooms, hospitals, and shared offices), robust methodologies to distinguish between occupants for in-situ monitoring are still emerging.
- A major advantage to in-situ studies is that they take place in the natural environments where occupants engage in their everyday activities, rather than an artificial environment (e.g., laboratory) with constant reminders that their actions and environment are being monitored. However, most in-situ studies have some minor contact between the researcher and participant wherein consent is obtained and possibly additional equipment is installed or surveys answered. Therefore, in-situ study participants may also be affected by the knowledge that they are being studied, and consequently alter their natural behavior to please the researcher or society (i.e., social desirability bias).
- Ethics plays a major guiding role in all occupant studies, as discussed in Section 11, because monitored occupants must give consent to being monitored.

While electronic sensors greatly improve the efficiency and accuracy of quantifying occupants and their actions, these sensed values should not be used to blindly develop models or draw conclusions because many confounding and contextual factors are likely to exist. Inventories should be performed before consideration of sensor-based monitoring to assess the available occupant interfaces, equipment, space geometry, and envelope features.

In-situ occupant monitoring studies are likely to be the most reliable method to obtain data for occupant models that are suitable for building simulation tools. They are naturalistic and do not rely on occupants' memory or their willingness to frequently respond to surveys or other polls. They are also relatively resistant to the Hawthorne effect due to their long-term and discreet nature. Their duration, which can last months or years, allows a relatively large temporal sample to be obtained.

Nonetheless, the cost to collect data—both hardware and researcher effort—may limit sample sizes to tens of occupants. Furthermore, purely sensor-based measurements limit researchers' ability to explain cause and effect relationships. In addition, the researchers generally cannot control major building and activity parameters, such as orientation, window size, and occupant traits. Thus, contrary to laboratory-based occupant studies, researchers of in-situ studies are at the mercy of having a suitable building—and willing participants—to perform in-situ studies.

Regardless of the recent popularity of performing in-situ occupant monitoring campaigns, many fundamental and technological challenges and questions remain, such as:

- Accurately counting occupants in spaces
- Measuring clothing level and other adaptive actions that do not relate to building systems
- Determining which occupant acted (in shared spaces)
- Accurately measuring representative indoor environmental quality parameters, particularly spatially sensitive quantities, such as illuminance, glare, and mean radiant temperature
- Determining adequate sample size (number of occupants and duration), depending on the purpose of the study
- Quantifying the impact of biases, such as the Hawthorne effect
- Cost-effectively obtaining large sample sizes

The next two sections discuss two complementary occupant study methods: laboratories and surveys. These methods—particularly surveys—should not be considered in isolation, but rather as critical tools to forming a complete picture of our understanding of occupants in buildings.

7. Laboratory Approaches to Studying Occupant Behavior

Laboratories offer the possibility to study occupant behavior in a very detailed manner. A wide range of indoor environmental scenarios can be simulated under precisely controlled conditions and human subjects can be selected based on pre-defined criteria. The degree of control over experiments is high and a large number of physical, physiological, and psychological quantities can be monitored.

There is a long tradition in research on indoor environmental quality (IEQ)—referring to thermal, visual, and aural comfort, as well as indoor air quality—to conduct experiments in labs. According to the different research questions from each field of comfort, the designs of lab facilities can differ substantially. In recent years, interest in subjects' reaction to their given environmental conditions has risen, particularly with regard to comfort and the related energy consumption. This aspect brought further variety to lab design – e.g. experimental environments have to provide a surrounding as realistic and familiar as possible for subjects, as experiments have to be performed over longer periods (half to a whole day, or even longer), and the lab's influence on the subjects' general perception should be kept to a minimum.

The following examples (summarized in Table 7.1) show the range of existing types of test facilities for IEQ research, as well as their experimental opportunities for comfort and behavioral studies in lab environments. There are numerous other climate chambers and lab facilities at different universities, research institutions, and private companies in the world which are not mentioned in this section. The intention was to foreground the variety of test facilities, rather than drawing a complete picture.

Table 7.1 Overview of test facilities described in this section

Name of the laboratory	**Location**	**Key features**
International Centre for Indoor Environment and Energy (ICIEE)	Danish Technical University (DTU), Denmark	Wide variety of different climate chambers and field laboratories, mainly for experiments on thermal comfort, air quality, air distribution, ventilation systems, and combined effects of indoor environmental variables
Controlled Environmental Chamber	Center for the Built Environment (CBE), University of California at Berkeley, USA	Chamber in real office design for thermal comfort experiments and reproducing the effect of different air distribution systems
Indoor Environmental Quality Laboratory (IEQ	University of Sydney, Australia	Two connected chambers, designed to be as realistic as possible to any setting (bedroom, office,

Lab)		etc.), to examine how combinations of the key IEQ factors relate to comfort, productivity, and health of occupants
Laboratory for Occupant Behavior, Satisfaction, Thermal comfort and Environmental Research (LOBSTER)	Karlsruhe Institute of Technology (KIT), Germany	Facility hosting two office-like rooms with real windows to the outdoors and providing different adaptive opportunities for occupants, to study adaptation and behavioral actions
SinBerBEST Test Bed	Berkeley Education Alliance for Research in Singapore (BEARS) Limited, Singapore	Fully configurable space with moveable and interchangeable wall panels, designed for experiments on air quality, in combination with thermal and visual comfort
Metabolic Research Unit Maastricht (MRUM)	University of Maastricht, The Netherlands	Facility with a variety of chambers to experimentally investigate human energy and substrate metabolism
Institute for Energy Efficient Buildings and Indoor Climate, E.ON Energy Research Center	RWTH Aachen University, Germany	Various labs from climate chambers over generic constructions of indoor environments (vehicle test facilities) to a living lab office building
The ZEB Living Laboratory	Norwegian University of Science and Technology (NTNU) and SINTEF, Norway	Single-family house built as a living lab, fully equipped to monitor occupants' interaction with the building and technical services
High Performance Indoor Environment Laboratory (HiPIE-Lab), Indoor Air Test Center (IATC), Modular Test Facility for Energy and Indoor Environments (VERU)	Fraunhofer Institute for Building Physics (IBP), Germany	Laboratories for IEQ tests, including impact of acoustics, lighting, and indoor climate on human beings; investigation of air quality, airflow, and effectiveness of active and passive air purification systems. Test bed for façade systems and their effects on indoor environments and energy consumption
Flight Test Facilities	Fraunhofer IBP and RWTH Aachen University, Germany	Air plane mock-ups to study cabin air quality and thermal comfort, as well as technical equipment

From the overview on different lab facilities and related studies on comfort and occupant behavior the following recommendations can be given for the design of climate chambers to be used for behavioral studies.

Labs for occupant behavior studies should be designed with real windows to the exterior (better yet, with a façade system which allows the mounting of different window types). Windows connect to the most healthy and appreciated source of light, help for orientation, and offer a view to the outside. Further, windows can connect indoor and outdoor climate and are therefore an undisputable prerequisite for studying thermal comfort adaptation by natural ventilation and cooling. Finally, operating windows is an important behavioral action with regard to different personal needs or preferences (indoor climate, air quality, and acoustics) and must not be neglected in research on occupant behavior. A number of test facilities are equipped with artificial/virtual windows or windows to the interior of the building which hosts the test chamber.

In order to simulate a most "non-artificial" and familiar environment for subjects, test rooms should provide all necessary furniture and means for the purpose which the experiment is designed for. Care has to be taken in terms of placing sensors in a lab, subjects should not be disturbed by any sensor to perform intended actions in a lab. Flexible room partitioning and furniture help for experiments with different numbers of occupants. Basically, a high standard of furnishing should be achieved in order to avoid side effects on well-being. In particular, care has to be taken with acoustics (appropriate reverberation times) and shading (adjustable blinds).

As lab facilities for occupant behavior studies have to allow user reactions on indoor environmental conditions on all levels, easy access with appropriate interfaces has to be provided for the subjects. The experimental design then regulates by activation/deactivation to which extent and under which circumstances occupants are allowed to take advantage of the different options.

Technical services and controls have to be designed in a way that all desired indoor climate profiles and combinations of different environmental parameters can be simulated without major restrictions. Aspects like ample heating and cooling capacity (also for compensating for effects of occupants' interactions), as well as different options for conditioning, e.g., mixed-mode, have to be considered carefully during design. Low thermal inertia of the chamber construction and the heating/cooling system is beneficial for fast reacting systems.

Apart from design aspects which directly refer to the lab itself the following issues are probably worthwhile being mentioned to support a smooth experimental procedure: good noise protection between experimental rooms and the researchers' area / operation room; ample space for the subjects to change clothes and to put on personalized sensors; pleasant area for acclimatization before the experiment; and sanitary facilities in close vicinity and reachable without leaving conditioned areas.

While designing experiments for labs, researchers have to be aware that occupants are exposed to an environment and situations in which they likely feel observed. In order to keep the so-called "Hawthorne effect" as small as possible, the real purpose and (scientific) objective of the experiment should not be explained to the subjects before and no feedback should be given during the experiment. Instructions should be given before the experiment in an objective (not encouraging or discouraging) way and information about the study should be kept as general and short as possible.

A point to be raised is whether an environment which is too pleasant might influence the perception and acceptance of the subjects—e.g., placing students in labs equipped like executive suite offices. Further, it has to be considered whether the instructed activities match the subjects' background. Another issue is to which extent certain situations can really be simulated. For example, if an office scenario with its typical behaviors is to be replicated, how can typical real-life stress situations of the occupants be provoked?

8. Occupant Survey and Interview Approaches to Studying Occupant Behavior

This section provides guidance for survey development related to occupant behavior research. Many researchers studying occupant behavior have used survey methods to collect self-reported data of occupant behaviors in buildings, either exclusively or in tandem with data gathered in field or laboratory studies. The section serves as a how-to guide for issues such as: (a) how should survey questions be conceptualized, (b) are the questions measuring what was intended, (c) how should questions be written so that participants understand the intent, (d) how can the validity be increased for the survey itself, (e) how does one select the appropriate sample for a survey, and (f) how should one select the appropriate survey tool for data collection? The last part presents a brief discussion of interview methods.

Surveys can provide a cost-effective solution for obtaining both a large sample size and useful information related to occupant behaviors, perceptions, and preferences; in many cases, they have been used to develop models. While surveys are not an appropriate tool in all instances or contexts, a well-designed survey can certainly offer useful and rich data for better understanding occupant behaviors in buildings. In many instances, surveys can be used in tandem with physical data collection and observations, through laboratory studies or in-situ studies, to holistically understand occupant behaviors and perceptions in any given building.

Surveys, focus groups, and interviews differ from in-situ and laboratory studies. Regardless of the data collection method(s) used, there are differing requirements and differing levels of rigor required for both implementation and analysis. Surveys rely on self-reporting of personal behaviors rather than observations and measured site data; some researchers may fear untruthful or inaccurate responses and avoid surveys altogether. However, a well-designed survey can help to alleviate these concerns and provide rich data if proper steps are taken to maximize the chances that occupants are reporting both valid and required/desired information.

In general, the purpose of survey research is to collect quantitative responses and to then generalize results from a sample to a population. However, surveys may also include open-ended questions that are qualitative in nature and at times, other qualitative methods such as interviews and focus groups may also be appropriate for understanding the causes of specific occupant behaviors. The section aims to explore the advantages and disadvantages of using surveys in place of, or in combination with, physical data collection.

A survey can provide a qualitative or quantitative perspective on trends, opinions, and attitudes of a sample of a target population. Surveys can also elicit qualitative data, if desired and if questions are formatted appropriately. To ensure that a survey instrument is delivering reliable and valid data, it is important to recognize and thoughtfully consider all elements of a survey. A good survey design should be based on theories, research questions, hypotheses, and well-defined variables and measurements (scales). There are several forms of data collection (also called "survey modes") for conducting a survey, including: mail/email, telephone, the Internet, video conferencing, personal interviews, and focus groups.

In occupant behavior research, although it may lead to a longer survey, it may be best to use multi-item measures to best understand psychological attributes. A single-item measure, such as overall indoor environmental quality (IEQ) satisfaction, is less desirable than breaking down IEQ into several, more nuanced measures (thermal, visual, acoustics, privacy, lighting, etc.). In general, when trying to understand occupant behaviors—and associated reasons for certain behaviors—being able to break down responses in a more granular fashion may yield the best results. When measuring any psychological or behavioral attribute, it is likewise important to implement multi-item measures. There are essentially three types of question structures that can be used in surveys: (1) open-ended; (2) closed-ended with ordered categories; and (3) closed-ended with unordered categories. A question could also be partially closed-ended, which would take the form of a closed-ended question with an additional open-ended option at the end of the answer options —usually "other" or "please specify".

To ensure reliability, validity, and error factors have been considered, and that they are working as intended (i.e., that questions are measuring what they are supposed to measure, questions are written well, participants understand what is being asked of them), it is necessary to deploy a pilot survey before the final survey is deployed. The primary purpose of the pilot study is to ensure that the survey instrument is working as intended; as such, the results of the pilot study should typically not be included in the results of the full survey deployment, especially if the sample selection differed between the two phases (i.e., convenience sampling for the pilot study and random sampling for the full survey implementation).

A commonly asked research question in survey research is, what sample size do I need? Numerous invaluable textbooks on social science methodologies contain formulas are available to determine what sample size is needed based upon the overall population. There are also several software programs available for calculating sample size if needed. In some cases, it may also be appropriate to refer to previous studies and their respective sample sizes.

There are many survey tools available for survey delivery; this section does not advocate for one tool over the other, but simply provides options for survey development and delivery. The selected tool (or method) should ultimately align with the project' goals and budget. There are many free survey tools, such as limesurvey and Google Forms, as well as paid tools, which vary in price (e.g., Surveymonkey, SurveyGizmo, Qualtrics, Amazon M-Turk tool).

Oftentimes, when conducting on-site data collection or surveys, it is valuable to also conduct individual face-to-face interviews with building occupants. Collecting qualitative data in addition to quantitative data via surveys and field studies can help provide valuable insights into *how* and *why* occupants may be acting a certain way. There are several formats for conducting interviews: individual face-to-face, telephone, video conferencing, email, and focus groups.

Individual face-to-face interviews are ideal if the researcher will be on-site collecting data already. In addition, one-on-one phone interviews can be conducted if the researcher cannot visit the actual research site, or if there was not enough time to conduct in person. It is also possible to conduct interviews via email. One of the cons of this method is that the responses received may be much shorter; however, one of the pros is that the researcher does not need to spend additional time transcribing the interview responses. Email interviews are an effective option if there are time or budgetary constraints and/or if the researcher(s) have structured questions to ask. Finally, focus groups can be conducted with several people at a building site at once. This has many advantages, such as: multiple perspectives can be obtained at one time, thus saving both time and resources; the researcher may discover issues that may not have arisen in a structured survey; and responses can build upon one another.

Ultimately, surveys can be used to ascertain a great deal of information from building occupants. Since these behaviors are self-reported, it is helpful to triangulate results with physical measurements, interviews, and/or observations when possible. Both surveys and interviews can be performed either in situ or remotely. In situ studies are advantageous because they allow the researcher to further investigate observations or issues that arise from survey or interview responses on site. Alternatively, online-based surveys can also be tremendously beneficial, especially if there are budget, time, or travel constraints; this method may also aid in increasing the overall sample size. Each type of survey has advantages and disadvantages, which should be carefully weighed and considered while designing the study.

Overall, survey research should be conducted with rigor and thoughtfulness. It is important to carefully craft survey questions, order the questions logically, and ensure that the questions are truly providing desired answers relevant to the research question, constructs, and theories. Questions can be either closed-ended or open-ended, and each type can yield different types of results. Consistency among measures and scales is also important. As discussed previously, different types of survey modes, the layout, the length of the survey, and even the font size and typeface selected can all affect the response rate.

This section provided brief guidance for survey and interview development in occupant behavior research; however, for many of the methods mentioned in this section (surveys, interviews, focus groups, etc.), it is necessary to seek out additional resources for more detailed explanations of appropriate and valid data collection methods and associated analyses. In addition, respected survey methods and resources should still be appropriately sought out for the following topics: longitudinal survey methods, additional available tools for survey delivery, incentives for increasing survey response rate, valid methods of evaluating surveys, proper triangulation of survey responses with additional, and more.

9. Validation and Ground Truth

It is essential to ensure the validation of measurements and the reliability of collected occupant behavior data. In the current contact, validation and verification are procedures for ensuring that collected data meet the required specifications for the purpose at hand. Historically, the various fields of occupant behavior research have lacked a shared theoretical and practical basis, not only due to variations in the tasks undertaken, but also due to differences in terminology and practices (e.g., calibration, validation, quality control) within the field.

In the context of any measurement system, terms such as “trueness”, “precision”, “accuracy”, etc., have been used to describe the quality of measurements. Figure 9.1 shows the interrelations between different error types (systematic, total, random), their corresponding performance characteristics (trueness, precision, accuracy), and the parameters for quantitatively expressing these performance characteristics (standard deviation, bias, measurement uncertainty). These terms and relationships are unpacked throughout this section.

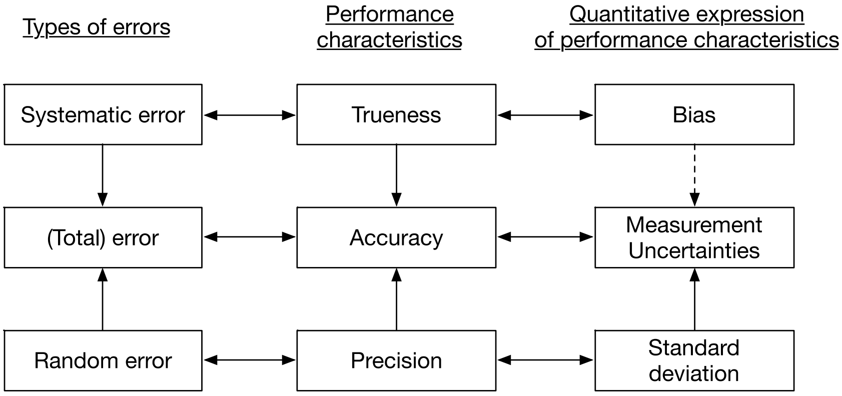

Figure 9.1 Measurement system variance and uncertainties

In order to validate or verify measurement methods, ground truth data are necessary. The purpose of gathering ground truth data is usually to construct occupant behavior measurement methods that can correct for known biases and quantify uncertainties in ordinary measurement data, thus allowing the collection of less costly data (relative to ground truth data) at scale for use in occupant behavior research, especially for the non-matured instrument measurements of occupancy and occupant actions. There are two main types of information that can be collected: (1) physically sensed variables, which can be measured and monitored via instruments and described in Section 4; and (2) reported variables, which can be derived from occupants through interviews, surveys, and manual observation and described in Section 8. Regardless of the instruments or methods used, there are always errors or uncertainties in measurement procedures, whether measuring physically sensed variables or using reported variables of occupant behaviors. In all cases, it is important for researchers to quantify any measurement uncertainties in the observations.

Finally, preparing ground truth data for the validation of occupant behavior measurement methods should consider: 1) Appropriateness: appropriate for the intended application and analysis; 2) Robustness: depending on how much the ground truth data represent real use cases; 3) Openness: It is necessary for different parties to publish their data and share them with the wider occupant behavior research community so that their work can be compared to and externally checked by others and contribute to further research.

10. Structured Building Data Management: Ontologies, Queries, and Platforms

Building data monitoring, in general, and occupancy-related data collection in particular have the potential to provide deep performance feedback for: (1) operational optimization of existing facilities and (2) improving future designs. For instance, building monitoring can support energy and performance contracting, preventive building maintenance, smart load balancing, and model-predictive building systems control. However, most currently implemented technical infrastructures do not appear to be mature enough. Likewise, the associated hardware resilience and software interoperability could benefit from major improvements.

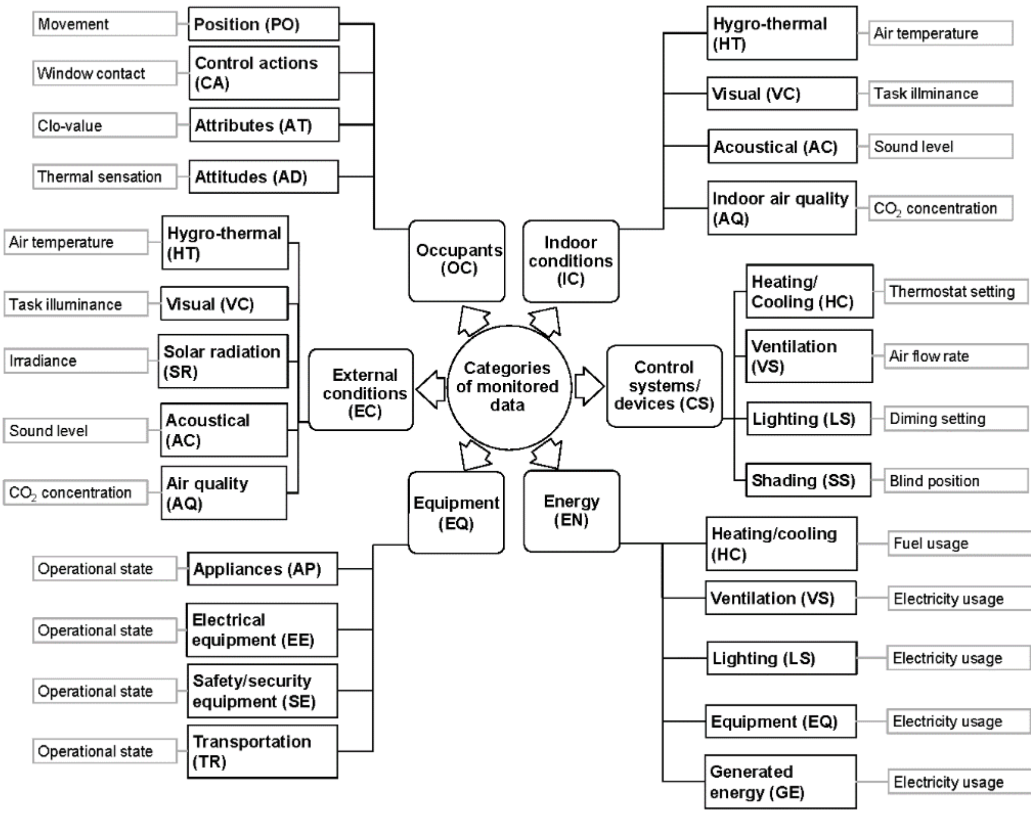

Figure 10.1: Fundamental elements of a building monitoring ontology: data categories, sub-categories, and examples of corresponding monitored variables

In order to address the above research gap, an ontology is developed for the representation and incorporation of various kinds of building monitoring data in a number of applications such as building performance simulation tools and building automation systems. The following six fundamental data categories are developed: (1) occupants (OC), (2) indoor environmental conditions (IC), (3) external environmental conditions (EC), (4) control systems and devices

(CS), (5) equipment (EQ), and (6) energy flows (EN). These categories can provide a coherent framework to classify the multiplicity of empirical information collected via buildings' monitoring systems. Figure 10.1 provides an overview of these categories together with associated sub-categories and illustrative examples of corresponding monitored variables

Subsequently, common data processing requirements are addressed and a number of typical queries are exemplified that building monitoring data repositories must support. Data post processing could be separated into two main categories, one for periodic data and the other for event-triggered or event-related data. The result for most typical data processing routines consists of periodic data streams with fixed intervals, whereby the time stamps are synchronized. In case periodically measured data are exported into building simulation tools, the interval values are typically generated such as to represent the averaged value of the preceding interval.

Finally, data repository specifications and implementations for structured collection, storage, processing, and multi-user exchange of monitored data are described. Creating high-performance data repositories implies a thorough requirement analysis. The stability of the data repository does not only depend on the amount of data that has to be stored, but also on the queries to be supported, necessary pre- and post-processing, number of requests, desired response time (real-time vs. historic data access), amount of data per request, distribution channels, caching, indexing and partitioning techniques, and many more. Depending on the data store concept to be adopted, the requirements will change. Most monitoring applications either store sensor data in files (e.g., CSV), relational databases (e.g., MySQL), NoSQL databases (e.g., MongoDB, Cassandra), embedded databases, in-memory databases, or NewSQL databases. Based on considerations pertaining to availability and market distribution.

Toward this end, the section addressed the need for richly structured approaches to the collection, storage, sharing, and analyses of monitored data, particularly as relevant to the occupants' presence/activities in (and their impact on) the buildings. Specifically, the present section introduced an ontology for the representation and incorporation of multiple layers of data (occupants' presence, control actions, indoor climate, outdoor conditions, devices, and equipment) in pertinent computational applications, such as building performance simulation tools and building automation systems. Moreover, a number of typical data processing requirements relevant to building monitoring data repositories were described. Finally, to illustrate modular and scalable monitoring system architectures, the requirements, characteristics, and specific implementations of data repositories for structured collection, storage, processing, and multi-user exchange of monitored data were explained.

11.Ethics and Privacy

When conducting research, one of the primary considerations should be to maintain high scientific and ethical standards, including protecting the rights and benefits of all participants. Researchers should take great care to ensure scientific validity during the design of a study; at the same time, ethical conduct should not be considered a researcher's burden, but rather an important consideration for any type of research. This section provides guidelines for ethics approval by discussing common types of ethics applications, the concepts of informed consent, privacy, and confidentiality, and additional ethical considerations particular to occupant research. While ethical review processes differ across countries and institutions, this section provides basic guidance to researchers in the field of occupant behavior to (a) improve their interactions with ethics review boards, (b) help them meet crucial requirements, and (c) ensure their studies are conducted ethically.

While researchers conduct important research and enjoy freedom of inquiry and expression, they must take efforts to apply high ethical standards, while also protecting the rights and benefits of participants[5]. Primarily, these efforts need to involve aspects related to the protection of an individuals' privacy. Besides these commonly known aspects of ethical standards, researchers conducting research involving human participants need to ensure that the time and effort of participants is not wasted due to a poorly designed study unable to answer a research question. Therefore, as part of a researcher's ethical conduct, the researcher needs to take great care to ensure scientific validity during the design of a study. Ethical conduct should not be considered as a researcher's burden, but as an important consideration for any type of research to minimize potential harm to participants, especially when considering the potentially high level of personal interaction that accompanies occupant behavioral studies or experiments. In addition, researchers have the responsibility, as members of the research community, to build the trust and confidence of the public by ethically conducting the research.

In most cases, research activities involving human participants are reviewed, monitored, and approved by a group of individuals independent from the researchers conducting the studies, i.e., an independent committee. Depending on the country or organization, there are different names for these review boards, including "ethical review board", "ethics committee", "research ethics board" ("REB"), or "research ethics committee" ("REC") or "institutional review board" ("IRB"). Depending on the research studies, an ethics application may be need to submit to the review boards.

The selection of participants should consider fairness and equity. Therefore, it is important to decide the criteria for including or excluding participants. There are three primary

[5] Canadian Institutes of Health Research, Natural Science and Engineering Research Council of Canada, Social Sciences and Humanities Research Council of Canada (2014) Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.

considerations: 1) Equitable selection regarding gender, race, ethnicity, etc., without personal bias, unless the use of one particular group has significance to the purposes of the study, which needs to be specified—for example, limiting the number of independent variables by choosing only young females; 2) Fair distribution of benefits among the populations (e.g., findings would serve not only high-income people who can afford the particular technology being investigated, but also low-income people), and 3) Provision of additional safeguards for vulnerable populations, as defined above (Collaborative Institutional Training Institute (CITI) 2016).

Researchers should also reflect on the probability and magnitude of each identified potential type of risk. In the case of research studies, "risk" can be defined as "the probability of harm or injury (physical, psychological, social, or economic) occurring as a result of participation in a study. Common risks associated with occupant behavior research and procedures to reduce them include: 1) Experimental study design; 2) Video data collection; 3) Sensor data collection; 4) Smart phone applications (Apps); and 5) Secondary data.

Informed consent addresses anonymity and consent issues and is one of the primary ethical requirements underpinning research with human participants (U.S. National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research 1979). Initial consent is the first requirement, but is not sufficient by itself; consent must be a continuous process because changes may be experienced throughout the course of a study.

As an example, typical ethics submissions may include the contents listed below: 1) Summary of research; 2) Recruiting procedures; 3) Inclusion and exclusion criteria; 4) Withheld information (i.e., deception); 5) Research procedures: methods of contacting and informing participants, length and location of the study, usage of foreign language(s), details of explaining the research procedures to the participants, consent procedures, incentive method, and so on; 6) Equipment; 7) Data collection procedures; 8) Data security and retention; 9) Staff training; 10) Dissemination results; 11) Consent process; 12) Risks; 13) Benefits; and 14) Risk/benefit assessment.

12.Conclusions and Outlook

This report covers all steps required to study occupants' behavior in buildings – whether by in-situ, laboratory experiment, or survey. It includes the definition of all relevant terms related to the field, basic guidance to research design as well as specifics of the above mentioned methodological approaches, information about collection, storage, and processing of data, and finally considerations about ground truth and ethics. The study of building occupants is truly multidisciplinary in nature and this report benefited from the diverse backgrounds of the contributing authors who bring their expertise in the fields of engineering, architecture, interior design, information technology and social sciences to bear on the question of studying occupant behavior in buildings. Accordingly, this report and the corresponding book will likely serve as introductory material for researchers and graduate students whose background is more specific. Advanced researchers will likely wish to read further on detailed techniques given the breadth and complexity of this field. For those wishing for a deeper dive into any of the concepts presented, the book by the same authors titled *Exploring Occupant Behavior in Buildings: Methods and Challenges* provides significantly more details.

At the time of this publication, the field of occupant research is relatively new but has seen rapidly increasing flurry of activity. Recent advances in building technologies have only served to highlight the importance occupants have on building energy use. The motivation for this work was to significantly improve the state of the art of occupant behavior research methodologies, while also documenting the practical lessons of the authors resulting from numerous studies. Readers who have read this report and/or book will realize that the field of occupant behavior research still holds a large number of unanswered fundamental questions to be tackled.

Research needs

As evidenced throughout this report, there have been numerous notable insights into building occupants' behavior; nonetheless, there is considerable potential for advancement in the field. To begin, there are few established precedents for deciding whether to measure certain predictors in occupant studies—in fact, many occupant action domains (e.g., window blinds) have only a handful of existing studies. Additionally, the sensors used for occupant studies are often borrowed from other applications and thus not optimized for the current studies. For instance, daylight illuminance sensors for occupant studies are often designed for building controls, where they serve a different purpose (e.g., measure relative illuminance on the ceiling). The slim selection of sensors aimed at measuring occupants directly is relatively immature and lacks the robustness and accuracy required for rigorous research. Furthermore, for large-scale and long-term studies, self-configured and “peel and stick” occupant sensors would be highly desirable, but do not yet exist in a readily available and affordable format. The four major components of a sensor—sensing element, power consumption, processing, and commutation—need further research and innovations.

It is essential to ensure the validity of measurements based on occupant sensing technologies and the reliability of the collected data. Unfortunately, there is not a standard procedure to collect, verify, and validate ground truth data. In addition, any sensing technology introduces measurement errors. Hence, it is a challenge to construct ground truth occupancy datasets and this requires further research.

The cost, effort, and technological and practical limitations of building occupancy research have resulted in most existing occupant studies involving no more than tens of participants (unless a survey approach is used). As of yet, it is unclear whether such small-scale studies can be extended to a broader population or different contexts—this is an issue of generalizability that suggests poor practice. Moreover, research methods largely vary from one to the next and therefore cannot be compared or cross-validated. Paradoxically, the remedy is more studies, yet the validity of those would also be in question. This is why the current work is so timely: consistency and quality of occupant research methods is critical to the advancement of this field.

While in-situ occupant studies have been fairly dominant for informing statistical occupant models for use in building performance simulation, surveys and laboratory studies are emerging as promising alternative methods. A major research need of the future is to establish the validity of these methods for simulation. However, in the broader sense, valuable qualitative and quantitative findings can emerge from such studies. We can assess the usability of building systems, establish occupants' building and energy literacy, and cause and effect relationships. Both, the studies and dissemination of these results to building designers and operators are lacking.

Ethics and privacy remain a major challenge for occupant researchers. While nearly all occupant studies require some form of ethics approval, the nature of the studies is often harmless and low-risk. Nevertheless, the ethics process sometimes hampers studies regarding to sample size, researcher effort, and even methodology. It is not well established whether participant knowledge and other social biases of studies affect their behavior (i.e., Hawthorne effect). And while interacting with participants, even for sensor-based quantitative studies, can afford extra insight through informal discussion and observations, ethical requirements often significantly dampen the opportunities available from studying vast quantities of occupants through existing mechanisms (e.g., electricity bills or building automation system sensors).

Despite – or perhaps as a result of – the cost of conducting occupant studies, occupant researchers are generally quite conservative about sharing data. At best, data are shared via personal communication. But this is in great contrast to more mature scientific fields, which often require datasets to be published alongside publications. Until now, an ontology for organizing occupant study data was not established. However, the opportunity to create a data repository is yet to be seriously pursued, which itself requires significant efforts to develop a scientifically sound approach for providing generally usable and comparable data sets.

One topic, which is not currently covered, is essentially connected to data: the modeling of occupant behavior where data are needed to train and validate these models. Modeling spans a huge field from physically-based to pure statistical approaches, also calling researchers from different disciplines on the scene. In line with experimental work on occupant behavior, numerous activities can be seen in the scientific community on model development and implementation in building simulation software. Likewise with results of occupant studies, the quality and transferability of models strongly depends on a sound scientific basis and knowledge about possibilities and constraints of the different modeling techniques.

Future outlook

The fundamental drivers for increased interest and research in occupant behavior are expected to remain for many decades to come. Heightened environmental awareness and policy-driven demands for better building performance will continue into the future, as well. Contrary to expectations, new technologies and deeper automation system have highlighted—not made obsolete—the importance of understanding occupants' needs, preferences, and interactions with buildings. As such, occupant behavior studies and their methods are predicted to remain center stage.

In the future, we expect many outstanding fundamental questions to be answered, such as: What is the best systematic way to collect ground truth data? What sample time and size of data are required to capture occupant behavior? Do laboratory and survey studies have sufficient ecological validity? Is the Hawthorne effect significant in this context? What are the critical contextual factors (e.g., climate, culture, presence of air conditioning) to be identified and what impact do they have on occupant behavior?

Meanwhile, we expect that technological advances will improve the accuracy and cost effectiveness of studying occupant behavior. Occupant sensors will be able to count number of occupants, comfort level, location, direction of movement, and even posture of occupants, while processing these phenomena locally to maintain data security. Already, sensors and sensor infrastructure (e.g., communication and data acquisition and storage) have advanced considerably to the extent that many of them are now applicable to studying occupants. Wireless communication for sensors will become commonplace. Sensors will routinely generate sufficient power to process signals and communicate to hubs. Industry will better cooperate in developing and adhering to communication protocols that will greatly improve accessibility of sensor data to researchers. In the future, we will see sensors that are better able to capture occupant comfort and indoor air quality, rather than measuring fairly indirect proxies. Weather stations and their integration into building automation systems will be commonplace as costs drop and communications protocols standardize. Finally, the spatial resolution of electricity and water meters will greatly improve as the ratio of the cost of the equipment and the measured substance continues to decrease.

Finally, and central to any research field, we expect a growing critical mass of worldwide occupant behavior researchers to remain strong and integrated. While a repository of occupant data will be a key ingredient for this thriving community, this report has contributed to standardizing and elevating the quality of future research in the field. Research programs like IEA EBC Annex 66 are one avenue for advancing a field and developing international standards and formalisms. Documentation of methods and results of occupant studies need to be targeted at all stakeholders, including building design practitioners, building technologies developers, building operators, and, of course, researchers.