ANNEX 79

EBC
Energy in Building and
Communities Programme

International Energy Agency

Occupant-Centric Building Design and Operation (Annex 79)

Energy in Buildings and Communities Technology Collaboration Programme

Technology Collaboration Programme
by iea

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October 2024

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Published by Karlsruhe Institute of Technology, Faculty of Architecture, Building Science Group, Englerstr. 7, 76131 Karlsruhe, Germany and Carleton University, Civil and Environmental Engineering, 3432 Mackenzie Building, 1125 Colonel By Drive, Ottawa, Ontario, Canada K1S 5B6

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ISBN 978-1-4884-0041-4

Participating countries in the EBC TCP: Australia, Austria, Belgium, Brazil, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Türkiye, United Kingdom and the United States of America.

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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 31 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 (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The R&D strategy of the EBC TCP for the five-year period from 2024 to 2029 was derived from the IEA Future Building Forum Think Tank Workshop convened jointly with the other buildings-related IEA TCPs, as the members of the IEA Buildings Co-ordination Group and held in October 2022 in Gatineau, Canada, as well as the strategic planning workshop held at the EBC Executive Committee meeting in Istanbul, Türkiye in November 2022. To this end, four main themes form the basis of the EBC Strategic Plan 2024-2029, which are as follows:

- Collaboration with other related IEA TCPs
- Refreshing the priority research topics
- Achieving impact from EBC research activities
- Developing EBC governance

A series of actions have been agreed for each, as shown below.

Collaboration with Other Related IEA TCPs

- Introduce a process for evaluating, and if appropriate, proposing collaboration with other IEA TCPs as part of the review of proposals at the project concept stage to ensure early communication with other TCPs.
- Introduce a process by which Executive Committee members from the EBC TCP can work with Executive Committee members from other TCPs to propose fully collaborative projects.
- Introduce a process to scrutinise project concepts put forward to the Executive Committee to decide if they are more relevant to another TCP and should be directed accordingly.

Refreshing the Priority Research Topics

- The overall objective should follow the IEA 'Net Zero by 2050 – A Roadmap for the Global Energy Sector', with a demand-led approach that focuses on reduction in energy use and energy demand.
- Members countries should be asked to actively propose topics for research based on their priorities.
- In developed countries the overriding objective must be to address the retrofit of the existing building stock. Whilst in emerging economies more emphasis should be placed on delivering net-zero new buildings.
- Recognising the need to deliver energy security, avoid unnecessary infrastructure reinforcement, and alongside energy efficiency pay equal attention to demand management and flexibility to fully utilise fluctuating renewable energy supplies.
- Achieving performance in practice by closing the performance gap will be vital to delivering net zero greenhouse gas emissions by 2050.
- Ensuring that energy efficiency / decarbonisation measures in buildings are future-proof and ready for our 2050 climate.

Achieving impact from EBC research activities

- The main responsibility for delivering impact rests with each EBC project ('Annex').
- Encourage Annexes to engage early with stakeholders that facilitate the introduction of the developed technologies and processes to practising engineers, architects, designers and the market.
- During project planning, apply criteria for evaluating legal 'Annex Texts' that scrutinise their anticipated pathways to impact.
- Use ‘theory of change’ to identify relevant actors and their information needs for Annex outputs.
- Tailor outputs to the information needs and literacy of the relevant stakeholders, for example policy briefings should follow best practice guidance.
- Work with established channels for dissemination.

Developing EBC Governance

- Modernise the EBC Implementing Agreement (the overarching legal agreement), including introducing ‘limited sponsors’ with their benefits and obligations to be defined.
- Develop EBC policy on equality, diversity and inclusion.
- Reduce the number of running Annexes.
- Nominated Executive Committee members will review new project proposals and will be selective.
- Create platform for EBC Operating Agents (project managers for the Annexes) to share experience.
- Consider cost-shared proposals for funding Executive Committee agreed activities.

The EBC Executive Committee

Overall control of the IEA EBC TCP 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 (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme 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 and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and 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 Behaviour 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 (*)
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings (*)
Annex 73: Towards Net Zero Energy Resilient Public Communities (*)
Annex 74: Competition and Living Lab Platform (*)
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables (*)
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions (*)
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting (*)

Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling (*)
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: ☼ EBC Annex 90 / SHC Task 70 Low Carbon, High Comfort Integrated Lighting
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy-efficient Heating, Cooling and IAQ Control in Residential Buildings
Annex 93: Energy Resilience of the Buildings in Remote Cold Regions
Annex 94: Validation and Verification of In-situ Building Energy Performance Measurement Techniques
Annex 95: Human-centric Building Design and Operation for a Changing Climate
Annex 96: Grid Integrated Control of Buildings

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 - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group - Building Energy Codes

Executive Summary

Occupant behaviour has a strong influence on building performance (e.g., energy consumption, emissions, comfort). Therefore, it has been in the focus of scientific research for many years. IEA EBC Annex 66 (2014-2017) provided a sound framework for experimentally studying and modelling different behavioural actions, including the implementation of these models into simulation platforms. However, design and building operation practice shows that many of the models do not adequately represent the manifold human interactions with a building, and that there is little guidance for designers and building managers on how to apply occupant behaviour knowledge and models in standard practice. IEA EBC Annex 79 continued tackling these topics with emphasis on the following objectives:

- Improvement of knowledge about occupants' interactions with building technologies. A specific focus will be on comfort-driven actions caused by multiple and interdependent environmental influences which were not yet covered by existing models.
- Deployment of 'big data' for the building sector as the availability of various data related to occupants' behaviour in buildings increases rapidly. A special focus was on new modelling strategies to represent occupant behaviour in an improved manner.
- Sustainable implementation of occupant behaviour models in building practice by developing guidelines and preparing strategies for applying occupant behaviour models during building design and operation. Focused case studies should demonstrate the implementation of new models in different design and operation phases.

As these three objectives spanned over a wide scope of scientific and practical questions, the work of Annex 79 was divided into four subtasks under which a variety of activities were launched to address different related topics of occupant behaviour.

Looking at relationships and interdependencies between different indoor environmental parameters and their impact on perception and behaviour, findings clearly confirm that

- occupants' expectations with regard to indoor-environmental conditions do influence their interactions with buildings and their systems, and
- such interactions influence, in turn, the energy performance of the built environment.

There are several gaps in knowledge on occupant-related topics, specifically in the theoretical foundations of i) human behaviour in buildings, ii) buildings' user interfaces, and iii) ontologies for representation of occupants in computational applications. It also became obvious that a truly interdisciplinary approach involving representatives of physical and human sciences is necessary to cover the complexity of the topic, and a concerted effort should be taken to more actively involve professionals (engineers, architects, building operation specialists) in future research and development.

As an important output a comprehensive reflection of the state of the art of occupant behaviour in buildings has been provided which revealed multiple challenges and deficiencies in related studies, including various methodological shortcomings. This can serve as a robust and useful foundation for continued research and education in this essential area, particularly for a next generation of occupant representations to be integrated in computational applications (building information modelling, building performance simulation). Findings also suggest that more intuitive and effective user interfaces for buildings and their systems are needed to support successful comfort-driven occupants' interactions and thus reach their satisfaction with building performance. This is particularly true for older adults' ability to use their spaces as desired and ultimately impacts aspects of their comfort, mobility, safety etc.

The work on deployment of 'big data' for the building sector showed that data-driven models have gained prominence in recent years and become the most widely utilized modelling approach, possibly due to the abundance of sensor-generated data and the availability of thorough statistical and machine learning software environments and programming languages. In order to maximize the potential of data-driven models, the establishment of a common data collection vocabulary or ontology is proposed, promoting data reuse and facilitating meta-analysis across different building types, sample sizes, and countries of origin. Additionally, providing occupant-related data in a standardized data model creates the opportunity to apply the data as inputs into the energy simulation tools.

For this purpose, an extended Brick schema appeared suitable for a standardized data structure as it provides a semantic framework to describe the various aspects from a building's structure to behavioural details of occupants, along with their relevant data. An important aspect is the availability of open data for modelling and simulation. In this view, separating data collection from data usage for research has to be considered. Finally, a variety of different modelling approaches were applied and tested for understanding and predicting occupant behaviour in building simulation, as well as for occupant-centric control.

A major output in this context was an occupant behaviour (OB) ecosystem of tools, datasets, guidelines, and methodologies. Specifically, a guideline for OB data collection and clear and transparent documentation of OB models was derived and published as a separate deliverable of the Annex. Furthermore, several OB datasets were collected and compiled in the ASHRAE Global Occupant Behaviour Database. It contains 34 field-measured datasets on different building occupant behaviours collected from 15 countries and 39 institutions across 10 climatic zones. A valuable addition was the Occupant Behaviour Library (OBLib), after several OB models had been gathered in GitHub. OBLib is a web-based platform for deciphering the details of the machine learning models trained from the data of the ASHRAE Global Occupant Behaviour Database.

Further work focused on integration of occupant information and application of occupant behaviour models in the building design process. An investigation of modelling tools and techniques regarding guiding and promoting occupant-centric building designs revealed that occupant behaviour integration into building performance simulation faces various adoption barriers. Studies showed an apparent disconnect between OB research and design practices as they were mainly at the proof-of-concept stage and lacked implementation and validation in actual buildings. A fundamental requirement for performing occupant-centric building design is establishing an effective mechanism to communicate occupant-related assumptions among project stakeholders. For this purpose, an information exchange platform is needed that is accessible to all design team members in order to establish an integrated design process. Furthermore, codes and standards should be updated because current occupant-related assumptions tend to be simplistic and are rarely dependent on design. These simplistic assumptions neglect the fact that building design affects occupant behaviour, which in turn affects building performance.

Theory and principles of occupant-centric design were brought to application through the presentation of seven real-world case studies. Major findings were that

- performing occupant-centric design requires information to be shared effectively among design stakeholders,
- occupant-related assumptions can influence the outcomes of design parametric analysis and affect the levels of comfort in buildings,
- occupant participation in the design process is useful in accurately representing occupants' presence and behaviour, and
- post-occupancy data collection is critical for continue improvement of operations and improving future building designs.

The research also identified several ways that building energy codes could be elevated with regard to occupant behaviour. Recommendations are to

- add prescriptive requirements that relate to occupancy,
- update schedules, densities, and other values based on recent field studies,
- incentivize buildings with greater flexibility towards different occupancy schedules, and
- introduce occupant modelling requirements.

Further, a framework called 'occupant-centric design patterns' (OCDP) was developed which is compatible with building information management (BIM) systems and building performance simulation (BPS) tools. By linking with BPS and BIM it is integrated into the information exchange happening between team members with different disciplinary backgrounds, supporting collaborative initiatives from a technical perspective. Finally, a Bayesian networks (BN) structural learning approach was adopted to synthesize populations of occupants in a multi-family housing case study. Results show that the BN approach is powerful in learning the structure of data sets and should be further elaborated in future research.

With regard to building operation, research focused on real world implementations of occupant-centric control and operation (OCC). OCC involves the sensing of indoor environmental quality and various occupant-related data and feeding this information directly back to the control system to optimize for both operational efficiency and occupant comfort. Rather than impose conditions on occupants, OCC is an occupant-in-the-loop approach that seeks to provide optimal and personalized conditions. For a systematic approach with regard to data collection and control strategies, a categorization was suggested relating to presence/absence of occupants, to occupant counts, and to occupant activities – all at system/building and zone/room levels, respectively.

The work also revealed that the inclusion of OCC in building operation will result in a fundamental role change for building operators, including expanding their expertise into advanced technology integration, communication, and education. However, training and knowledge is necessary to properly apply these technologies. It is also necessary that organizations value their use and understand the benefits they present in supporting operators' work.

An important output in this context was a classification for occupant-centric operations case studies. It consists of a multi-level structure addressing

- observation- versus intervention-based studies,
- human- versus system-related studies, and
- further sub-categories for differentiating occupant actions or system occurrences.

Additionally, a repository of OCC case studies was set up, offering a platform for presenting key information about practical implementations of these strategies in real-world scenarios.

Finally, future methodological expansions of OCC were investigated which include

- the clustering of tailored personalized models for demand-response programs in the residential sector,
- a more comprehensive approach to comfort that includes occupants' health, well-being and productivity,
- integration of occupants into the decision loop through different approaches, e.g., collecting qualitative data by surveys or interviews, allowing manual control within an automated OCC environment or feedback systems. OCCs should aim at modulating operation around their inputs to reduce energy waste and dissatisfaction, and
- new ways of collecting direct occupant feedback, such as using smart phone or watch applications for continuous and real-time data collection instead of making inferences from historical building automation systems' data.

To leverage the multidisciplinary project team, cross-subtask activities that involved multiple research areas were performed. One major output was the advancement of agent-based modelling (ABM) for integration with building performance simulation to evaluate the impact of occupants on building design and operation and vice versa. Further, an activity on human factors and ergonomics focused on employing methods that are well established in other interactive system domains, to design buildings that meet the physical, physiological, and psychological needs of human operators. A database of consumer-focused building control interfaces was developed.

Finally, one of the major efforts of Annex 79 is a book on 'Occupant-Centric Simulation-Aided Building Design', which is aimed at researchers as well as advanced designers. It provides theoretical and practical means to bring occupants and their needs into the centre of the building design process. The book also summarizes well the achievements of Annex 79 which not only contributed to new fundamental scientific knowledge in the field of multi-domain environmental exposure and the impact on buildings' occupants but also to new data-driven modelling approaches based on machine learning to integrate occupant behaviour in building performance simulation and occupant-centric control. Further, strong advancements in implementing occupant behaviour into the design practice were demonstrated by suggesting the enhancement of standards, to review the design process itself, and to integrate models into the digital design and simulation environment. And finally, the consideration of occupants in building operation and control as a further approach to implement occupant behaviour in building practice was successfully shown with different activities.

Acknowledgments

This research was supported by funding programs, grants, and other subsidies from various institutions on national, regional or university level in the respective countries of the participants of Annex 79. Special thanks to the German Federal Ministry of Economic Affairs and Climate Protection for funding Operating Agent Andreas Wagner (FKZ 03EN1002A) and to the Natural Sciences and Engineering Research Council of Canada for supporting Operating Agent Liam O'Brien.

The Operating Agents of Annex 79 appreciate the strong leadership and significant technical contributions of the Subtask leaders and thank all the participants for their scientific work and contributions to Annex 79, and particularly for their passion and commitment to Annex 79 even in difficult times through the worldwide pandemic.

Special thanks go to the Executive Committee of IEA EBC for the strong support and reviews during the five-year period of Annex 79; we particularly appreciate the feedback and advice from our Annex advisors Xudong Yang of China and Per Heiselberg of Denmark.

Thanks to Ruth Tamas and Nina Doré for editing and formatting various aspects of this report. Thank you to Astrid Roetzel for the illustrations at the start of each subtask chapter.

Last but not least, many internal (participants of Annex 79) and external (IEA EBC) reviewers have provided detailed and constructive comments, which have helped the authors to arrive at the final version of this report.

Table of Contents

Glossary

Action	An interaction event between an occupant and a building system or other system that causes a change in state
Adaptive behaviours	Occupant behaviours that are triggered by IEQ-related phenomena
Agent-based model	A modelling technique to represent occupants as autonomous agents who interact with other occupants, building systems, and the building
American National Standards Institute (ANSI)	An organization responsible for establishing and publishing technical standards spanning a wide range of products, systems, processes, and services
American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)	A professional association responsible for research, standards, and best practices regarding building mechanical systems and more broadly building performance, design, and controls
Architecture, engineering, and construction (AEC)	The industry responsible for delivering buildings – from design and occupancy
ASHRAE Guideline 36	A standard describing best-practice sequences of operation for HVAC systems including certain occupant-centric controls
Asset management standards	Standards that define the ontology, requirements (of the organization, leadership, planning, support, operation, performance evaluation, and improvement) and management of a built asset
Aural comfort	A measure of the objective and subjective elements of the satisfaction of the acoustic environment of space
Binomial model	A common statistical model, also referred to as logistic regression, that as used to predict binary outcomes
Boundary condition	Condition defining how a system (such as a building) interacts with the environment
Building Automation System (BAS)	The system of hardware and software used to control electrical and mechanical systems in a building
Building information modelling (BIM)	The process of creating and managing the digital federate model that contains all the information of a project structured according to information containers mirroring the different disciplines involved in the project
Building operator	The person(s) responsible for the electrical, plumbing, and mechanical operations of a building or facility
Building Performance	A measure of a building's efficiency or how well it functions; in this context, usually with regard to energy use
Building performance simulation (BPS)	A software system that employs mathematical models representing buildings to predict various aspects of building performance (energy use, comfort, indoor air quality, etc.)
Building physics	Application of the principles of physics to the built environment (e.g., acoustics, air movement, thermodynamics)
Building Research Establishment Environmental Assessment Method (BREEAM)	A sustainability assessment method for master-planning projects, infrastructure, and buildings
Building Services Research and Information Association (BSRIA)	A UK-based testing, instrumentation, research, and consultancy organization, providing specialist services in construction and building services engineering
Cognitive load	The amount of effort required to reason and/or process information
Computational model	A computer-generated model used to simulate and study complex systems using mathematics, physics, and computer science
Controls-oriented occupant data	Data acquired from sensors or through interactions with control interfaces about a group of occupants' presence, count, identities, and activities
Cooling degree days (CDD)	A measure of the magnitude and duration of outdoor air temperatures that can be used as an indication of the expected building cooling load
Data-driven model	A model that is trained or otherwise constructed using measured data

Degree-occupant-hour	Sum of occupied hours multiplied by the number of occupants and derivation of a measurement exceeding a threshold
Design aims	The set of goals or objectives a given design needs to achieve as specified by the client and all other involved stakeholders
Design decisions	Any technical decision made by a designer (architect, mechanical engineer, civil engineer, etc.) during the design process
Design parameter (DP)	A variable used to define an aspect or characteristic of a building or building system
Design pattern	An abstract design problem-solution pair which appears repeatedly in design contexts and which can be clearly identified and recorded
Design requirements	The set of requirements established by the project team, with or without the client and other stakeholders, that a given design needs to fulfill
Design stages	Different stages of project delivery with milestones for information preparation and exchange, client approval, and payments as specified in plans of work from a given accreditation body
Design workflow	A process for laying out all tasks and processes in a visual map, in order to give team members and stakeholders a high-level overview of each task involved in a particular process
Deterministic model	A mathematical model that yields the same results, with no randomness, each time it is simulated
Distributed energy resources (DER)	An electrical power source sited close to customers that can provide all or some of their immediate needs and/or can be used by the utility system to either reduce demand or provide supply to satisfy the energy, capacity, or ancillary service needs of the grid
Diversity schedule	A series of values (typically ranging from 0 to 1) to indicate the relative intensity of occupant-related phenomena (e.g., occupancy, plug loads)
Double hermeneutic	A characterization of social science research that acknowledges interactions between researcher and research subject, and the subjectivity inherent in performing such research
Energy conservation measure (ECM)	A building upgrade designed to save energy
Energy efficiency (EE)	A measure of the ability for a building to use energy effectively compared to the service it provides
Energy management system (EMS)	A building tool used to analyze and process building energy data to monitor energy use and efficiency
Energy modelling	The process of building computer models of energy systems to analyze and predict a building's energy use over time
EnergyPlus	A comprehensive building performance simulation tool
Epistemology	The study of knowledge; that is, how we know what we claim to know
eQuest	A building performance simulation tool
Factor, contextual	A circumstance in a building that influences occupancy or behaviour; this factor can be categorized as physical environment, psychological, social, or physiological
Factor, personal	A factor related to the personal characteristics of the occupant, like age, weight, and personality.
Factor, physical environmental	The physical circumstances of a space, such as the building envelope and availability of adaptive opportunities, that affect an occupant's behaviour
Factor, physiological	The physical circumstances of an occupant that affect behaviour and comfort such as their demographics and level of health
Factor, psychological	The mental circumstances of an occupant that affect behaviour and comfort, such as preferences, expectations, and perceived control.
Factor, social	The influence of other people (e.g., in a shared room) on one's behaviour or presence
Fit-for-purpose model	A model that generates the required results to the necessary level of accuracy within a manageable amount of time and effort
Formative evaluation	Evaluation activities designed to specify directional targets, monitor progress, and provide ongoing feedback

Grid-interactive efficient building (GEB)	An energy-efficient building that uses smart technologies and on-site DERs to provide demand flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences, in a continuous and integrated way
Haptics	Electronically or mechanically generated movement or vibration, often felt through the sense of touch
Heat index (HI)	The temperature feels like to the human body when relative humidity is combined with the air temperature (AKA apparent temperature)
Heating degree days (HDD)	A measure of the magnitude and duration of outdoor air temperatures that can be used as an indication of the expected building heating load
Hidden Markov model (HMM)	A statistical model to predict a series of events, based in part on indirect observations
Human–building interactions (HBI)	The study of the interactions between occupants and a building's physical space and the interfaces within it
Human Factors and Ergonomics Society (HFES)	A society representing professionals who work in the field of human factors and ergonomics
Human information processing (HIP)	A model that describes how people receive, use, and act upon information provided to them based on attentional resources and inputs
Indoor environmental quality (IEQ)	A holistic measure of comfort and healthiness of an indoor space for human occupants, which comprises four main components: thermal comfort, visual comfort, aural comfort, and indoor air quality
Information delivery plans	The information deliverables for each task in a project, including their format and who is responsible for delivering them
Information management	The process of producing, collecting, storing, curating, distributing, using, archiving, etc. all the information related to a design project
Information management standards	Standards which define information management concepts, principles, organization, functions, delivery cycles and planning, team capability and capacity, common data environments, and workflows for built projects
Information management systems	Processes designed to store, organize, retrieve, and distribute information to be used in decision-making
Institute of Electrical and Electronics Engineers (IEEE)	A professional organization representing electrical and electronics engineers
Integrated design process (IDP)	A design approach which involves all stakeholders of a project from the early design stages (i.e., from the specification of design requirements and objectives) so that integrated and optimum design solutions are developed through common agreement and interdisciplinary methods
Integrated project delivery (IPD)	A project delivery model that embraces a collaboration between stakeholders to distribute the risk and reward of the project
International Electrotechnical Commission (IEC)	An international organization that publishes standards for electrical and electronic equipment
International Organization for Standardization (ISO)	International Organization for Standardization
Leadership in Energy and Environmental Design (LEED)	A green building certification program with a set of rating systems for the design, construction, operation, and maintenance of green buildings, homes, and neighborhoods
Lighting load	The installed power of the luminaires in a building
Markov chain model	A stochastic model to predict a series of events, whereby the transition of state probability only depends on the previous state
Model complexity	Level of detail in a model, which in turn depends on its size and resolution
Model resolution	Number of variables in the model and their precision or granularity
Model size	Number of components in a coupled model
NABERS Building Standard	A rating system that measures the operational environmental performance of buildings and tenancies, e.g., the energy efficiency, water usage, waste management, and indoor environment quality of a building or tenancy and its impact on the environment
Non-adaptive behaviours	Occupant behaviours that are related to habits, tasks, and other phenomena that are not triggered by IEQ-related phenomena
Objective data	Data that is directly observable by reliable instruments or people

Objective function	A mathematical construct of building performance metrics in a design optimization problem that is to be maximized or minimized
Object-oriented structures	Structures composed of clearly defined and identifiable objects or building blocks
Observational measure	Measure that provides an objective view of occupant behaviour in a space, such as behaviour tracking, mapping, instrument-based data collection, photography, and videography
Occupancy	The presence of occupants, which can be defined as a binary state (occupied or unoccupied/vacant), number of occupants presence, and/or details on present occupants (e.g., demographics)
Occupant behaviour	The actions or resulting states caused by the interactions between occupants and buildings/building systems
Occupant discomfort hours (ODH)	The sum of the product of the number of occupants present and the number of hours that they suffer from discomfort
Occupant preference learning	Inferring occupant preferences through algorithms assimilating occupant activity data concerning adaptive behaviours
Occupant-centric control (OCC) variables	Occupant-related variables defined within a building controller which are used in control sequences. An example of an occupant-centric control variable is the latest expected arrival time. It can be used in a sequence to switch an HVAC zone's mode of operation to unoccupied, when the current time exceeds the latest expected arrival time in a vacant space
Occupant-centric controls (OCC)	Occupant-centric controls (OCC) is an indoor climate control approach whereby occupancy and occupant comfort information are used in the sequence of operation of building energy systems
Occupant-centric metrics	Building performance metrics that capture the quality of services occupants receive and the degree of buildings' flexibility to accommodate occupants' interactions with building systems which influence building operations and thus resource usage and environmental performance
Occupant-hour	Sum of hours multiplied by the number of occupants in corresponding hours
Occupants	Human inhabitants of buildings
Occupant distribution scenarios (ODS)	Set of assumptions about how occupants are distributed within a building
Offline learning for OCC variables	Algorithms used to transform occupant data from sensors or control interfaces to OCC variables using archived historical data
Olfactory	The sense of smell of occupants, referring to their ability to perceive odor of indoor air
Online learning for OCC variables	Algorithms used to transform occupant data from sensors or control interfaces to OCC variables in an online fashion. It is broadly categorized as recursive or batch online learning algorithms
OpenStudio	A cross-platform collection of software tools to support whole building energy modelling using EnergyPlus and advanced daylight analysis using Radiance
Parallel coordinates plot	A graph used in parametric simulation to illustrate the performance of an individual or multiple design variants in terms of multiple metrics, whereby each metric is represented by a separate axis and the axes are equally spaced and parallel to each other
Participatory measure	A method that allows occupants to participate directly in research, such as a design charrette or crowd-sourced data collection effort
Perceived control	Level of subjectively perceived control over one or more of the IEQ factors via building systems or other adaptive opportunities. This may differ from objectively available control, e.g. when a person is not aware of a control opportunity or considers it ineffective
Performance indicator	In the context of building simulation, a quantitative measurement by which the performance, efficiency, etc. of a building can be assessed, stand-alone or by comparison with a defined target
Persona	A fictional or nonfictional set of characteristics that define a representative occupant for design and modelling purposes

Personalized control	A control strategy that provides individual control opportunities to an occupant to control the IEQ factors of its immediate personal surrounding without affecting the IEQ factors of other occupants in the same room
Plans of work	Document issued by professional accreditation body to provide a road map for the building industry on design process management
Post occupancy evaluation (POE)	The process of objectively or subjectively measuring the comfort level of a building is after users have begun occupying it
Practitioners	Professionals who apply skills and knowledge to one or more phases of the building life cycle (design, operations, management, etc.)
Project information requirements	The information required by each party at key decision points throughout the life of a building project (from building design to building in use)
Reversal function	In the context of occupant behaviour modelling, a function indicating the returning of a building component in the position prior to the action (e.g., closing a window or opening a shading system)
Self-report measure	A method that allows researchers and designers to understand how users perceive a space and their own needs, such as questionnaires, interviews, focus groups, and diaries
Sequences of operation	A specification defining how each building system, subsystem, and device shall interact with each other to deliver building services
Simulation-aided building design	An approach to building design in which the design process is informed by building performance simulation and analysis
State	The resulting condition after an occupant has acted or a building system has changed (e.g., window is open, light is on)
Stochastic model	A model that introduces randomness such that the output varies each time it is simulated
Subjective data	Data that is not directly observable in the same way by all instruments and people
Summative evaluation	Evaluation activities designed to measure how well the building works
Task Illuminance	The total amount of light falling on a surface, in this case, the amount of light needed to perform a task such as reading and writing.
Technology acceptance model (TAM)	A model that illustrates how users accept and use new technologies
Test-Reference Year (TRY)	Datasets with a sequence of 8,670 hourly data values of typical meteorological variables for a specified location
Theory of planned behaviour (TPB)	A psychological theory that attempts to predict human behaviour based on expressed intentions, attitudes, beliefs, given perceived controllability of environmental features
Thermal comfort	A measure of occupants' satisfaction with thermal conditions, which is frequently defined as “That condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.” according to ANSI/ASHRAE Standard 55-2020)
Triangulation	Use of multiple sources of data to see whether results point in the same direction, thereby increasing confidence in the validity of outcomes.
Trigger	External event or circumstance that causes an occupant to initiate an action or relocate
User experience (UX)	An area of research and industry that focuses on how people interact with devices, controls, or products
User journey	A technique mimicking a person's experience during one session of using a building, consisting of the series of actions performed to achieve a particular goal (e.g., typical day of a facility manager in an office building)
Variable air volume – air handling unit (VAV AHU) system	A widely used air-based HVAC approach in commercial and institutional buildings whereby the centrally-supplied air supply rate is varied at the zone level to control the heating and cooling rate
Visual comfort	A measure of the objective and subjective elements of the satisfaction of the luminance from electric lighting and daylight in space
WELL Building Standard	A performance-based system for measuring, certifying, and monitoring features of the built environment that impact human health and well-being, through air, water, nourishment, light, fitness, comfort, and mind

Window-to-wall ratio (WWR)	The fraction of a building's facade area that comprises windows

1. Introduction

According to the International Energy Agency's Energy Efficiency report (IEA, 2023), total energy use of the building sector continues to increase. While energy efficiency (measured by energy use intensity) is slowly improving (mostly driven by technology and policy), it is being exceeded by the global floor area growth rate. This means the total absolute energy use of the buildings sector is still increasing. The majority of policies (e.g., building codes, standards, and incentives) are focused on traditional domains, including building envelopes and HVAC efficiency. However, relatively little attention has been paid to the role that occupants play in building performance – likely because occupants are much more complex and uncertain than the aforementioned building systems. This notion transcends practice, where occupants are often seen as passive recipients of indoor environments, rather than active building users who have tremendous influence over comfort and building energy use.

Depending on the building type and degree of automation, occupants remain one of the greatest influences of building energy use. For instance, Hong and Lin (2013) performed a simulation study to show that occupant behaviour at the office scale could increase energy use by 80% or reduce it by 50% from standard assumptions. Other similar studies, including field studies, have concluded similarly large magnitudes (Gram-Hanssen, 2010, Clevenger, Haymaker et al., 2013). Diversity in the way occupants operate HVAC equipment, lighting, appliances, and other building systems (e.g., windows, blinds as in Figure 1-1) have been explained as a major cause of the "performance gap" between predicted and measured building energy use. Such performance gaps can be frustrating to building designers and occupants alike.

Figure 1-1: A large office building façade, showing the juxtaposition of the occupant-controlled window shades and the operator-controlled lighting

In larger buildings, building operators can be seen as super-occupants, who can affect energy use by orders of magnitude more than individual occupants (André, Bandurski et al., 2023). Their energy-related actions can include setting and adjusting operating schedules for entire buildings or campuses (e.g., lights in Figure 1-1), and overriding controls logic in response to complaints because the building is behaving unexpectedly or contrary to their understanding or beliefs (Abuimara, Hobson et al., 2021).

Sub-optimal building performance resulting from short- and long-term occupant interventions is often frustrating for building designers, operators, and owners. However, the temptation to restrict occupant autonomy often comes at the cost of poorer comfort and perceived control. And thus, we have a major multi-objective optimization problem to satisfy the needs of all stakeholders, while ensuring occupant well-being. While modern automation technologies have been introduced into buildings – in part to reduce absolute energy use and uncertainty of energy use associated with occupants – emerging evidence suggests that occupants are often dissatisfied with automation and may intervene (e.g., Lee, Fernandes et al., 2013). Such interventions can include energy-intensive behaviours such as leaving a window open in winter when heating is on, covering motion sensors that control lighting, inefficiently using a space heater, or prompting building operators to make permanent overrides to reduce further complaints (Gunay, Shen et al., 2018). Designers often overlook or do not understand the fact that providing greater control to occupants increases their acceptance and preference for a wider range of indoor environmental conditions (Brager, Paliaga et al., 2004). Thus, a major question emerges and remains in the field: what is the ideal solution between building automation and manual systems to optimize occupant comfort, usability, perception of control, and energy efficiency (Figure 1-2)?

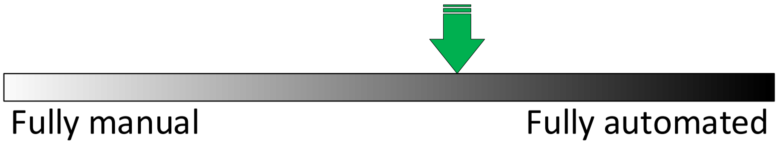


Figure 1-2: The spectrum of fully manual buildings to fully automated buildings; the optimal solution, when occupant psychology and physiology are considered, is not evident

And thus, there is a strong connection between energy performance of buildings and occupant comfort and well-being. As we spend more time in buildings (and for many, this exceeds 90% of the day), buildings play an increasing role in our lives. Their design and operation can affect how we interact with each other and building systems, our perceived control over the indoor environment, our physical activity, our connection to nature, our environmental behaviours, and our attitudes.

In the past several years, occupant well-being gained heightened widespread interest by the public due to the global COVID-19 pandemic. Suddenly, nearly everyone was concerned about indoor air quality, ventilation, and the well-being and productivity of occupants who abruptly changed their daily lives (e.g., lockdowns, work-from-home). This world event heightened the importance and awareness of Annex 79 topics.

Prior to the project we are reporting on, Annex 79, IEA EBC Annex 66 (2014-2017) identified the strong influence of occupants on building performance and provided a sound framework for experimentally studying and modelling different behavioural actions, including the implementation of these models into simulation platforms. However, at that time, design and building operation practice showed that many of the models do not represent the manifold human interactions with a building appropriately enough, and that there is no guidance for designers and building managers on how to apply occupant behaviour models in standard practice.

Annex 79 built upon IEA EBC Annex 66 – particularly regarding definitions, modelling fundamentals, and a strong understanding of current design practice. Annex 79 places greater emphasis on occupant comfort, data-driven methods, focused case studies projects, and policy. Some key questions that emerged out of the above problems and circumstances that Annex 79 sought to answer, include:

- What are the relationships and interdependencies between different indoor environmental parameters (thermal, visual, olfactory, and aural comfort) and their impact on occupant perception and behaviour? (see Figure 1-3)?
- How do building controls' interfaces and their underlying logic affect behaviour? How can and should interfaces be systematically tested in experimental, in situ, immersive environments, and simulation approaches?
- How can we leverage building automation systems and other readily-available data sources (e.g., using data-mining and artificial intelligence methods) to develop occupant models, inform building design, and optimize building controls and operations?
- How should experimental and occupant modelling findings be used to influence building codes, standards, and policies?
- How much impact does occupant behaviour have across building types, climates, and against other agents (e.g., building operators)?
- How can uncertainty and risks from occupants be managed and exploited in building design?
- Are current post-occupancy surveys adequate to study behaviour?

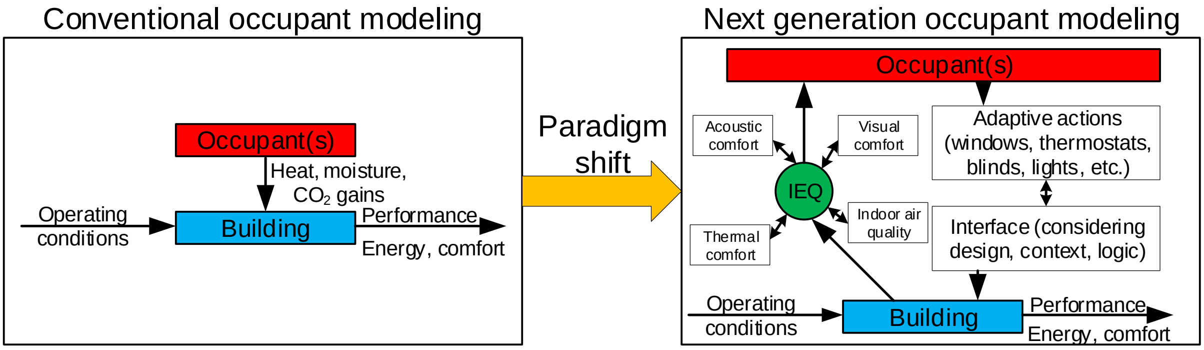


Figure 1-3: Paradigm shift in the way occupants are modelled in buildings: from occupants as passive sources of heat, moisture, and emissions to active decision-making agents that respond to indoor environmental conditions

2. Framework

2.1. Approach and research questions

In order to achieve the objectives outlined in Chapter 1, the following research questions were established:

- How do the different indoor environmental parameters (thermal, visual, olfactory, and aural comfort) relate to each other and influence occupants' perception and behaviours?
- How do building interfaces**,** their context (e.g., placement), and their underlying logic affect behaviour? What interface features and characteristics are most effective at delivering a comfortable environment, outstanding perceived control, and reductions in energy consumption?
- How can new and existing data sources (e.g., building automation systems, human resource databases, information technology networks, Internet of Things, etc.) and advanced data analytics (e.g., machine learning, artificial intelligence, statistical modelling) be exploited to develop new fundamental knowledge about occupant behaviour, indoor environmental quality, energy, and the relationship between them?
- How can simulation-aided building design processes, energy code and standards be advanced to properly account for occupants in order to yield more comfortable, healthy, usable, and energy-efficient buildings?
- How can building operations and controls be advanced to exploit new data sources and on-line learning methods to adapt to occupancy and occupant preferences to provide more comfortable environments using less energy or less carbon emission?

For each question, the Annex: (1) reviewed and develop methodological approaches, (2) developed new knowledge, (3) performed focused case studies, where applicable, and (4) transferred new methods and knowledge to key stakeholders (policy makers, researchers, building designers, technology companies).

2.2. Subtasks of the Annex

Figure 2-1 shows the four subtasks that were established to provide solutions addressing the Annex objectives. Subtasks 1 and 2 focused on fundamental research in the fields of multi-domain comfort and occupant behaviour as well as data mining and analytics, whereas Subtasks 3 and 4 focused on practical applications in building design and operation. In addition, as the arrows in the figures shall indicate, a number of cross-subtask activities were initiated during the course of the Annex which covered topics of interest in between the main subtask topics.

In Table 2-1 the interdependencies between research methods to be applied and the Annex's main topics are shown. New knowledge about multi-aspect environmental exposure and building interfaces which is relevant for advanced models was gained in ST1 mainly by extensive literature reviews and surveys. ST2 collected and deployed data sources of different kinds for applying data-driven modelling techniques. As a result, open platforms for occupant behaviour data and models were developed. The implementation of advanced occupant behaviour models and strategies (emerging out of ST1 and ST2, but also existing ones) into building design and operation was the main focus of ST3 and ST4. This was supported by preparing guidelines and recommendations for standards. ST 4 specifically investigated occupant-centered control (OCC) strategies and tested algorithms in a simulation testbed. Finally, applications were tested in case studies in order to challenge them in real design contexts and building environments.

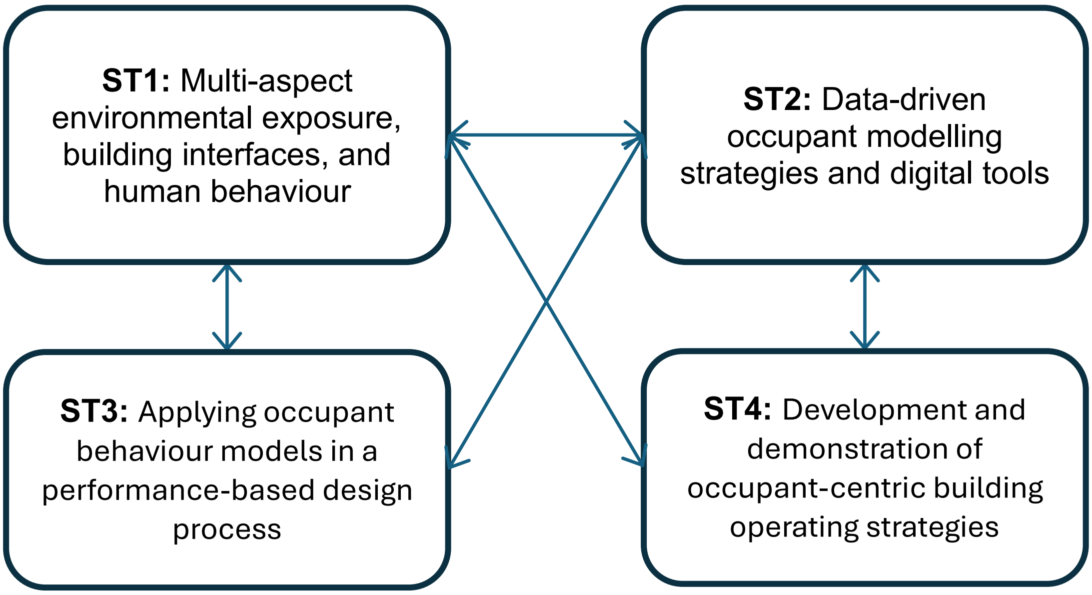


Figure 2-1: Structure of Annex 79 with 4 Subtasks

Table 2-1: Relationships between research methods and topics (dark shaded areas are particularly emphasized, while lightly-shaded areas are still important)

	Occupant behaviour	**Technologies, interfaces**	**“Big data” from BMS, etc.**	**Advanced models**
Literature reviews, surveys, etc.	ST1	ST1		
Data mining, machine learning	▨	▨	ST2	
Modelling and design guidelines, building policy (standard and code) recommendations	▨	▨	▨	ST3/4
Field application - testing, monitoring and verification in case studies	▨	▨	ST3/4	ST3/4

2.3. Overview and deliverables of the Annex

Annex 79 provides new insight into comfort-related occupant behaviour in buildings and its impact on building energy performance. It further promotes the usage of this knowledge in building design and operation by supporting standardization processes and providing guidelines for practitioners. Table 2-2 gives an overview on all deliverables which are available from Annex 79 – besides a huge number of publications and four special issues of scientific journals (see Appendices).

Table 2-2: Deliverables of Annex 79

No.	**Description of deliverable**
Text-based deliverables:	
1	**Comprehensive final Annex Report, summarizing most essential activities:** - Four main chapters which give an overview of the most significant contributions of each subtask - A chapter about further outputs of the Annex (Cross-subtask activities, a book, digital deliverables) - Comprehensive summary with conclusions and recommendations for future work, as well as all further relevant information about Annex 79
2	**Open-access book: Occupant-centric building design** A comprehensive book that includes fundamentals on occupant comfort, consideration of occupants and occupant behaviour in design processes, occupant modelling and simulation, and case studies focused on occupant centric design.
3	**A Comprehensive Guideline for Documenting and Implementing Occupant Behaviour Models in Building Performance Simulation and Advanced Building Controls** A guideline for technologies and best practices to collect occupant-related data for applications in occupant modelling for simulation and for occupant-centric controls
Deliverables in digital format:	
4	**ASHRAE Global OB Database** A centrally-coordinated database of occupancy and occupant behaviour data. Currently available: www.ashraeobdatabase.com. (only if ASHRAE agrees to credit the database to EBC).
5	**Platform for sharing and evaluating OB models** A database with occupant behaviour models that is based partially on the ASHRAE Global OB Database.
6	**Online library of case studies on OCC projects** A large international collection of documented case studies of buildings or spaces that demonstrate occupant-centric controls

The deliverables are addressed to four main target groups:

Science: Researchers/academics, such as building scientists, psychologists, sociologists, computer scientists, and ergonomists who will gain new knowledge on multi-stressor-based occupant behaviour in buildings and data-based models.

Practice: Architects, planners, energy consultants, HVAC engineers, building managers and operators who will receive advanced models and tools as well as guidelines to consider occupant behaviour in energy-efficient building design and operation.

Industry: Manufacturers of building technologies (HVAC and lighting systems, controls, controls interfaces) who will be able to incorporate occupants' demands into product development.

Policy: Persons responsible for formulating new standards and codes, who can evaluate and adopt the guideline and recommendations of integrating explicit occupant aspects.

3. Organization of the Annex and participation

The leaders of Annex 79 and its Subtasks are shown in Table 3-1.

Table 3-1: Operating agents and subtask leaders of Annex 79

Operating Agents: Andreas Wagner (KIT, Germany) and Liam O'Brien (Carleton University, Canada)	
Subtask leaders	
1	**Ardeshir Mahdavi,** TU Wien, Austria **Marcel Schweiker**, University Hospital RWTH Aachen, Germany **Julia Day**, Washington State University, USA
2	**Bing Dong**, Syracuse University, USA **Salvatore Carlucci**, The Cyprus Institute, Cyprus **Romana Markovic** (KIT, Germany), until March 2022
3	**Farhang Tahmasebi**, University College London, UK **Tianzhen Hong**, LBNL, USA **Da Yan**, Tsinghua University, China
4	**Burak Gunay**, Carleton University, Canada **Zoltan Nagy**, University of Texas Austin, USA **Clayton Miller**, National University of Singapore, Singapore

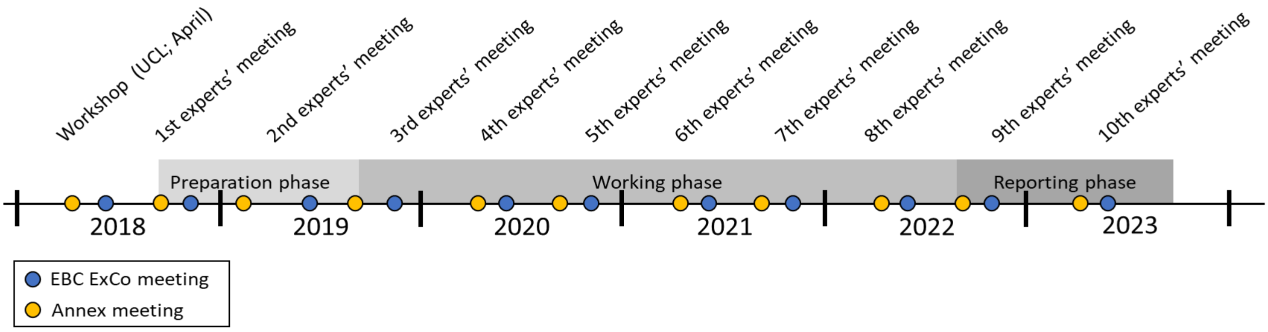
In total, 18 countries officially participated in Annex 79: Austria, Australia, Belgium, Brazil, Canada, China, Denmark, France, Germany, Italy, Netherlands, Norway, Singapore, Sweden, Switzerland, Turkey, UK, and USA (
Figure **3-1**). UAE, Hungary, and Poland were approved as observers.

The tables in the Appendices list 144 Annex 79 participants (Table 12-1 and Table 12-2).

Figure 3-1: Participating countries in Annex 79

3.1. Annex meetings

Unfortunately, Annex 79 was affected by COVID-19 during the working phase which resulted in 5 out of 10 online meetings (though 3 meetings were organized in hybrid format). However, the impact of this circumstance was relatively minor since the majority of participants had established working relationships with each other by the time COVID-19 began. The main challenge with online meetings was accommodating diverse time zones – especially considering the meetings were approximately eight hours long over two days.



shows the timeline of the Annex meetings over the five years and Figure 3-3 the group photos from these meetings. For more details see the Appendices.

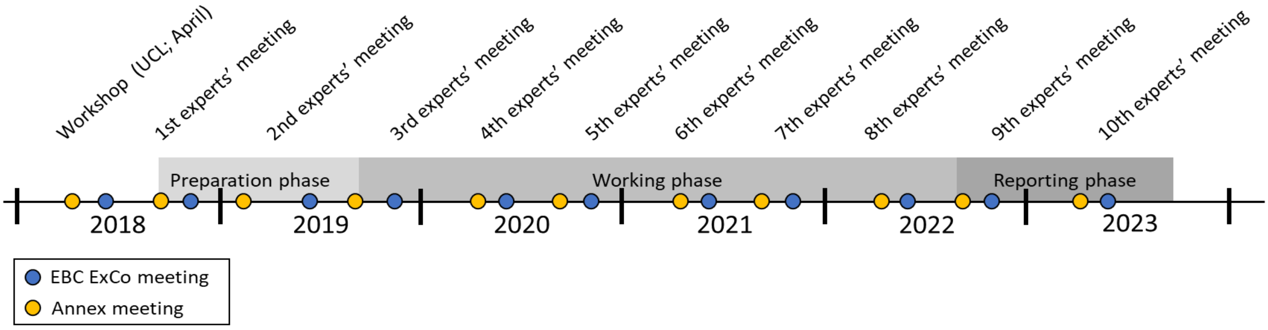
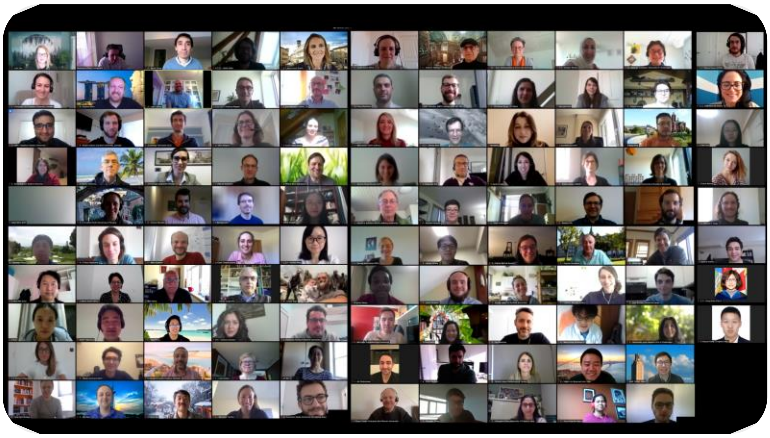


Figure 3-2: Timeline of Annex 79 meetings

1st meeting in Ottawa, Canada

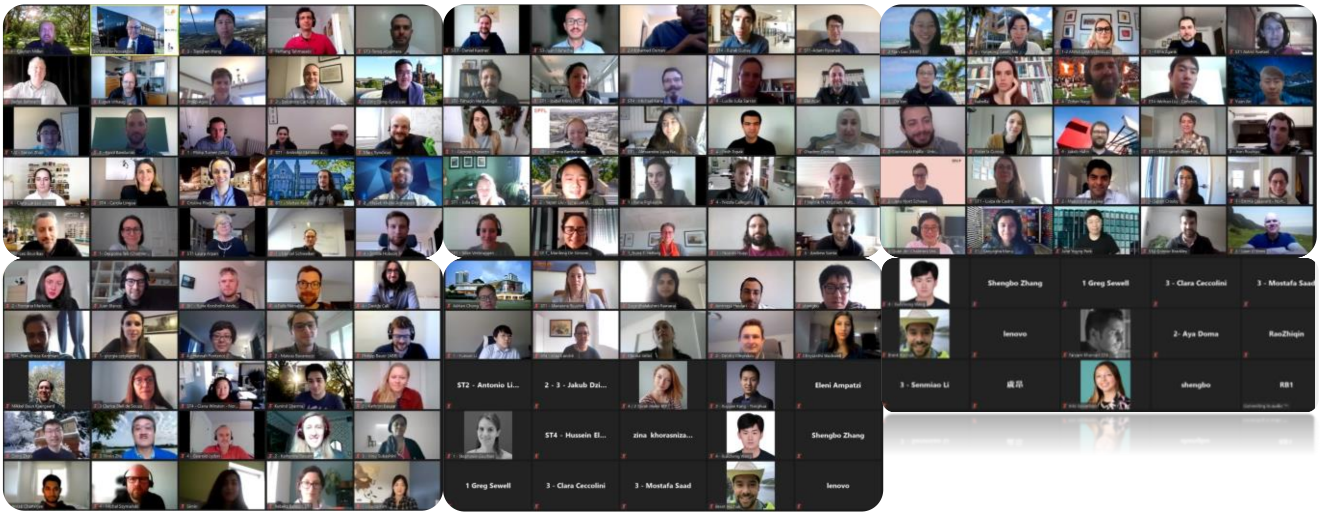
2nd meeting in San Antonio, USA

3rd meeting in Perugia, Italy

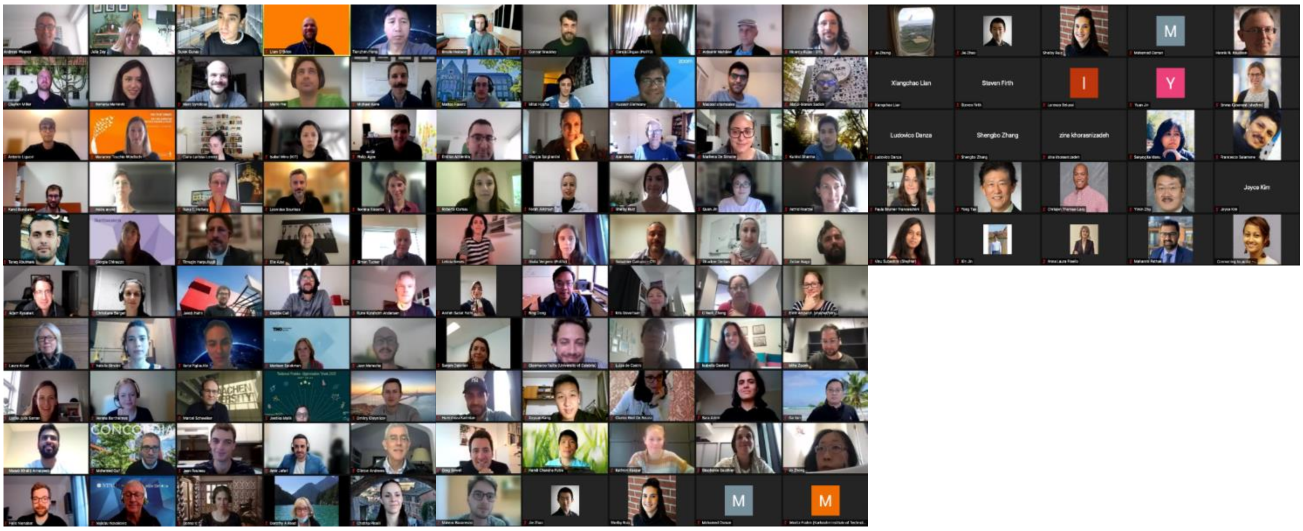


4th meeting Southampton, UK (online)

5th meeting in Odense, Denmark (hybrid)

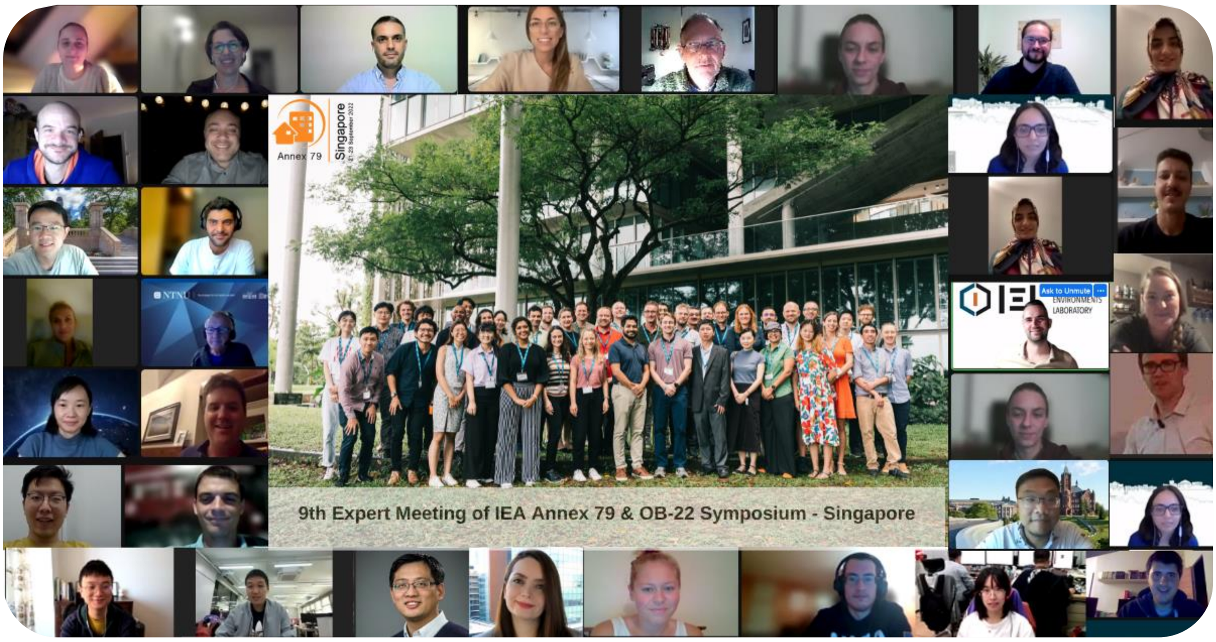


6th meeting in Trondheim, Norway (online)



7th meeting in Spokane, USA (online)

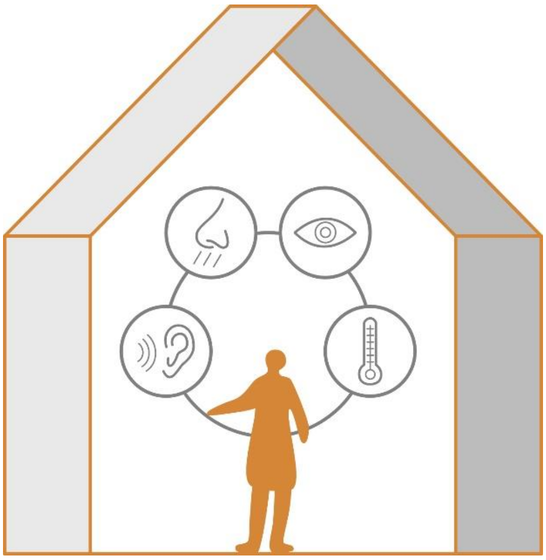
8th meeting in London, UK (online)



9th meeting in Singapore, Singapore

10th meeting in Aachen, Germany

Figure 3-3: Group photos of Annex 79 meetings



4. Multi-aspect environmental exposure, building interfaces, and human behaviour

4.1. Introduction

In the face of climate change, resource depletion and other planetary boundaries (Raworth, 2017), further understanding of the role of occupants' needs, behaviours, and interactions with the building can contribute to reducing the built environment's impact on these boundaries as well as to identify potentials and limits of adaptation and mitigation measures from the human perspective.

Occupants' needs have been targeted in research for decades (see e.g. IEA EBC Annex 69 in relation to thermal aspects). Likewise, occupant behaviour has also been the focus of previous activities (see e.g. IEA EBC Annex 53 and 66 (Yoshino, 2013, Yan and Hong, 2018)). On the one hand, such previous work formulated summaries of theoretical foundations (see e.g. Polinder, Schweiker et al., 2013). On the other hand, it pointed to the influence of occupants on the energy use of buildings. For example, depending on the building type and degree of automation, the work by (Hong and Lin, 2013), which is based on simulations, suggests that occupant behaviour at the office scale could increase energy use by 80% or reduce it by 50% compared to standard-based assumptions. Nonetheless, questions remain regarding the generalizability and validity of such claims (Mahdavi, Berger et al., 2021).

In addition, existing models of human comfort, perception, and behaviour have been commonly formulated for single-domain environmental exposure circumstances (e.g., thermal, visual, aural), but failed to address the multi-domain nature of typical human exposure settings during everyday life (Frontczak and Wargocki, 2011), which involves thermal, visual, aural, and indoor air quality domains together with further factors such as building systems and their user interfaces (Figure 4-1).

To encourage user behaviour patterns that are desirable from the operational standpoint (i.e., patterns that can bring about desirable indoor environmental conditions while meeting the operational efficiency criteria), a better understanding of interfaces to control-relevant building features and systems (and corresponding occupant behaviours) is critical. There is a multitude of building interfaces that can have either a positive or negative impact on energy use or occupant comfort. However, many such interfaces are poorly understood in terms of occupant behaviour and resulting energy impact or comfort. Moreover, designers often overlook the fact that providing greater control to occupants increases their acceptance of a wider range of indoor environmental conditions (Brager, Paliaga et al., 2004).

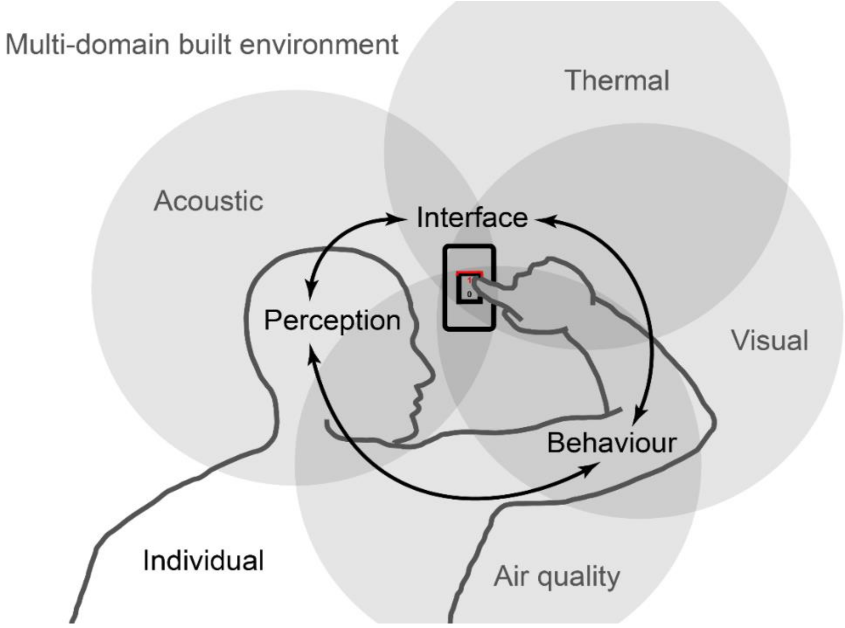


Figure 4-1: Main elements of the multi-domain built environment considered within Subtask 1 Figure provided by Marcel Schweiker based on Schweiker, Berger et al. (2023)

In summary, in the scientific literature, several gaps and limitations have been identified in relation to research on (1) multi-aspect environmental exposure, (2) building interfaces and (3) human behaviour. Therefore, the objective of the work conducted within Subtask 1 of IEA EBC Annex 79 was to better understand and develop research techniques to study energy and comfort-related occupant perception and behaviour in the context of multiple aspects of indoor environmental exposure, to understand how occupants interact with building interfaces, and to acquire more knowledge regarding the potential to affect real and perceived control and building energy performance.

To address these gaps and limitations, 18 collaborative activities were started within the Subtask 1. These can be grouped into four distinct types: (1) review activities to thoroughly summarize the state-of-art; (2) activities to set quality guidance for future multi-domain research; (3) new research to address specific gaps identified; and (4) a review of evidence provided in current standards and ways forward with this respect. While the first two sets of activities were coordinated within the common agenda of this subtask, the covered scope and topics depended on the participants' individual research interests and resources. Given the wide array of gaps that could have been addressed, availability of resources and the timeframe of Annex 79, the undertaken research activities could neither cover all areas of multi-domain built environments nor could they offer final conclusions. Rather, the results provide a robust stepping stone toward further research and development in the explored areas. The fourth set of activities related to standardization was not included in the initial plan of work in Subtask 1. However, in the course of the Annex work progress, it was identified as a crucial topic, given its significance for bridging the gap between research and practice.

The main findings of these activities are provided in the following Section 4.2, which pertains to multi-domain research from theory to implementation into standards. More detailed descriptions of the activities of Subtask 1 are provided in the subsequent sections of the report, organized along the following headings: 3: State-of-the-art assessments; 4: Setting new quality standards and guidance for methods used in the field of multi-domain and interface research; 5: New field and laboratory studies; and 6: Transfer to IEQ standards. The seventh and last section includes general conclusions and the future outlook. Given this outline, readers are provided in Section 4.2 with a first overview of scope and outcome of the activities conducted within Subtask 1. For further details, they can consult the more detailed descriptions in the remaining sections starting with Section 4.3. Further details can be found in the numerous original publications that resulted from the activities of Subtask 1.

4.2. Multi-domain research from theory to implementation into standards

A fundamental understanding of the interrelations between the built environment and occupants' needs is a first step towards occupant-centric building design and operation for health, well- being, and productivity of the occupants. These interrelations have been summarized and conceptualized to a framework (Figure 4-2) that is presented in Chapter 2 of the book that evolved from Annex 79 as a deliverable (Schweiker, Berger et al., 2023). Further work on multi-domain environmental exposure was motivated by the observation that the bulk of existing studies on the impact of indoor-environmental factors on building occupants are single-domain, that is they focus on one domain at a time (e.g., thermal, visual, auditory). Such observation was confirmed by the comprehensive reviews conducted during Subtask 1 work (Schweiker, Ampatzi et al., 2020) (Section 4.3.1). This circumstance is less than ideal, given the fact that occupants are regularly exposed to a combination of multiple indoor-environmental variables, whose cross-domain effects are insufficiently understood. In relation to building interfaces, a systematic review (Day, McIlvennie et al., 2020) defined human-building interfaces and explored interface characteristics, and current design challenges (Section 4.3.2). This investigation also explored building interfaces and occupants' behaviours resulting. Also, with respect to interface-related research it was found that these relationships are complex and more research is needed to understand design, use, and interface characteristics. In addition, the review on the role of building occupants in the energy performance gap concluded that, whereas such a role is discernible in a number of cases, the review of the pertinent studies in this area does not provide a clear and conclusive attribution of the energy performance gap to occupants' behaviour (Mahdavi, Berger et al., 2021).

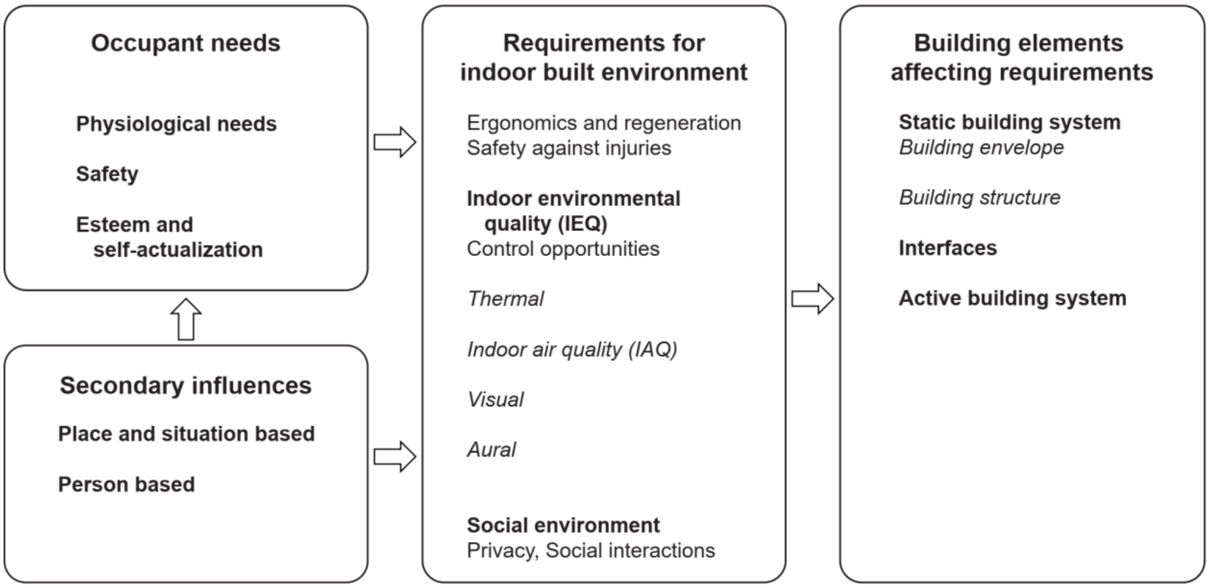


Figure 4-2: Main elements of the framework reflecting the design flow from human needs to building elements affecting requirements (figure provided by Marcel Schweiker based on (Schweiker, Berger et al., 2023))

In addition to the observed gaps, these reviews also revealed multiple challenges and deficiencies in related studies, including various methodological shortcomings (such as lack of standardized protocols and adequate strategies for data collection) and frequent absence of foundational theories. Hence, the participants of Subtask 1 got involved in several activities to set new quality standards and guidance for methods used in the fields of multi-domain and interface research (Section 4.4). One of the results was a terminology derived for conducting multi-domain investigations, including the quality criteria to prepare and conduct studies and analyse their outcomes (Chinazzo, Andersen et al., 2022). Moreover, common features were identified for experimental facilities and living laboratories that would warrant standardised test procedures for reproducible experimental investigations (including large-scale round robin tests) in different contexts, thus encouraging cumulative generation of common knowledge (Pisello, Pigliautile et al., 2021, Cureau, Pigliautile et al., 2022). Finally a framework for occupant behaviour documentation was developed, that gives researchers guidance regarding elements of the documentation facilitating researchers and practitioners understanding scope, performance, and applicability of the presented model (Vellei, Azar et al., 2022).

Addressing some of the identified gaps, new field and laboratory studies have been conducted as collaborative activities of this Subtask (Section 4.5). As identified with before mentioned reviews, multiple domains beyond the four indoor environmental domains exist. Hence, one activity looked at the influence of pro-environmental values on thermal expectations in energy-saving buildings. A As a result, more positive IEQ expectations were associated with less anticipated need to use personal appliances (fan or heater) and less anticipated need to make personal adjustments (e.g., wear warmer or lighter clothes) but not with perceived need to interact with building systems (e.g., adjust the thermostat or open a window) in a hypothetical building/workspace. A-priori information provided to future building occupants who care about sustainable building features appears to have a positive influence on indoor environmental quality-related expectations. Hence such information offers the potential for further energy saving. Due to this study having been an online experiment, actual behaviours and energy savings could not be measured.

A second activity further explored the classic hue-heat-hypothesis within the context of laboratory studies. This activity is in the core of multi-domain topics and consists of a laboratory approach. As such, this activity it is methodologically and content-wise setting a contrast to previous activity described, which was at the edge of multi-domain topics and taking a field study approach. Based on a unique collaboration between nine participant laboratories from around the world, the same experimental protocol was applied. Initial results contrasted with previous studies and did not show significant cross-modal influence.

Building interfaces continued to be an important aspect of Subtask 1 participants, who contributed to Ch. 9 (*Building Interfaces: Design and Considerations for Simulation*) of the Annex 79 book, completed in Subtask 3 (Day, Agee et al., 2023). In this chapter, human-building interfaces and interactions were defined in the context of user experience and human-building interaction theories, as well as applied interface characteristics and use patterns. They represent some of the current challenges of incorporating interfaces into simulation. While case studies were provided, more work is needed in this area. Lastly, another activity highlighted the importance of understanding interface needs and behavioural requirements for older adults in assisted living facilities (Ruiz, Day et al., 2022, Ruiz and Day, 2022, Ruiz and Day, 2022). This research revealed that some well-intentioned building features or design choices (e.g., lighting controls, windows, and thermostats) were hindering older adults' ability to use their spaces as desired, which ultimately impacted aspects of comfort, mobility, safety, physical and cognitive wellbeing, and/or preferences. While some important progress was made in this area of human-building interfaces, one of the key outcomes was the realization that much more work needs to be done in this area, and additional Annex participants are needed to help fill in some of the gaps in human-building interactions, technology, and behaviours – an important topic for the next Annex.

Despite systemizing existing knowledge, setting a foundation for future standards and generating new knowledge, it is evident to transfer scientific knowledge into standards and as such to practice. Therefore, Subtask 1 also identified the necessary conditions for the development of a new generation of multi-domain IEQ standards and reflected on the evidentiary basis of existing IEQ standards (Section 0). With respect to the new generation of IEQ standard, findings suggest that transparency and plausibility of the deployed point allocation and weighting approaches would need to be enhanced alongside conveying deeper empirically-based understanding once more research becomes available (Mahdavi, Berger et al., 2020). This point is evident as current IEQ standards have been found to lack transparency and consistency in the chain of evidence from scientific findings to the content of these standards (Berger, Mahdavi et al., 2022, Berger, Mahdavi et al., 2023, Mahdavi, Cappelletti et al., 2023).

4.3. State-of-the-art assessments

4.3.1. Multi-aspect comfort and behaviour models

Existing models of human comfort, perception, and behaviour are commonly formulated for single-domain environmental exposure circumstances (e.g., thermal, visual, or aural). At the same time, studies combining two or more domains exist; they have been summarized in a first step of this Subtask in a set of comprehensive review papers related to existing theoretical and experimental work relevant to multi-domain comfort models.

4.3.1.1. Theories of perception and behaviour

Research in the social sciences suggests that different psychological factors may drive human behaviour and interactions with the surrounding environment. Bringing that perspective into buildings, occupant behaviour and interactions with building systems can be motivated by different psychological factors, resulting in how different systems (e.g., lighting, heating/cooling, shading, etc.) may operate and impact the overall building energy consumption. A first review summarized work related to theories from psychology and economics looking at human-building interaction (Heydarian, McIlvennie et al., 2020). The five most applied psychological theories identified were the Theory of Reasoned Action, Theory of Planned Behaviour, Norm Activation Model, Value-Belief-Norm Theory, and Theory of Interpersonal Behaviour. Sociological and economic theories are considered less often as a basis in this area of research. A strong need to base future studies on existing theories as well as further developments in theorizing are required to bring the field of perception and behaviour forward within interdisciplinary projects.

4.3.1.2. Multi-domain comfort and behaviour

A second review summarized existing research related to human comfort perception and behaviour dealing with interactions between single domain (e.g., thermal, visual, or aural) environmental exposure circumstances. As mentioned above, there was a need for a comprehensive and systematic overview of the state of the knowledge regarding multi-aspect exposure situations. An international literature review was performed for this purpose leading to an overview of the state-of-the-art (Schweiker, Ampatzi et al., 2020). Overall, 219 scientific papers were identified that dealt with two or more domains, which is still a tiny number compared to several thousand papers on individual domains. Most prominent combinations related to comfort were thermal and visual interactions followed by thermal and acoustic interactions. For studies dealing with occupant behaviour, window opening behaviour in relation to thermal conditions and air quality were most often researched. Further behaviours analysed individually but with lower number of articles considering multi-domain influences were thermal behaviours like clothing level adjustments and fan usage, light switch behaviour, and blind usage. Results show on the one hand the scarcity of findings in relation to the number of potential combinations, with several combinations having been investigated only once so far (Figure 4-3). On the other hand, even when several studies have dealt with the same combination, results not necessarily support each other. For example, the paper reported that higher illuminance has been shown in one study to decrease thermal sensation, while in two other studies, sensation increased with higher illuminance (Figure 4-3). Furthermore, knowledge gaps in this area have been identified, mainly related to methodological approaches. Most important findings suggest that “convenience” variables and samples are most frequently used and that studies often lack a theoretical foundation.

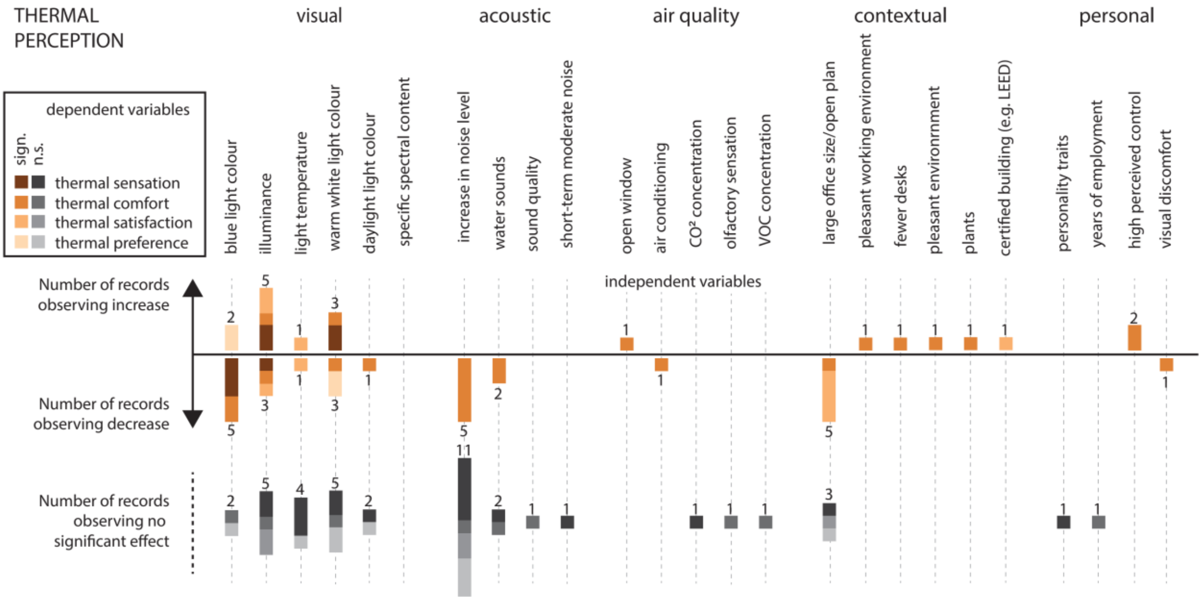


Figure 4-3: Overview of crossed main effects in studies with thermal perception as dependent and other domains as independent variable including significance tests (Schweiker, Ampatzi et al., 2020)

4.3.1.3. Multi-domain IEQ studies in residential buildings and work-from-home (WFH) settings

The COVID-19 pandemic forced workers to rapidly transition to working from home in large numbers and at a global scale. Ever since, more people have been working in a hybrid mode. This hybrid mode lends itself as a very interesting and eminent area of study with both theoretical and practical implications. Commercial buildings, particularly offices, are generally held to more stringent IEQ performance standards and upkeep as compared to residential buildings. Work-from-home (WFH) has emerged as an important environmental context, but it sits, quite literally, within the residential setting. This raises concerns related to workers' well-being and productivity while working from home, which formed the motivation for this activity.

The goal of this activity was to build a state-of-art review of studies focusing on investigating IEQ in WFH settings. The main objectives were to summarize which IEQ variables and non-IEQ impact variables are being measured; compare the methodologies used in assessing IEQ; identify important determinants of occupant productivity or health impacts; and identify gaps in the literature. A literature search for this review was conducted in two phases, starting from several thousands of abstracts related to research on different aspects of WFH domain and narrowed down to 41 records related to IEQ research in WFH settings finalized for inclusion (Manu, Burgholz et al., 2024).

The most important research contribution of this review was that it provided a hitherto undocumented knowledge of the status of current research, and the gaps therein, pertaining to IEQ conditions in WFH settings. Overall, the review highlighted a need for larger samples and in general more studies with high qualities as there were only limited number of studies available and, similar to observations in other reviews conducted within this ST, the quality and scientific rigour of those publications had a large variance. Based on the available findings, the review concluded that the IEQ conditions at home were mainly within recommendations of international standards, high satisfaction rates across all IEQ domains were obtained, while - especially related to air pollutants, high peaks above recommended thresholds were observed. This knowledge will, in turn, be useful for researchers to design studies that may provide a more exhaustive and conclusive view of this domain, particularly in terms of establishing the relationship between WFH IEQ conditions and workers' well-being and productivity, both perceived as well as measured. While building codes mandate requirements regarding materials, equipment, and design, private dwellings' IEQ during operation is not covered in codes. At the same time, to what extent actual conditions can be mandated within a WFH environment that is also considered as private space is a sensible topic requiring further discussion that was not touched within this Annex. Therefore, future work should consider whether and how recommended WFH IEQ conditions could be applied to standardization.

The long-term practical implications of this knowledge base may have a potential pathway through policy, such as codes and regulations pertaining to IEQ in buildings. At present, commercial spaces, offices in particular, are held to stringent IEQ performance standards. This requires that the IEQ conditions be maintained within a 'comfort' range, although this range varies across standards. Data from field studies often suggest that IEQ conditions in residential spaces may float beyond the comfort ranges established in standards and occupants in such spaces tend to be forgiving of minor discomfort, perhaps because there are more opportunities for adaptive measures. This review highlights the need to perform a systematic and systemic evaluation of WFH spaces with regard to regulations pertaining to occupational health. It also brings to fore the need for WFH-specific IEQ performance standards, also necessitating the development of standardized performance assessment frameworks for this context and driving the need and market for low-cost, high-quality IEQ monitors.

4.3.1.4. The role of building occupants in the energy performance gap

It is commonly known that buildings' predicted (calculated) energy use frequently deviates from actual post-construction or post-retrofit observations. This phenomenon is generally referred to as the energy performance gap. Many variables may be responsible for this discrepancy between projections and observations. Such variables include, for instance, buildings' as-designed versus as-built construction and equipment. Moreover, uncertainties in prediction of weather conditions can represent a major challenge in prediction of buildings' future energy consumption. However, recently the research community has paid increased attention to the role of building occupants in the energy performance gap phenomenon. It has been also suggested that more advanced models of occupant behaviour have the potential to significantly diminish the magnitude of the energy performance gap. This activity reviewed and evaluated the availability and quality of evidence for such assertions (Mahdavi, Berger et al., 2021). Thereby, a comprehensive literature search was performed, relevant scientific studies were identified, and content review was conducted. This systematic review involved the categorization of the literature items in terms of the nature and quality of the existing empirical evidence for the purported role of occupants in the energy performance gap. The review also documented the applied methods of computation and monitoring, the normalization procedures, and the reported circumstances and quantities of the energy performance gap. Figure 4-4 shows the energy performance gap is, on average, higher for residential buildings than non-residential buildings, likely owing to the greater control that occupants have in their homes and the associated adaptive. A key finding of the review suggests that there is insufficient evidence for the claim that occupants' role in the energy performance gap is the only significant or exclusive contributor to the building-related energy performance gap. Moreover, existing data does not provide a conclusive break-down of the magnitudes of various potential contributing factors to the energy performance (construction, systems, operation, weather, occupant behaviour).

The relevance of the activity to the practitioners may be summarized as follows: In the building design and construction process, practitioners often make projections about the future performance of the newly constructed or retrofitted building. Thereby, projections of energy use play a major part. The result of this activity suggests that practitioners must be very careful with the reliability of such predictions. As such, it may be appropriate to distinguish between calculations that are meant to specify the thermal quality of the building versus calculations that aim to predict future performance. The activity results imply that the latter is subject to multiple uncertainties. Hence, any such prediction should be accompanied by the explicit reference to multiple sources of uncertainty including weather conditions, construction quality, and occupant behaviour.

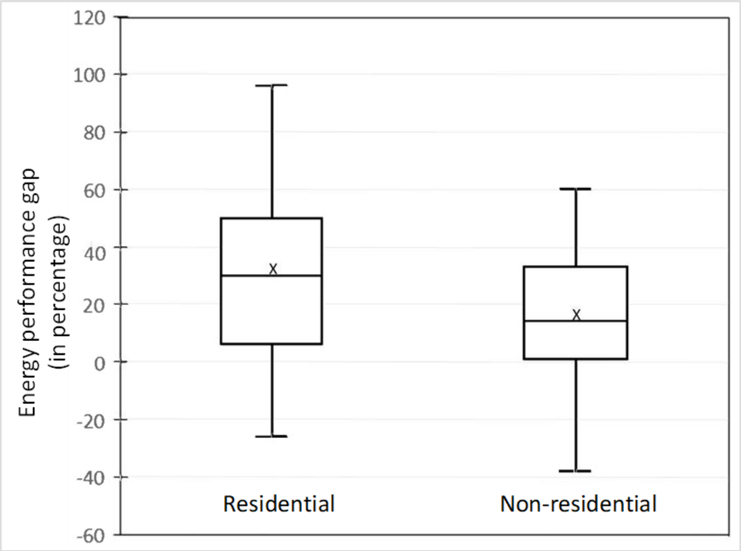


Figure 4-4: Boxplot of energy performance gap magnitude for residential and non-residential buildings (adapted from Mahdavi, Berger et al., 2021)

4.3.2. Building interfaces and human behaviour

4.3.2.1. Human interaction with building interfaces

To encourage user behaviour patterns that are desirable from the operational standpoint (i.e., patterns that can bring about desirable indoor environmental conditions while meeting the operational efficiency criteria), a better understanding of interfaces to control-relevant building features and systems (and corresponding occupant behaviours) is critical. There are many building interfaces that can have either a positive or negative impact on energy use or occupant comfort; however, many interfaces are poorly understood in terms of occupant behaviour and resulting energy impacts or comfort. In a systematic review, human-building interfaces have been explored and categorized (Day, McIlvennie et al., 2020). Main findings show the complexity of human-building interface interactions and the need for more research to understand design, use, and characteristics. Themes that were frequently highlighted in the literature included “thermal and visual comfort, ease and access of control, interface/control placement, poor interface/control design, lack of understanding, and social-behavioural dynamics”.

The findings of the review formed the base for further research in this field which is addressed in Section 4.5.2. More work was done on this topic in a cross-subtask activity between Subtask 1 and Subtask 4 which is described in Section 4.5.

4.4. Setting new quality standards and guidance for methods used in the field of multi-domain and interface research

Given the large and various gaps and limitations observed through the reviews introduced in the previous section, the need to summarize existing research standards and define and suggest ways forward in relation to applied methods emerged. These collaborative works led to some articles highly evaluated by the research community, that will give guidance to existing and future generations of researchers.

4.4.1. Ways forward for collecting information in multi-domain studies

Multi-domain studies of human-building interaction are key to understand occupant needs and requirements in an indoor environment for suitable building design and operation. However, performing this type of research is challenging in terms of data collection due to the number of variables involved. Moreover, findings are impacted by methodological approaches, and its diversity makes meta-analysis less effective. Therefore, a review of multi-domain studies of human-building interaction was done to analyse their methodological approach and data collection strategies: 933 records were screened, and 163 papers were deeply reviewed. For this purpose, a classification framework for data collection methods and tools was developed. For each paper, it was identified which were human-building interactions (e.g., window operation, heating, and cooling adjustment) and domains (indoor environment physical parameters, contextual and personal aspects) it addressed. Methods for each of these categories were classified on an objective and subjective approach. Each method was described considering technical aspects of data collection procedures, and characteristics of the tools used. Key findings of this activity are, firstly, that the most popular are objective methods, which are not able to fully explain complex processes of human-building interaction. Secondly, the lack of a framework of methodological approach in multi-domain studies was recognised. It manifested by difficulties in the reviewing process: incomplete methodological data in papers (tools specification, cost) and misunderstanding between reviewers (even under standardized parameters, different interpretations of variables/domains). The activity findings are important feedback for the scientific community about the state-of-the-art in data collection methods and tools, and gaps in current approaches. It also calls for establishing a data collection framework to improve research quality and enable the future synthesis of research work realized across the world.

From the findings it became obvious that a new approach is necessary to answer questions like: Do we understand building occupants and their needs sufficiently? How could interactions with the building systems be improved to help occupants reaching comfort? Since humans experience indoor environmental conditions (thermal aspects, light, sound, air quality) simultaneously, a multi-domain approach to building performance assessment is necessary to improve working and living spaces. The most common approach nowadays to follow occupant needs in buildings is automatic control of building services by many sensors. However, in many cases, this does not guarantee satisfactory performance. Therefore, continuous monitoring of occupants' perceptions and actions is needed to recognise human-building interaction principles and use them for better building design and operation. The way this type of data is collected and processed impacts what can be done with it and what improvements can be made for occupants. The findings of this activity and needed future work can help building professionals in the design and construction sectors to define strategies to monitor the indoor environment, occupants' actions and perceptions, to properly select equipment, as well as standardized protocols for surveys according to size and budget.

4.4.2. Quality criteria for multi-domain studies in the indoor environment

Going beyond summarizing the state-of-art as addressed above, another activity aimed to explicitly propose research guidelines and recommendations for multi-domain studies, i.e., investigations on the simultaneous presence of multiple environmental stimuli, namely visual, thermal, acoustic, and air quality, as well as including other personal and contextual factors. The goal of the activity was to propose sound research guidelines and recommendations for designing, deploying, and reporting multi-domain studies to address this challenge and foster more structured and coherent multi-domain studies. The activity stemmed from the need to provide a foundation for future investigations on the topic and allow future meta-analyses and comparisons across studies, which nowadays are difficult to be conducted given the heterogeneous and inconsistent methodological approaches and inconsistent study reporting of existing literature. Such differences and lack of information reporting were highlighted through accurate analysis and critical review of multi-domain studies' content during the activity's initial stage. From this work, it was possible to define the terminology related to multi-domain investigations and the quality criteria to guide the study set-up, study conduction and analysis, and study outcome (Chinazzo, Andersen et al., 2022).

By following the guidelines and recommendations detailed as quality criteria in the article, future multi-domain investigations can be designed, conducted, and documented in a systematic and transparent way. Thanks to future work in this area, it will be possible to consolidate the knowledge of multi-domain exposures for its integration into regulatory resources and guidelines currently dominated by single-domain knowledge.

The perception, physiology, behaviour, and performance of building occupants are influenced by multi-domain exposures: the simultaneous presence of multiple environmental stimuli, i.e., visual, thermal, acoustic, and air quality. To further improve the health and well-being of people in buildings, it is necessary to investigate in which way and to what extend multi-domain exposures influence building occupants. Many studies have been conducted in this area, but due to the aforementioned inconsistencies with regards to methods and reporting it is difficult to compare results across studies to untangle the complex relationships between multiple exposures and human responses. Standardizing methods and reporting formats for multi-domain studies will enhance the rigor in reviewing these studies and enable future meta-analyses. The final goal is to consolidate the knowledge on multi-domain exposures for its integration into regulatory resources and guidelines currently dominated by single-domain knowledge.

4.4.3. Test room-like experimental facilities

Many studies on multi-domain perception and behaviour have been conducted in test room-like facilities. The objectives, features and concepts vary largely, so that this activity aimed at reviewing characteristics of existing laboratory facilities for human comfort studies, i.e., the test rooms, defined as enclosed spaces, environmentally controlled and properly instrumented, in which human-centric comfort studies can be performed through actual occupants' presence and monitoring. In fact, laboratory experiments exposing recruited subjects to controlled environmental conditions could provide significant insights for the understanding of human comfort and environmental perception mechanisms. Nevertheless, implemented experimental procedures and test rooms characteristics could affect research outcomes that consequently are difficult to generalize and compare. The activity focused on the identification of test rooms' common features that would allow standardizing test procedures, reproducing the same experiments in different contexts, and sharing knowledge and test possibilities. Overall, 187 existing test rooms worldwide were identified, and 396 related papers were thoroughly reviewed in terms of performed experiments and related test room details (Pisello, Pigliautile et al., 2021). A growing interest in multi-domain studies was identified and this is leading also to a change in test rooms design, associated monitoring equipment and environmental control possibilities. Moreover, some lacks in comfort investigation are highlighted including underrepresented climate zones and occupants' categories (being generally focused on students performing office tasks.

The activity concerned the analysis of test room facilities for laboratory studies with a specific focus on multi-domain comfort models and human perception in those controlled environments. To this aim, the available information related to 187 test rooms for human comfort studies was reviewed with the main aim to guide scientists and professionals toward the improved design or the audit of the same laboratory facilities. These kinds of facilities are fundamental for better understanding human responses to controlled environmental stimuli and thus move forward on multi-domain comfort theories. To maximize the impact of experimental campaigns in test rooms, it is important to generalize and compare the outcomes, but such result could be achieved only by standardizing test procedures, reproducing the same experiments in different contexts, and sharing knowledge and test possibilities. Therefore, this review activity (Pisello, Pigliautile et al., 2021) put the basis for this process highlighting existing opportunities and guiding those institutions that are interest in the field on best test room design practices.

4.4.4. Living-labs

In addition to test room-like facilities, the number of so-called living labs is increasing. Therefore, another activity aimed at recognizing the potentials of living-lab facilities as an intermediate experimental set-up between test rooms and field studies that include controlling possibilities (typical for test rooms) and real-life environments (evaluated in field studies without direct control of the environment). Available information has been systematically reviewed for 34 living labs dedicated to host human comfort studies, detailing their systems and sensing characteristics (Cureau, Pigliautile et al., 2022). Through the assessment of comfort studies carried out within these facilities, it was found that they are usually longer than the experiments conducted in test rooms, so, in this way, living labs permit more extensive adaptive processes and, consequently, allow evaluating specific environmental parameters on long-term occupancy to understand the impacts of contextual factors on occupants' comfort. In addition, most of these studies aimed to compare or test different building systems or controls, which reveals that living labs are helpful for testing innovative system technologies and their user interfaces. However, further comfort studies in living labs are required to clarify the full spectrum these facilities facilitate, acquiring different knowledge compared to laboratory and field experiments and to demonstrate how living labs can enrich the current practices.

Living labs for human comfort studies were defined as a space to host experiments while monitoring and controlling the environmental conditions and/or the layout where occupants perform their everyday tasks over a significant period that allows characterizing their activities and responses. The reviewed living labs were detailed in terms of their building systems (cooling, heating, ventilation, and shading), control systems, and sensors' architecture, which is useful as a guideline for the construction of new experimental facilities that follow this approach. The main strength of living labs is the possibility of combining environmental control (typical for test rooms) with real-life spaces (normally investigated through field experiments that do not allow controlling). Hence, as living labs are closer to real environments than test rooms, they favour catching true human responses to environmental parameters and testing occupants' productivity. Considering the final purpose of getting closer to experiments and tests in realistic contexts, this review showed that living labs also provide good prospects for testing innovative building systems and controls that improve environmental comfort and energy efficiency in buildings considering the occupants' acceptance of the innovations. Overall, living labs increase the possibility of evaluating and improving human-centric building solutions by holistically capturing the influence of environmental quality on occupant perception, and facilitating the execution of multi-domain and interdisciplinary comfort experiments with larger and more diverse groups considering real-life settings. Therefore, the development of new living labs that carefully follow the design and sensing recommendations presented in this review provides good opportunities to enhance the current practices related to human comfort indoors.

4.4.5. Framework for occupant behaviour models documentation

A standard framework and/or guideline for occupant models' description, documentation, and communication is currently missing. This activity provided a documentation framework to guide researchers in the transparent communication of their occupant behaviour models that are developed for building performance simulation (BPS). An overview of the state-of-the-art of occupant behaviour model documentation was also provided by systematically reviewing to which degree existing academic papers on occupant models meet the framework. It was found that most of the papers provide occupant models without specifying their purpose and without providing any information about their implementation. The two aspects appear to be related and indicate that occupant models have been so far developed without any specific BPS application in mind. This further indicates the need for such a framework.

This activity provided a framework to document occupant behaviour models that are developed for building performance simulation (Vellei, Azar et al., 2022). The framework should help modellers, practitioners, and stakeholders to better comprehend the utility of OB models, as well as to select and adopt the most suitable model for their design application.

4.5. New field and laboratory studies

The reviews introduced in previous sections demonstrated large gaps in multi-domain research on human perception, human behaviour, and building interfaces. To close some of these gaps, the following activities were conducted.

4.5.1. New research on human comfort and behaviour with respect to multi-aspect environmental variables

Based on the reviews regarding state-of-art and the developed frameworks, new field and laboratory studies were conducted together with qualitative studies to close knowledge gaps identified. These are briefly described in the following sections.

4.5.1.1. Influence of pro-environmental values on thermal expectations in energy-saving buildings

Originally proposed as a lab study of priming of pro-environmental values and subsequent influence on thermal sensation, the aim of this research work was to understand the influence of potential occupants' individual differences (e.g., environmental values and personal norms) and emotions (specifically, hope) on their a priori expectations of indoor conditions/indoor environmental quality (IEQ) in sustainable buildings (Arpan, Rissetto et al., 2022). Prior research suggested that occupants have a priori expectations of building conditions that could influence their perceptions of indoor conditions once inside a building. Participants in this study were randomly assigned to view a depiction/description of either a sustainable or conventional building and were then asked questions about anticipated emotions related to working in the building, expectations of indoor environmental conditions (air quality and thermal conditions), expected comfort, and anticipated need to interact with building systems or make adjustments (adjust clothing; use personal heater or fans). Data indicated a priori expectations of indoor conditions and comfort were predicted by anticipated hope when research participants envisioned working in a sustainable (as opposed to a conventional) building. Findings from this study indicate a positive predisposition related to sustainable buildings, such that participants had more positive a priori expectations of IEQ in a sustainable building as compared to a conventional building. Those positive expectations should be associated with anticipated, and, possibly, actual need to take adaptive actions in a building to be comfortable. Findings also indicate an important influence of the emotion of hope on IEQ expectations.

Results from this study indicate that potential building occupants who are informed about sustainable building features and are asked to envision working in a sustainable building can have more positive a priori expectations of indoor environmental quality (IEQ) of the building. Therefore, it might be useful to address and attempt to influence occupants' expectations of building environmental conditions and operations. By influencing occupants' IEQ expectations ‘driven by provided information’, building simulation and design could account for potential tolerance of a wider range of indoor thermal and visual conditions among occupants, which could, in turn, inform the design and operation of building mechanical systems for human-centred adaptation. This may have implications both in the reduction of energy consumption and the increase of occupant satisfaction with the indoor conditions in sustainable buildings. However, more research is necessary before the extent of such wider ranges can be quantified.

4.5.1.2. Round robin large scale experiment to challenge the hue-heat-hypothesis

The Round Robin Test is an inter-laboratory experiment performed independently in a variety of contexts, applied usually to check the effect of such contextual variables in the analysis of potentially different results. In the case of this research activity, the same methodology of multi-domain comfort experimental triggers and perception analysis was replicated in different test rooms designed for human comfort studies. These facilities presented unavoidably differences in terms of dimensions and envelope properties, installed systems (e.g., conditioning, lighting etc.), environmental monitoring setup and environmental control setup capacity/efficiency. Considering the mentioned construction disparities, added up to the laboratory locations and possible differences in cultural backgrounds of the recruited sample, this activity intended to investigate the impact of these different arrangements to the experimental results, also evaluating the possibility of comparing the outcomes. The experimental procedure chosen to be applied to the nine laboratories involved (Italy, Germany, Hungary, USA, Canada, and Brazil) is the hue-heat-hypothesis (HHH). It consists of the analysis of the influence of the coloured light on people's thermal response. Despite the HHH was already tested by different authors, there is still not a widespread agreement in the scientific community about potentials of this hypothesis in keeping high occupants' comfort level while minimizing energy expenditures, especially due to heating/cooling systems' operation. The first stage of the experimental procedures was performed during June to September 2022 (Pigliautile, Jacoby Cureau et al., 2023).

The main contribution provided for the scientific community was the test rooms network created between the working groups that allowed them to share not only the same experimental protocol, but also a unique database summarizing the collected data through the Open Science Framework (OSF) platform (https://osf.io/wvkzb/). Furthermore, outcomes of the research will enhance current knowledge on multi-domain and cross-modal perception analysis within the framework of human comfort studies with variable contextual backgrounds.

Within the Round Robin Test for test rooms activity, the results obtained from different institutions were analysed based on contextual variables (e.g., location, gender, experimental settings), using environmental, physiological and subjective judgment information to compare the outcomes. The first results, using the data collected by four of the nine participant laboratories during the summer campaign (June-September 2022), did not show significant cross-modal influence. Further potential results from more experiments can inform the efforts to reduce the energy use (and consequently carbon footprint) of buildings, due to the change of human thermal perception caused by the alteration of coloured light.

4.5.2. New research on building interfaces

Day, McIlvennie et al. (2020) encouraged the planning of new research studies to explore the identified gaps of knowledge. This should include experimental studies in laboratories, field study campaigns, studies based on both surveys and qualitative methods (i.e., photographs, interviews, etc.), as well as virtual experiments via agent-based modelling approaches. This is expected to result in an enhanced knowledge base regarding the acceptance and usability of interfaces and their effect on human comfort and behaviour.

4.5.2.1. Occupants’ willingness to share information

Human perception and occupant behaviour are driven by a multitude of factors, including demographics, preferences, etc. The amount of information/data has increased manifold in recent times, including very personal data. Benefits may arise in getting access to such information/data for research and operation/control through new types of building interfaces for purposes as demonstrated in several tasks and projects within this Annex. However, with the amount and type of data collecting, a question arises, which formed the basis of a survey on occupants’ willingness to share information: which personal information are occupants willing to share and under which conditions? A stated-preference experiment was developed which was implemented in a wider survey on people's preferences and attitudes towards sharing information. At the time of writing this report, this work is ongoing and not yet published.

4.5.2.2. Generational building resilience: learning about buildings and interface use

The goal of this pilot project was to meet with older adults from around the world to learn from their generational knowledge and their stories surrounding their experiences with and in the built environment. This pilot study implemented qualitative and narrative methods to interview and observe older adults in buildings (homes and senior/assisted living facilities) to better understand how the passing of time has changed their relationship with and their interactions within the built environment. The research team collected (and is still collecting) qualitative data about well-being, health, socialization, building interfaces, lifestyles across lifetimes, adaptive comfort strategies etc. Data were gathered from the Pacific Northwest in the United States, and additional data will be gathered in Canada, Denmark, and Australia. The pilot study is completed, and different aspects of the preliminary results were presented at four conferences (e.g., Ruiz and Day, 2023).

While this was a relatively small-scale study, there were many meaningful stories told about building safety, personal wellbeing, mental health, and many of the participants had valuable recommendations they felt would improve their experience staying in senior living communities. While the data that resulted from this study is highly saturated with important takeaways regarding the way that seniors interact with their built environment, it also tells the stories that capture their personhood and lived experiences within their living spaces.

The results of this activity suggest that designers need to better consider how older adults use their buildings, and the special needs they may have as they move to assisted living facilities or age in place. The qualitative approach, while quite time consuming, allowed the researchers to gather very rich data about older adults’ needs, wants, and frustrations with current building practices. Several areas for improvement were found, many of which relate to energy use, such as better and more legible and usable building interfaces (e.g., thermostats). For instance, many occupants were often uncomfortable simply because the numbers were too small, or there was not enough contrast on the screen for them to see and interact with their thermostats. Issues like these present equity and health issues and are a seemingly easy fix with some awareness.

Additionally, occupant training may be important for this demographic, as older adults often reported not knowing when or how to make adaptive measures to manage their comfort in their new homes or buildings. A key finding relates to health and safety of older adults, and the need for clear planning and integrated resiliency as many climates face unplanned power outages and rolling blackouts. There is much more to do in terms of learning more about how to better design and build for the aging population, especially in the areas of health, comfort, and energy (Ruiz, Day et al., 2022, Ruiz and Day, 2022, Ruiz and Day, 2022, Ruiz and Day, 2023).

This project was highlighted and published as a part of a collection of online case studies on the United Nations (UN) Decade Platform's progress report hub.

4.5.2.3. Educational studies: influence of availability of IAQ information on user behaviour

This activity aimed to investigate the influence of the availability of IAQ information on user behaviour. More specifically, the influence of displaying the CO_2 concentration on a meter display on the resulting user behaviour and indoor air quality in residential dwellings was examined. A study was performed in student's dwelling in Denmark and Switzerland. The CO_2 concentration, temperature and relative humidity were measured with and without access to the visual display. Equivalent ventilation rates were calculated from the monitored data. Results indicate that visual displays are a simple and effective tool to improve the IAQ in many students' dwellings.

The work aimed to investigate whether having access to simple indicators characterizing the indoor air quality in a house could help occupants improving the air quality. In class the students were presented with recommended CO2 levels according to some standards (ASHRAE, local national standards) They were instructed only to take steps to improve IAQ, no specific target was specifically called for. Then, the indoor air quality was monitored for two weeks; no energy consumption was measured. During the first week, the visual display of the meter was hidden, and students carried out activities as usual. During the second week, the students had access to the readings on the display. Many students were able to take simple actions like opening of windows, opening of passive vents, adjustment to mechanical airflow rates, the addition of plants, or use of recirculation for improving their indoor air quality, using the visual display as a guidance for helping to know how much fresh air was needed. After the two weeks, students were asked by means of a questionnaire to assess the effectiveness of their actions. They noted: purge natural ventilation less than 5mn once a day (slightly-fairly effective), purge natural ventilation less than 5mn three times a day (fairly-very effective), keeping bedroom window open (very effective) keeping bedroom door open more than 5cm (fairly-very effective), opening windows in other rooms than bedroom (fairly-very effective), adding plants (ineffective), using exhaust fan more often (effective). This research shows that in many instances, simple tools such as a low-cost CO_2 meters can help building occupants to improve their indoor air quality. In some cases, especially when occupants had limited possibilities for ventilating either naturally or mechanically, the meter couldn't help much. This highlights the importance of providing adequate possibilities for ventilating effectively without hindering comfort and energy consumption too much.

4.6. Transfer to IEQ standards

During the working phase of the Annex activities, it became apparent that it will not be sufficient to increase the number of research on multi-domain aspects, but a transfer to IEQ standards is required as well. Therefore, two activities reviewed existing standards according to the way they incorporate multi-domain aspects and then developed recommendations for future work in this context.

4.6.1. Necessary conditions for a new generation of multi-domain IEQ standards

The starting point of this activity was the explicit formulation of the realization that sustainable architecture should create indoor environments that are responsive to the needs and requirements of the occupants. In this context, it is expected that professionals in charge of building design and operation demonstrate that their buildings meet the requirements formulated in indoor environmental quality (IEQ) codes and standards. Thereby, a challenge lies in the fact that most common IEQ codes, standards, and guidelines can be suggested to be of a single-domain character. In other words, these documents typically deal with IEQ agenda in terms of separate domains (i.e., thermal, visual, acoustic, air quality). This activity explored the state-of-the-art in multi-domain approaches to IEQ evaluation and highlighted the necessary conditions for their future development and application instances (Mahdavi, Berger et al., 2020). To achieve the objectives of the activity, a sample of common building rating schemes were analysed in detail. The findings of the activity suggest the need for a) basic enhancements of the existing rating schemes in terms of their transparency and the plausibility of the deployed point allocation and weighting approaches, and b) a deeper empirically based understanding of the fundamental nature of occupants' patterns of perception of and behaviour in buildings.

The relevance of the activity to the practitioners may be summarized as follows: The results of this activity suggest that, whereas there is an emerging realization in the professional community regarding the significance of a multi-domain approach for indoor environmental design, respective standards are yet not available. Certain existing rating systems, such as LEED and DGNB, provide schemes to concurrently address multiple quality criteria. However, these systems typically rely on point-based evaluation of such criteria, without deeper exploration of the underlying physiological and psychological mechanisms.

4.6.2. Exploring IEQ standards' evidentiary basis

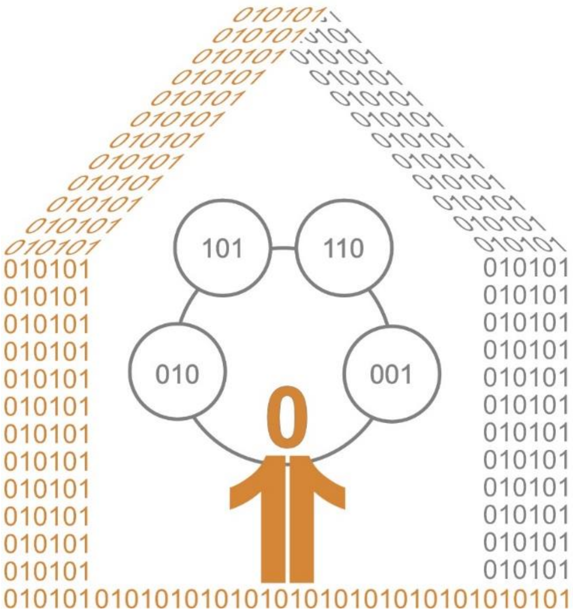
This activity investigated indoor environmental quality (IEQ) standards in view of the strength of their embedded reasoning and evidentiary basis. Accordingly, the activity targeted a critical examination of a number of frequently applied standards in the IEQ domain, particularly in view of the technical evidence they entail. Thereby, five IEQ domains were taken into consideration, namely 1. Thermal, 2. Visual, 3. Auditory, 4. Air Quality, and 5. User Controls. A large number of standards in these domains were reviewed in detail to investigate if and to which extent the requirements and mandates that they entail are supported by either direct or indirect references to pertinent scientific literature. The findings thus far have identified several issues regarding the transparency and consistency of the chain of evidence from scientific findings to explicit IEQ mandates in standards. Furthermore, recommendations have been formulated toward developing future standards and guidelines that would be more transparent in disclosing their underlying evidentiary basis (Berger, Mahdavi et al., 2022, Berger, Mahdavi et al., 2023, Mahdavi, Cappelletti et al., 2023).

The relevance of the activity to the practitioners may be summarized as follows: We expect from buildings to provide indoor environmental conditions that meet the health and comfort needs of their occupants. These conditions are multifaceted and include diverse dimensions pertaining to thermal, visual, auditory, olfactory, and air quality requirements. IEQ codes, standards, and guidelines are generally expected to inform stakeholders and professionals in the building design and operation regarding the procedural and contractual aspects of the building delivery process. Recognizing this critical and practically relevant role of standards, the activity focused on the scrutiny of their applicability and scientific validity. As such, the activity focused on the standard-based definition of indoor environmental quality. This is believed to add to the credibility and usefulness of indoor environmental quality standards for practitioners in the building design and operation domain.

4.7. Conclusions and future outlook

Subtask 1 of the IEA EBC Annex 79 was engaged in assessment of the state of art as well as knowledge generation and dissemination with regard to multi-aspect environmental exposure, building interfaces, and human behaviour. The starting key premise of this subtask was the belief that energy issues in the built environment (performance, efficiency) cannot be satisfactorily addressed and treated at a purely technical level. Specifically, the contributors to this subtask were in general agreement that conclusive solutions in this area require the in-depth consideration of the role of human being as relevant professionals in general and building occupants in particular. To this end, participants in the Subtask engaged in a host of interrelated activities (and corresponding deliverables) in terms of numerous meetings, workshops, reports, and publications. The findings of the subtask clearly confirm the starting premises. Occupants' expectations with regard to the indoor-environmental conditions do influence their interactions with buildings and their systems, and such interactions influence, in turn, the energy performance of the built environment. The research results generated in the course of subtask activities also revealed a number of gaps in the state of knowledge in occupant-related energy-specific topics. Specifically, the perceived gaps in the theoretical foundations of i) human behaviour in buildings, ii) buildings' user interfaces, iii) ontologies for representation of occupants in computational applications were confirmed via state-of-the-art reviews and resulted in development and publications of related high-level theories. Likewise, common views on the role of occupants in buildings' energy performance gap was critically reviewed, resulting in a more differentiated understanding of the contributing factors.

The outcome of the subtask activities represents a comprehensive reflection of the state-of-the-art. However, it can be suggested that the activities also provide a proper and useful foundation for continued research and education in this essential area. The quest for a deeper understanding of the impact of multi-domain exposure situations on buildings' occupants is long from over: ongoing and future efforts in this area will hopefully provide additional insights. Likewise, integration of versatile occupant representations in computational applications (Building Information Modelling, Building Performance Simulation) requires further undertakings. Development, integration, and promotion of intuitive and effective user interfaces for buildings and their systems is yet another area in need of further research and development. But perhaps the most high-level insight gained in the course of collaborative work in subtask 1 was the realization that substantial and qualitatively consequential progress in this area requires a) a truly interdisciplinary attitude involving representatives of physical and human sciences, and b) a concerted effort to more actively involve professionals (among others engineers, architects, building operation specialists, social workers, occupational health experts) as well as representatives of the society in future research and development endeavours.



5. Data-driven occupant-centric modelling and digital tools

5.1. Introduction

In the last few decades, researchers have investigated different aspects of the impact of people on building performance by simulation. However, most of the developed models do not adequately capture the varied interactions that people have with the building's various systems and devices. Therefore, numerous approaches have been employed to simulate the occupants' presence and actions (OPA) within buildings, tailored to specific research goals and considering available computational power and technical solutions. The primary aim has consistently been to gain insights into how individuals utilize spaces and how their actions influence a building's energy performance.

Notably, occupant behaviour (OB) represents a major source of uncertainty in building energy modelling, particularly in highly efficient buildings, where oversimplified OPA descriptions can lead to substantial discrepancies between simulated and actual energy consumption (Ahn, Kim et al., 2017, O'Brien, Gaetani et al., 2017, Gaetani, Hoes et al., 2018). These challenges have prompted the adoption of diverse approaches to comprehend and predict OPA accurately, thus enhancing building energy simulation tools and optimizing building management systems to reduce energy consumption. Consequently, the research community in building science has shown an increasing interest in OPA modelling in recent years (Zhang, Bai et al., 2018). This topic also formed Subtask 2 of EBC Annex 79 which had a specific focus on advancing methodologies and tools for data-driven modelling and occupant behaviour in buildings (i) by deploying "big data" for the building sector based on various sources of building and occupant data as well as fostering the penetration of newer sensing technologies, (ii) by developing and sharing methods and guidelines for integrating occupant models in building design and operation, and (iii) by developing digital tools and platforms for enabling occupant behaviour research. For the purposes of Subtask 2, data-driven OPA modelling can be defined as "an approach to modelling that prioritizes the use of computational intelligence, particularly machine learning (ML) methods, in building models, complementing or replacing 'knowledge-driven' models that describe physical behaviour" (Solomatine and Ostfeld, 2008).

The objectives of Subtask 2 have been pursued by carrying out three main activities consisting of (i) developing a novel occupant data collection approach for occupant data, (ii) investigating different methods for occupant behaviour, and (iii) promoting the creation of a research community interested in sharing occupant data and data-driven methods.

5.2. Current trends in modelling occupant behaviour in buildings

To examine actual trends in modelling occupant behaviour in buildings, we conducted a comprehensive and meticulously designed literature review on various methods and techniques employed for occupant presence and actions (OPA) modelling within buildings. To ensure a comprehensive analysis and minimize the risk of overlooking crucial contributions in the field, we adopted a systematic approach to exploring the scientific literature. We further utilized bibliometric analysis tools to extract patterns, information, and insights from the extensive database of identified documents. Our investigation classified existing OPA studies into three modelling categories: rule-based models, stochastic OPA models, and data-driven methods. The first category includes time-dependent users' profiles, as exemplified in the Standard 90.1 (ANSI/ASHRAE/IES, 2022). The second category considers occupant behaviour as stochastic, acknowledging its variability between individuals and over time (Yan, O'Brien et al., 2015). It results from complex relationships among contextual factors, adaptive triggers, and non-adaptive triggers (Schweiker, Carlucci et al., 2018). The third category revolves around data-driven methods, where black-box models are derived from input and output data (Formentin, Van Heusden et al., 2014) without a primary aim of explicitly understanding OPA, sometimes incorporating limited domain engineering knowledge (Solomatine and Ostfeld, 2008). (Carlucci, De Simone et al., 2020) aimed to describe the features of methods used for OPA modelling in buildings rather than reporting their mathematical formulation that can be found in statistical and machine learning handbooks. The review aimed to systematically cover all aspects of OPA modelling in different typologies of buildings.

For our analysis, an extensive database of relevant research documents was systematically assembled[1], and the scientific production and landscape were described using data-driven bibliometric analysis techniques. From the initial screening, we identified over 750 studies, and after careful selection, 278

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[1] accessible at this link https://osf.io/gnvp2/?view_only=00b08233881f471795d1d8dee79e9828

publications were included in the analysis. The research field has undergone significant development through long-term collaborative efforts since the late 1970s, with a primary focus on diverse building typologies mainly concentrated in a few specific climate zones. The bibliometric analysis indicated North America, Europe, and China as the most productive geographic regions, exhibiting robust and well-established collaborations among research groups. Notably, the analyzed documents primarily revolved around measurement data collected from office buildings situated in temperate and continental climates. Consequently, there is a crucial need to extend research beyond these established domains, aiming to broaden the coverage of knowledge, particularly in regions where modelling approaches are lacking and where a substantial increase in population and construction is expected (e.g., Africa, the Indo-China region, Latin America).

In recent years, data-driven models have gained prominence and become the most widely utilized modelling approach, possibly due to the abundance of sensor-generated data and the availability of thorough statistical and machine learning software environments and programming languages like Python, MATLAB, R, and SPSS. A noteworthy trend is a growing interest of the scientific community in adopting deep learning to model various aspects of OPAs, serving both explanatory and predictive purposes. While most research on OPA detection focuses on understanding occupant behaviour, a significant portion of studies look at predicting occupants' interactions with specific building devices for the development of adaptive controls. Currently, there is an emerging emphasis on investigating multi-domain occupant behavioural models, aiming to provide a more comprehensive and realistic depiction of how occupants utilize a building and its technical systems, a subject extensively discussed in Subtask 1 of Annex 79.

The three model categories - rule-based models, stochastic OPA modelling, and data-driven methods - aim to model occupancy-related target functions and a set of occupants' actions, such as window usage, solar shading, electric lighting, thermostat adjustment, clothing adjustment, and appliance use. Notably, explanatory modelling typically follows a model-based paradigm, where occupant behaviour is assumed to be stochastic. In contrast, the data-driven paradigm finds widespread applications in the predictive modelling of OPA, particularly concerning control systems. Despite the significance of standard evaluation protocols, this aspect remains a scientifically essential but often overlooked research question.

In light of maximizing the potential of current and future datasets, we propose the establishment of a common data collection vocabulary or ontology, promoting data reuse and facilitating meta-analysis across different building types, sample sizes, and countries of origin. It is important to acknowledge that limitations in this study may have resulted in the unintentional exclusion of documents not identified during the literature search and, thus, remained unknown to the authors. Nonetheless, the adoption of the PRISMA methodology mitigates such oversights to the best extent possible.

5.3. State-of-the-art and advances in collecting and sharing data for OB modelling

In this section, the current trends and future outlooks in modelling occupant behaviour in buildings are drafted and serve as the basis for identifying areas and applications that require more transparent and structured model documentation to promote a fairer adoption of OB models and increase the transferability of occupant-centric models across different climate zones, building usages, and applications.

5.3.1. Occupant-centric data curation, organization, and storage

The inputs relating to occupants significantly impact the accuracy of energy simulations at both the building and urban levels. Datasets from various sources have been used to model occupant behaviour in buildings, such as energy management systems (EMS) data, Internet of Things (IoT), surveys, and census data (Dabirian, Panchabikesan et al., 2022). Other sources of data that can be used for occupancy modelling at the urban level include Global Positioning System (GPS) data, Call Detail Records (CDR) data, social media apps, city image-based data, and Location-Based Services (LBS) (Dong, Markovic et al., 2021). In some cases, a fusion of more than one heterogeneous data source may be utilized to provide occupant-centric data.

In order to prepare occupant-related data for simulation purposes in the city context, Salim, Dong et al. (2020) defined occupant-centric archetypes. Such archetypes provide a simplified structure for occupant-related data since it does not need to use very detailed data. However, considering the resolution of occupant-related data, it is highly correlated to the purpose of simulation. For example, simple occupancy models (deterministic schedules) are sufficient to estimate the building's energy demand on an annual or sub-annual basis. However, for building control purposes, hourly and sub-hourly data are required for building control purposes to provide a more accurate result.

After data collection and organization in a standardized data structure, the raw data are used to develop the occupancy models. Providing occupant-related data in a standardized data model creates the opportunity to apply different methods to prepare the occupancy data as inputs into the energy simulation tools. The occupant-related models include deterministic rule-based, statistical/ stochastic, and data-driven models (Dong, Markovic et al., 2022). For each approach mentioned above, the data preprocessing has to be specified. Preprocessing generally includes data cleaning, filling in missing data, dimension reduction, data scaling, feature creation, and data partitioning. After data preprocessing, the processed data can then be stored in the standardized data model. The methods used for different parts of the preprocessing depend on the data type and modelling purposes. Selecting the modelling approaches also depends on the data type and its nature.

5.3.2. Representing occupant-related input at the building and urban scale

Building energy simulations, particularly at the city scale, utilize a wide variety of data sources with varying sizes and formats, and their flexibility and interoperability are complex. Thus, to organize various data sources, a standardized data structure is essential. The Brick schema is an open-source, community-driven effort to develop a unified, extensible data model for representing and integrating building-related data. It provides a semantic framework to describe the various aspects of a building's structure, systems, and operations. Luo, Fierro et al. (2022) proposed an extension to the Brick schema, which was implemented to consider the contextual, demographic, and behavioural details of occupants, along with their relevant data. This extension incorporates occupant information such as occupancy, attributes, and attitudes, as well as captures occupants' adaptive behaviours such as thermostat adjustments and window openings. Building on top of previous occupant ontology and schemas, this extension introduces substantial semantic representations within the Brick schema (Balaji, Bhattacharya et al., 2016) through an open-source code at GitHub[2]. Such extension could be used for occupant-centric building design and operation by exchanging occupant behaviour information with data sources. The proposed extension includes four key additions to the schema: (i) Introducing a new "Occupant" class to capture information regarding occupants' demographics and energy-related behavioural patterns, (ii) Creating new subclasses under the Equipment class to specifically represent envelope systems and personal thermal comfort devices, (iii) Establishing new subclasses under the Point class to effectively represent occupant sensing and status, and (iv) Introducing new auxiliary properties for occupant-interactable equipment to denote the degree of control that occupants have over each individual equipment.

The applicability of the brick schema was tested using the ASHRAE Global Occupant Database. The results demonstrated a significant improvement in the coverage of occupant information compared to other parameters, thereby validating the proposed schema's effectiveness. The proposed schema has some limitations and challenges, mainly regarding the links between the actual occupancy data and the extended Brick schema.

For incorporating occupant-related data models into urban models, the Energy Application Domain Extension (ADE) is used. The Energy Application Domain Extension (ADE) expands upon the CityGML standard (open data model and XML-based format for the representation, storage, and exchange of 3D urban models) by incorporating energy-related features necessary for simulating the energy consumption of either an individual building or an entire city (Agugiaro, Benner et al., 2018). A variety of energy simulation platforms use the Energy ADE to provide input parameters (Figure 5-1), including occupant-related information (Remmen, Lauster et al., 2018). In Dabirian, Panchabikesan et al. (2022) , an occupancy data model was proposed that could provide inputs related to occupants to urban building energy modelling (UBEM) models. However, integrating the occupant-related data models into the simulation tools is still challenging.

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[2] https://github.com/BrickSchema

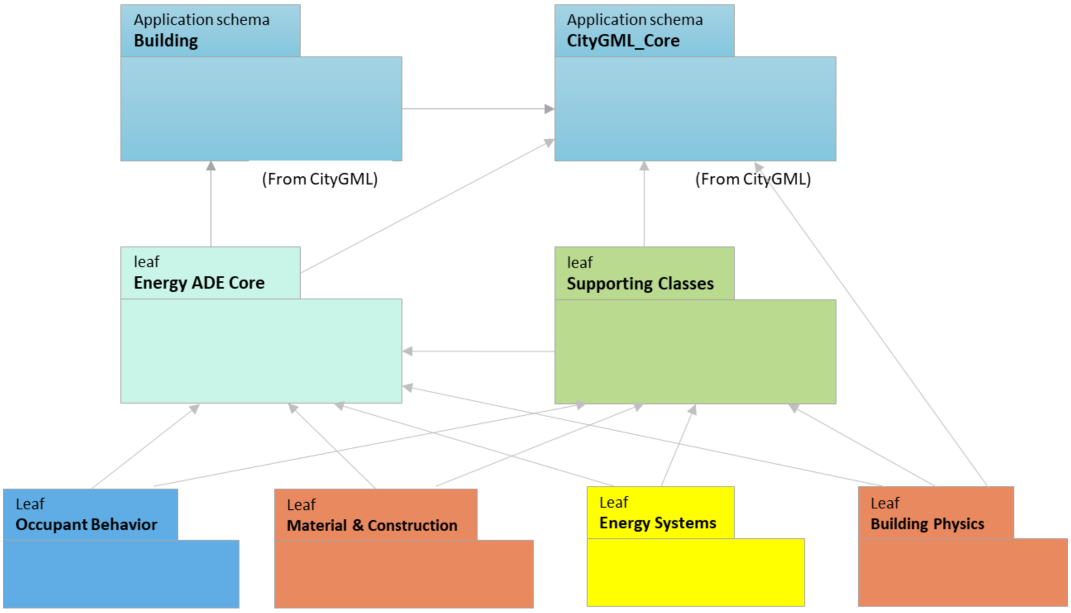

Figure 5-1: The modular structure of the Energy ADE UML diagram (Benner, 2018)

In 2022, the extension was integrated into the official Brick schema and may undergo further refinements to align with other Brick features currently in development. These refinements aim to enhance compliance with the FAIR (Findable, Accessible, Interoperable, and Reusable) data principles and ensure improved consistency.

5.3.3. Privacy hazards in sharing occupant data

The development of affordable IoT sensors has made it possible to monitor several aspects of human life. These sensors are, among others, being used by Cyber-Physical Systems (CPS) as input for the control of systems. One class of such CPS is used for controlling smart buildings. The sensor infrastructure is used to optimize both the energy efficiency and the comfort of the occupants of these buildings. Recent work in the smart building domain uses the collected data to develop and deploy data-driven applications for further optimizations. The owners of the smart building may be interested in sharing some of the collected sensor data with external contractors operating in the building or as open data in order for them to train data-driven applications for optimizing their operations. The data-sharing process is regulated by a number of privacy laws and regulations, including the European Union's General Data Protection Regulation (GDPR). To identify the potential privacy implications of sharing the data, an organization should perform a privacy risk analysis identifying the risks for both the monitored occupants and the organization. However, the task of identifying all the related privacy implications is particularly challenging due to advancements enabling many inference and correlation possibilities. Based on the results of the privacy risk analysis, the organization must apply appropriate privacy protection to the data before it can be shared. In Schwee (2022) and Schwee, Sangogboye et al. (2020) , several aspects of the data-sharing process are explored. The work presents a study identifying problem areas in how State-of-the-Practice methods are used to protect smart building datasets. They found that the methods could not properly protect the explored dataset. Furthermore, the authors have contributed to the open data pool by publishing a smart building dataset and creating an ontology, improving the ability to model privacy-related risks and attacks against datasets. Likewise, they present a solution to lower the amount of effort needed to identify privacy-related risks for a specific dataset by designing and evaluating semi-automatic tools. The tools use knowledge from state-of-the-art methods to identify both the inference and correlation possibilities. It accounts for the type of data and the spatiotemporal granularity for the identification of the risks. Furthermore, they have designed and evaluated a privacy protection method, which can be applied to data at zone-level granularity with a limited number of each sensor. This work thereby contributes to tooling that reduces the amount of information needed to perform privacy risk analyses, enabling more datasets to be adequately protected and safely shared.

5.3.4. Open data about occupants

Recent studies have shown that occupants' presence and actions can significantly impact energy consumption and thermal comfort in buildings. Nonetheless, it is worth noting that, up to this point, the role of building occupants has not received adequate consideration. The uncertainty surrounding occupants' presence and activities may lead to significant disparities between actual energy consumption and simulated energy usage. The majority of building energy simulation tools tend to prioritize physical design factors, such as building materials, construction, technical systems, and external weather conditions, rather than examining the interactions between occupants and building systems and equipment. Furthermore, many methodologies employed in building operations and modelling tend to rely on fixed operation schedules governed by specific rules, such as the ASHRAE standard 90.1. Unfortunately, this approach often results in unnecessary energy waste and discomfort for occupants. Consequently, there is a pressing need for an increased influx of data pertaining to human presence and behavioural patterns to effectively manage contemporary built environments. With access to such data, it becomes possible to create digital twin representations of buildings, which can then serve as the foundation for innovative data-driven approaches to building operations. For instance, knowledge about human presence can be harnessed to provide real-time insights into space utilization, while predictive analytics can leverage information concerning both occupants' presence and their behaviours to optimize the operation of the building.

The concept of open data is still new, with relatively sparse definitions capturing their essence and purpose. Earlier work identified that open data is characterized by freely available data with limited restrictions with respect to the reuse, republishing, and redistribution of data. Janssen, Charalabidis et al. (2012) define open data as "non-privacy-restricted and non-confidential data which is produced with public money and is made available without any restrictions on its usage or distribution." Recently, the concept of open data has been increasingly expanding from its numerous and concerted outsets, mainly from governmental initiatives, and it is now receiving increasing attention in many fields in the scientific community. Gray (2014) presents a genealogical perspective on the advances in open data. This work provides a reflection of how open data has been utilized as a tool for shaping various governmental and scientific discourses and for ensuring transparency and openness in empirical studies. More specifically, Sangogboye (2018) underscores the significance of leveraging open data to facilitate the development of data-driven models within the cyber-physical domain, particularly within the realm of building performance research, with a focus on occupant behaviours and activities.

Access to open data regarding occupant presence and behaviour holds the potential to enhance researchers' comprehension of the intricate interplay between occupants and buildings across diverse contexts. This holds substantial importance for the optimization of building energy utilization and the creation of enhanced indoor environments. A crucial aspect to consider when acquiring and utilizing data related to occupant presence and behaviour revolves around the potential privacy implications and the necessity for safeguarding privacy. Compared to various other categories of building data, safeguarding the privacy of occupant presence and behaviour data stands out as a particularly critical concern. Given that open data sourced from the public domain can play a pivotal role in advancing building performance research, especially in the context of occupant behaviour studies, it becomes imperative to cultivate a deeper understanding of the advantages and challenges associated with the utilization of open data. This understanding can be immensely beneficial for researchers and scholars engaged in such pursuits. It is necessary to reach a consensus about accepted methodologies and technical solutions to enable the research communities to apply and utilize open data highlights the methodology and technical solutions for the successful application of open data (Figure 5-2).

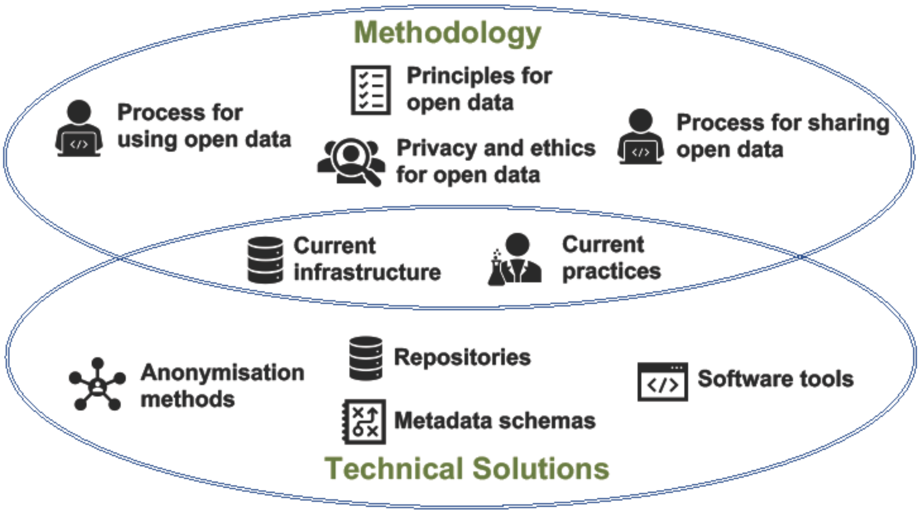

Figure 5-2: Venn diagram of OB methodological components and technical solutions

Regarding methodology, the community needs to develop procedures for the exchange and utilization of open data, establish guiding principles governing open data, and formulate guidelines to address the specific ethical and privacy concerns associated with open data. On a technical front, the community should create platforms or repositories dedicated to sharing data, devise algorithms capable of anonymizing data, define metadata schemas to impart meaning to shared data, and design software tools that can monitor data transformations, simplifying the process of sharing and using open data. A central technical challenge revolves around ensuring interoperability, ensuring that individual systems can effectively communicate and exchange information in a coherent and meaningful manner. The intersection of methodology and technical solutions encompasses the existing practices and infrastructures that underpin the community's efforts in this domain.

Kjærgaard, Ardakanian et al. (2020) reviewed the current procedures and infrastructure associated with open data-driven research in the context of designing and operating occupant-centric buildings. This review encompasses an examination of related open data efforts, the presentation of survey findings regarding existing scientific practices, an analysis of the accessibility and utilization of open data and its accompanying infrastructure, and an exploration of the considerations related to data privacy and ethical concerns. The review reveals several challenges when it comes to sharing and utilizing open datasets, including (i) limited awareness of available datasets, (ii) insufficient detailed documentation for existing datasets, (iii) concerns regarding the time-consuming nature of providing open data, and (iv) apprehensions about restricting the release of data. Moreover, the review suggests that there are existing solutions to address some of these challenges, such as employing data anonymization methods to address privacy issues and adhering to data-sharing principles like FAIR. However, these solutions are not widely adopted within the realm of occupant behaviour research.

Furthermore, the work underscores the need to adopt a comprehensive perspective on open data, recognizing it as more than just a set of technical solutions. It may involve:

1. Separating data collection from data usage for research due to the complexity of open data processes.
2. Managing a blend of open and non-open data from a data user's perspective necessitating specialized data portals.
3. Developing policies and guidelines to protect data providers.
4. Defining specific purposes for utilizing open data to ensure project success.

This multifaceted approach involves addressing various factors, including human, technical, and policy-related aspects, shaping an open data ecosystem that encompasses data owners/providers, data consumers, repositories, application platforms (for tasks like discovery, analysis, and visualization), and governing policies and guidelines. It appears that researchers within the building science community possess the requisite skills for conducting research using open data. However, the lack of organized and readily accessible open data may have constrained their full adoption of the concept, thereby impeding progress in building science research. Despite the presence of numerous technical platforms and software tools to aid researchers in generating, managing, and employing open data, there remain specific challenges that necessitate collective community action. These include the proper provision of metadata for occupant data, addressing ethics and privacy considerations in utilizing building occupancy data and promoting familiarity with best practices for data sharing, such as adherence to the FAIR principles. Lastly, it is essential to encourage extensive discussions on open data and the dissemination of best practices among stakeholders to boost awareness and utilization of open data within the building science community.

5.4. Advances in data-driven occupant behaviour modelling

5.4.1. Towards transparent and transferable occupant-centric models

Recently, occupant behaviour models have been created to incorporate individuals into building control systems. However, in scientific research, crucial goals include ensuring that results can be reproduced and replicated. Unfortunately, not all necessary information is readily available in published documents. Consequently, this endeavor aimed to establish a comprehensive and standardized guideline for documenting occupant behaviour models.

To achieve this, an extensive review of the literature was undertaken to identify existing occupant behaviour models within the realm of building control. The processes associated with modelling occupant behaviour were scrutinized to extract best practices and identify gaps in the documentation for various phases, including defining the problem, data collection and preprocessing, model development, model evaluation, and model implementation.

The literature review illuminated a notable lack of uniformity in the current state-of-the-art documentation of these models. This lack of standardization poses specific challenges when applying and replicating models in real-world field studies. In addition to proposing standardized model documentation practices which resulted in a separate deliverable of the Annex, this initiative also devised a model evaluation framework that facilitates the comparison of different models in field applications. This framework was established as an internet platform and is one of the digital deliverables of the Annex. Furthermore, recommendations were formulated regarding the integration of occupant behaviour models with building automation and control systems.

Based on the review and analysis of current documentation of the OB model for advanced building controls, it can be concluded that (i) there is no standard representation of various OB models; (ii) there are no unified guidelines for the OB model development; (iii) a standardized evaluation schema is needed for each distinct form of OB models; (iv) a set of indirect metrics for evaluating the impact of OB models for the inclusion in thermal systems' control is needed; (v) systematic documentation of indented model implementation is needed; and (vi) OB models should be integrated into model-based predictive control (MPC) for heating, ventilation and air conditioning (HVAC) systems as predicted setpoints, constraints, or disturbances according to the different application needs.

This activity also provided the following future research opportunities: (i) a formal representation of OB models based on the same schema and semantics. While there is an ongoing effort in the Brick schema (Balaji, Bhattacharya et al., 2016), such a presentation can be further enriched with more common data sets (Fierro, Koh et al., 2020); (ii) open-sourcing a library with OB model documentation that follows this guideline; (iii) deployment of existing OB models in building control studies.

Due to the availability of data, this investigation was limited to adults using office environments and did not cover other occupant types, such as older people, who have different interactions in response to thermal stimuli. Also, our examination revealed a limited number of research papers addressing the integration of sensor drift into control systems. Despite its critical relevance in the context of control implementation, our current endeavor primarily concentrated on the documentation of occupant behaviour. Subsequent research endeavors could delve deeper into this subject matter, encompassing occupant behaviour influenced by personalized cooling and heating systems.

5.4.2. Approaches for inferring occupant-related patterns

Estimation of occupant count in commercial and institutional buildings enables energy experts to make better decisions on which buildings to prioritize for green upgrading and retrofitting from a large building portfolio. A cheap, easy-to-install solution could help to obtain occupancy estimation by easily scaling to large building portfolios. In Egemose, Hobson et al. (2022) , a method for estimating occupancy based on sparse coverage of low-cost IoT sensors is presented. We tested the method on two datasets: one academic building in Denmark (DK) and one academic building in Canada (CAN). The datasets contain passive infrared sensors (PIR), CO_2 measurements, and electric energy data, together with ground truth occupancy counts. It was shown that 20% sensor coverage is comparable to full sensor coverage (60%) with a normalized root mean squared error (NRMSE) of 0.142 (Denmark) and 0.174 (Canada) for 20% sensor coverage and an NRMSE of 0.129 (Denmark) and 0.163 (Canada) for full sensor coverage. Results show that with less sensor coverage, sensor placement becomes more important and that even with 20%, it is possible to get as good of accuracy as full coverage. This activity also showed to which extent occupant counts can be used to calculate occupancy-based key performance indicators of the building's energy usage, which shows higher energy use per occupant at low occupancy.

Schedules for occupancy and plug loads could be derived from the Wi-Fi connections (Chong, Augenbroe et al., 2021). Indeed, Hou, Pawlak et al. (2020) proposed a novel framework for modelling the interaction between building occupants and urban energy systems. In order to determine the number of occupants in a specific building, the real-time data extracted from Location-Based Services (LBS), such as Google Maps and Facebook, could be used based on a typical 24-hour profile for each day of the week (Happle, Fonseca et al., 2020). Another source of real-time positioning and orientation information for occupants is novel image-based technology. In order to detect human poses that are not uniformly distributed within buildings, digital image processing and three-dimensional reconstruction were developed (Wang, Wang et al., 2021).

Furthermore, in this activity, occupancy patterns in university office buildings were profiled by using data collected with a sensor fusion-based experimental apparatus consisting of sensors for the measurement of occupant actions, environmental variables, and electric power (Mora, Fajilla et al., 2019). The aim of the investigation was to evaluate the effectiveness of the monitored parameters in reproducing occupancy patterns with diverse temporal granularity and identify the most proper variables for the accurate profiling of occupancy. The research activity, more specifically, explored two heuristic approaches (clustering and rules-based flowcharts) of unusual applications in the building sector. Clustering techniques were employed to analyze continuous variables, specifically CO2 levels and power consumption, with the aim of delineating daily occupancy patterns. This analysis entailed comparing the clusters derived from actual occupancy data with those generated from sensor data, considering both full-day patterns and distinct time slots (morning, lunchtime, and afternoon). The application of cluster analysis revealed the capacity of continuous internal variables to accurately replicate daily occupancy patterns, marking a noteworthy advancement within this particular field. Furthermore, models employing logical flowcharts incorporating conditional stages were developed, incorporating all the most significant parameters to construct occupancy profiles at one-minute intervals. The development of these flowcharts affirmed the benefits of sensor fusion and the effectiveness of combining sensor data in recreating occupancy profiles with one-minute granularity. Both approaches exhibit considerable promise, as they exhibit comparable accuracy to established methods found in the existing literature. In summary, the combination of these methodologies allowed for the acquisition of occupancy information at various temporal resolutions, spanning from weekly and daily down to hourly and minute-by-minute levels. This diverse temporal granularity proves valuable in catering to distinct requirements: the use of larger temporal scales is essential for energy balance predictions, while real-time building occupancy data facilitates intelligent control of building energy systems.

Another research activity (Fajilla, Austin et al., 2021) was conducted to investigate the potentialities of straightforward probabilistic models, such as the Law of Total Probability (LTP), the Naïve Bayesian model (NB), the Classification and Regression Tree (CART), in estimating occupancy state in office buildings by using indoor environmental parameters (air temperature and relative humidity, CO_2, volatile organic compound) and user action-related variables (electricity power, window, door state, and air conditioning use). The main objectives were to evaluate the effectiveness of these three models in estimating the occupancy state using indoor measurements and analyze how the number and typology of occupancy predictors affect the performance of the models. Thirty-four combinations of parameters were considered to assess the influence of the number and the typology of parameters (environmental and human-activity related) on the models' performance. In general, the CART model outperformed NB and the LTP model. On the other hand, NB and LTP were more suitable to provide a true positive rate (TPR) than a true negative rate (TNR). Reducing the number of variables from eight to the four most correlated ones determined using Pearson's correlation coefficients, an accuracy decrease of less than 1% was observed for LTP and NB, while the accuracy of CART remained unchanged. Regarding the parameters' typology, the models performed better using only the four human-activity parameters instead of adopting the environmental variables. By analyzing the results of these three models, it can be inferred that they are promising despite their simplicity of formulation and understanding. This research activity provided more insights into the performance of simple probabilistic models and highlighted that the knowledge of the parameters' correlation with the occupancy state could provide the same satisfactory results using fewer parameters, reducing data processing and models' complexity.

In a further activity, Carlucci, Causone et al. (2021) conducted an investigation into how the uncertainty associated with occupant behaviour can impede the reliability of building performance simulations. This uncertainty linked to occupant behaviour was introduced into the annual electric energy consumption assessment of a standard office building. This was accomplished by implementing stochastic models designed to simulate Occupant Presence and Actions (OPAs). To comprehensively explore the impact of this uncertainty, a global sensitivity analysis was meticulously planned and executed. This analysis involved the examination of inputs and energy outputs across 144 permutations generated from 15 distinct stochastic models for OPAs, totaling 7200 simulations. The outcome of this exercise was a notable increase in building energy consumption when stochastic OPA modelling was considered, compared to the reference value derived from scheduled occupancy and rule-based occupant actions, as per established standards. In fact, the median electric energy usage was found to be 58.6% higher than the base case electric energy consumption. Furthermore, it was determined that the stochastic models employed to replicate window operation had the most pronounced effect on energy output, followed by models simulating light switch-off and occupancy. Conversely, models for light switch-on exhibited a comparatively lower influence on the overall building's energy performance. To evaluate the interrelationships among the stochastic models for OPA, the Generalized Estimating Equations method was adopted. This analysis underscored the significant impact of altering the stochastic model used for window operation, occupancy estimation, and light switch-off behaviour on the building's energy performance. In contrast, the available stochastic models for light switch-on and blind operation demonstrated similar performance and had a limited impact on the building's overall energy performance.

5.4.3. Occupant-centric predictions

Prediction of occupancy and relevant environmental parameters can enable a range of applications in the building sector. In this activity, predictive models were used to improve comfort and energy efficiency. In Shahin, Das et al. (2023) , a probabilistic machine learning (ML) method was proposed to predict the indoor temperature of an office environment. An Input-Output Hidden Markov Model (IOHMM)-based framework has been devised for the representation of the office environment across various scenarios of space heating sources. A comprehensive analysis was conducted on one year's worth of time series data, with the aim of comprehending the intricate dynamics governing indoor thermal conditions. The model's construction thoughtfully accounts for the uncertainties stemming from the mutable aspects of indoor temperature and its interrelation with outdoor temperature fluctuations. To equip the model with the requisite parameters, well-established techniques such as the Baum-Welch and forward-backward algorithms were adapted and employed. Subsequently, the Viterbi algorithm was harnessed to anticipate the optimal sequence of hidden states, thereby enabling the prediction of the most probable future temperature values. The practical application of the model is illustrated through a numerical example, outlining the procedural steps involved in model development and showcasing the outcomes of training and testing. To gauge the model's effectiveness, a leave-one-out cross-validation approach was implemented, providing compelling evidence that the model achieved a prediction accuracy rate of approximately 78%. That represents the input to a preference algorithm matching the user's preferences with the predicted thermal conditions of the indoor environment and suggests desirable seating options to the user.

Moreover, the investigation presented by De Simone, Callea et al. (2022) considered the evaluation of domestic hot water (DHW) energy demand and consumption patterns using a survey conducted in residential buildings in Southern Italy. Descriptive statistics were performed to characterize DHW production by climatic zone, and inferential statistics were conducted to discover significant contextual and personal variables and identify user groups. Contextual variables, such as climate, system design, and occupants, and personal factors, such as behaviour, income, employment, and education, were identified as important influencing factors. Cluster analysis identified four groups of dwellings considering the daily DHW usage hours. Successively, analysis of variance (ANOVA) models were applied to analyze the variables' distribution and significance among the clusters. The following useful indications were deduced: no significant correlations were found between clusters and contextual factors such as climate and system design. On the other hand, considering occupants' variables, the average age of families and the number of family members were significant variables. Concerning personal variables, the presence in the family of at least one student, graduated member, and employed components were statistically different among clusters. Also, behaviour and occupancy were significant. In particular, the number of weekly baths and/or showers, DHW usage hours, and occupancy hours in the kitchen and bathroom differed significantly between the four clusters. The results of this activity contributed to filling the investigation on DHW profiles in the Mediterranean area and provided a systematic approach to expand the limited knowledge about the influencing factors on DHW production and usage in this geographic and social contest. Moreover, daily usage profiles and clusters could be applied in simulation tools to improve DHW demand prediction and support the dimensioning of production systems that include solar panels.

Liguori, Yang et al. (2021) implemented a Recurrent Neural Network (RNN)-based autoencoder with Long Short-Term Memory (LSTM) units in order to reconstruct missing OB-related data time series from a commercial building in Aachen. Before further development, the time series were rearranged into a matrix of sub-sequences in order to be used as input data for the models. In particular, since the analyzed variables had clear recurrent daily patterns, these were grouped into day-to-day matrices. Here, indoor air temperature (T), relative humidity (RH), and CO_2 concentration data were artificially corrupted by replacing sub-daily sequences of random length with zeros. Additionally, the same models were evaluated for forecasting faulty real-time data by simulating the missing values at the end of each input sequence. The optimal model architecture varied with respect to the target variable. However, in general, every model had at least one encoder and one decoder layer with recurrent connections and LSTM units. The results for the reconstruction and forecasting cases are presented in Table 5-1. Here, the root mean squared error (RMSE) and normalized RMSE (NRMSE) are the metrics used to evaluate the models. It could be observed that the RNN-based autoencoders could reconstruct the corresponding variables with average RMSEs of 0.56 °C, 2.20 %, and 95.69 ppm, respectively. Additionally, the models could forecast the same variables with average RMSEs of 0.48 °C, 2.23 %, and 76.48 ppm, respectively.

The generalization capabilities of the same models to alternative buildings were further evaluated for the indoor air temperature data and presented in a successive study by Liguori, Markovic et al. (2021) . The results proved that the domain adaptation could be conducted effectively by adapting the model on a few data samples from the target domain. For the same purpose, a data-augmentation technique for energy data time series was proposed by Liguori, Markovic et al. (2023) . The authors created multiple synthetic copies of the same training dataset with repeated masking noise. It was observed that data augmentation could be effectively performed on a nine-day-long dataset. In particular, the RMSE was reduced by 37% and 48%, respectively, for continuous and random missing scenarios. Furthermore, the presented technique did not require additional computational costs due to hyperparameter tuning.

Table 5-1: Performance of the RNN-based autoencoder neural network with LSTM units for reconstructing and forecasting sub-daily indoor OB data with different masking noise (CR) (Liguori, Markovic et al., 2021)

	Reconstruction			**Forecasting**			
	CR [-]	**T [°C]**	**RH [%]**	**CO_2 [ppm]**	**T [°C]**	**RH [%]**	**CO_2 [ppm]**
RMSE	0.10	0.33	1.05	64.88	0.17	0.89	25.34
	0.20	0.47	1.47	82.51	0.29	1.37	39.33
	0.30	0.53	1.78	89.00	0.40	1.76	56.11
	0.40	0.59	2.11	101.64	0.46	2.18	74.21
	0.50	0.62	2.33	107.85	0.52	2.41	82.11
	0.60	0.64	2.54	110.28	0.59	2.67	104.51

	0.70	0.63	2.72	106.16	0.66	2.81	107.79
	0.80	0.61	2.80	102.18	0.63	2.84	102.02
	0.90	0.60	3.00	96.75	0.60	3.18	96.88
	Avg	0.56	2.20	95.69	0.48	2.23	76.48
NRMSE [-]	0.10	0.22	0.06	0.56	0.11	0.05	0.22
	0.20	0.31	0.08	0.72	0.19	0.08	0.34
	0.30	0.35	0.10	0.78	0.27	0.10	0.49
	0.40	0.39	0.12	0.88	0.31	0.12	0.65
	0.50	0.41	0.13	0.94	0.35	0.14	0.71
	0.60	0.42	0.14	0.96	0.40	0.15	0.91
	0.70	0.42	0.15	0.92	0.44	0.16	0.94
	0.80	0.41	0.16	0.89	0.42	0.16	0.89
	0.90	0.40	0.17	0.84	0.40	0.18	0.84
	Avg	0.37	0.12	0.83	0.32	0.13	0.67

Finally, Liguori, Yang et al. (2021) studied the impact of spatial resolution on the forecasting performance of data-driven HVAC energy consumption models. In particular, the aforementioned data-driven method was an RNN model with feed-forward layers. Here, the optimal model configuration consisted of one RNN layer with 128 hidden units, three feed-forward layers with 64 hidden units, and an output layer. No performance improvements were recorded by using a 0.5 dropout in every layer. In particular, the optimal RNN model architecture was data set-agnostic, meaning that it was the same in the case of data sets collected in different buildings, namely Seattle and Aachen. The final model was evaluated on both the whole datasets and varied space discretization, such as room and floor-wise scenarios. The final evaluation for all the studied cases can be observed in

Table 5-2. Here, the mean absolute error (MAE), RMSE, NRMSE, and coefficient of determination (R^2) were used to evaluate the model. In order to assess the robustness of the model, different cases are presented. It could be concluded that the chosen spatial granularity directly impacted the predictive model's performance. In particular, the forecasting performance could be significantly reduced in the office case compared to the floor-wise or building-wise spatial granularity.

Table 5-2: Performance evaluation of the RNN model for the energy consumption prediction with different target variables, seasons, buildings, and spatial granularities (Liguori, Yang et al., 2021)

Case	Target variable	Season	Spatial granularity	MAE [MJ]	RMSE [MJ]	NRMSE [-]	R^2 [-]
Seattle	Electricity consumption	tot	Building	37.71	45.55	0.05	0.97
Aachen	HVAC load	Summer	Building	4.56	5.79	0.07	0.92
		Winter	Building	2.94	3.87	0.06	0.88
		Summer	Floor 1	1.17	1.56	0.10	0.85
			Floor 2	2.03	2.69	0.07	0.88
			Floor 3	2.46	3.14	0.07	0.89
		Winter	Floor 1	1.04	1.31	0.09	0.69
			Floor 2	1.37	1.85	0.08	0.81
			Floor 3	1.81	2.22	0.07	0.85
		Summer	Room [max]	0.57	0.80	0.23	0.44
			Room [mean]	0.21	0.33	0.21	0.45
			Room [min]	0.05	0.11	0.14	-2.62
		Winter	Room [max]	0.72	0.96	0.27	0.16
			Room [mean]	0.15	0.26	0.19	-0.14
			Room [min]	0.02	0.04	0.06	-0.53

5.4.4. Integrating occupant behaviour models into building control

Occupant-centric control (OCC) strategies necessitate the integration of occupant behaviour models into building control. With that, OCC can provide comfortable indoor environments and reduced energy consumption by focusing on the time-variant needs of occupants (current and future) while minimizing energy consumption. OCC is commonly used for HVAC control, lighting, shading, or appliance control. Real-time building measurement data and future predictions are integrated as signals into building control systems to consider the time-variant needs and behaviours of occupants. For example, these signals can contain information about current and future occupants' attendance, temperature preference, or window operations behaviour. As a result, OCC can optimally coordinate control decisions, such as heating, cooling, shading, or lighting, based on the actual needs of occupants (O'Brien, Wagner et al., 2020).

The quality of OCC depends on the OB model. To evaluate the OB model performance, we considered three different types of metrics: absolute, domain, and indirect/control metrics. Absolute metrics are used for general statistical or data-driven modelling. They describe how accurately or often the OB model provides correct predictions, for example, by evaluating the mean average error (MAE). Domain metrics are defined explicitly in the context of human behaviour or buildings' physics. They assess how well a model represents a particular aspect of human behaviour, for example, average occupancy duration. Indirect/control metrics are even more specifically designed to characterize the impact of the modeled OB on the building control objective, for example, the resulting impact on energy consumption and thermal or visual comfort (Dong, Markovic et al., 2022). Overall, the first two metrics help to give a general overview of the model performance, while the indirect/control metrics show the actual benefits in the productive building operation.

A literature screening about indirect/control metrics indicated that most OCCs focus on maintaining comfort constraints while minimizing energy consumption. When applying OCC, energy use can be reduced by about 20 to 50% without violating the actual needs of occupants (Naylor, Gillott et al., 2018). Despite this high potential to save energy, more evidence of the documented indirect/control metrics for OB models must be provided. That could result from the rare application of OB models in building control (Dong, Markovic et al., 2022). Because of the identified gaps between OB model development and building control, we present a model-evaluation schema that enables benchmarking indirect/control metrics of different OB models (Figure 5-3). The model-evaluation schema uses Model-based Predictive Control (MPC). As a predictive controller, MPC explicitly considers future predictions of occupants' needs and behaviour. OB predictions in MPC yields significantly higher performance than when included in a standard real-time controller (e.g., PI-controller) (Frahm, Zwickel et al., 2022). Real-time controllers can only consider present signals, for example, present setpoints. In contrast, MPC can also consider future signals (e.g., future setpoints or heat flows) and their impact on future system dynamics. A detailed overview of how to include OB models in MPC can fill the gap between OB model development and building control and enable a more performant OCC.

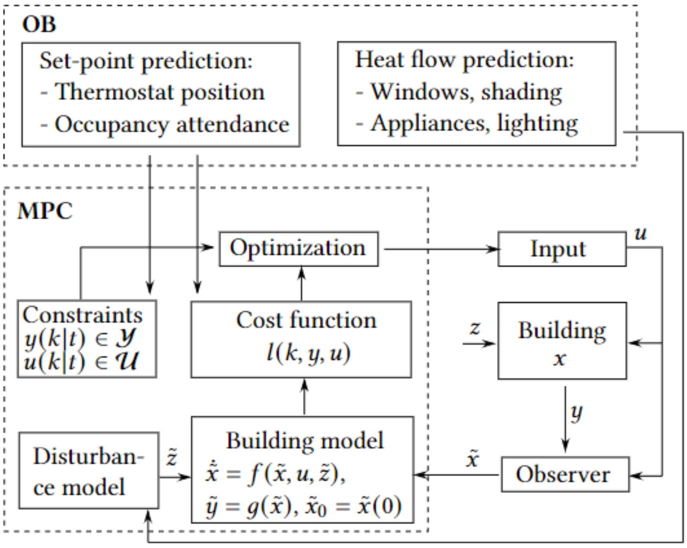

Figure 5-3: Integration of occupant behaviour models into MPC Model-evaluation schema

Integrating OB models into MPC can be used to evaluate indirect/control metrics and enable highly performant OCC. As illustrated in Figure 5-3, OB models can be integrated into MPC for (1) setpoint/reference scheduling, (2) shaping constraints, or (3) including measurable and predictable disturbances.

1. Setpoint/reference scheduling: defining an optimization objective as a cost function, for example, meeting a desired setpoint during occupied periods (thermostat position, occupancy hours).
2. Shaping constraints: setting upper and lower boundaries, for example, the range of permitted temperatures during occupancy hours.
3. Including measurable and predictable disturbances: OB is considered a cause of thermal gains from people or appliances and losses during windows or shading operations (number of occupants, time of use, and used equipment).

The performance of OCC also depends on the length of the forecast horizon and the data quality. OB models should forecast occupancy behaviour over the length of the prediction horizon (typically between 1 and 24 hours). Shorter forecast horizons reduce the predictive control quality. For valid OB models, measurement sensors should be sufficiently precise for the specific OB type. For example, occupancy-dedicated sensors (PIR or cameras) deliver the most accurate predictions. However, CO_2 and plug power can also provide sufficient quality for control-oriented occupancy models (Jorissen, Boydens et al., 2017).

Moreover, Favero, Møller et al. (2022) conducted a study where comfortable set-point modulations that considered explicit occupant feedback were designed to increase comfort, potentially reduce energy consumption, and significantly support the clean energy transition. This study presented an initial investigation aimed at predicting the thermal preferences of individuals exposed to a dynamic thermal environment. The study utilized data collected from a controlled laboratory experiment in which participants were subjected to precisely managed thermal changes within an environment resembling an office setting (Favero, Sartori et al., 2021). To handle group-level variations when predicting thermal preference ratings, two distinct methods were devised: one tailored to specific clusters of occupants and another designed to represent the average preferences of the entire population. The results indicate that both of these approaches represent valid strategies for modelling thermal preference ratings and prove effective in supporting occupant-centric building design and building operation strategies. Furthermore, the population-averaged approach is well-suited for the initial phases of occupant-centric building design, where the focus is on the preferences of the "average" occupant. Conversely, the cluster-specific method is better equipped to cater to the unique preferences of individual occupants and is more suitable for implementation during the operational phase of the building.

5.4.5. Robust occupant-centric models concerning the pandemic and climate change

The recent COVID-19 pandemic but also climate change events showed clearly that robust occupant-centric models are crucial for designing sustainable and healthy buildings. The pandemic has changed the way that people use buildings, with an increased focus on health and safety measures such as social distancing, mask-wearing, and hand hygiene. This has led to changes in occupancy patterns and behaviour, with people spending more time indoors and using different areas of buildings in different ways. As a result, occupant behaviour models need to be able to account for these changes and adjust their predictions accordingly. Similarly, climate change can also impact occupant behaviour and building performance (Fajilla, De Simone et al., 2020). Events such as extreme weather scenarios, including heatwaves, bushfires, floods, and storms, have the potential to affect the well-being and safety of occupants, leading to changes in their behaviour, such as increased use of air conditioning or crowding in buildings. In addition, climate change can affect the availability and cost of energy, which can impact occupant behaviour around energy use and conservation.

Robust, and at the same time flexible occupant-centric models are needed to account for these types of changes and uncertainties to provide accurate predictions of building performance and occupant behaviour. This can involve incorporating data from sensors, surveys, and other sources to capture changes in occupancy patterns and behaviour, as well as using advanced modelling techniques to identify patterns and make predictions based on the new incoming data.

In this activity, it was found that domain adaptation is one promising technique that can be used to design robust models for occupant behaviour modelling in the face of changing conditions such as those posed by the pandemic and climate change. Domain adaptation is a specific technique in transfer learning. Transfer learning has previously been used in dealing with a lack of data in the target domain (e.g., new buildings, new regions). For example, in Gao, Shao et al. (2021) , transfer learning is used to predict thermal comfort in a previously unseen building in the training stage. The goal of domain adaptation is to train a model on data from one domain (e.g., a pre-pandemic building occupancy pattern) and adapt it to perform well on data from another related but different domain (e.g., a (post-) pandemic occupancy pattern). By doing so, domain adaptation can help to create occupant-centric models that are more resilient and better able to adapt to changing conditions. For example, Shao, Zhao et al. (2021) demonstrated using a transfer learning framework to forecast parking occupancy in regions with insufficient parking data to feed data-intensive models. This was achieved by employing domain adaptation techniques to leverage data from other areas that share similar characteristics. With proper design, transfer learning-based occupant behaviour models can be more robust. However, one potential challenge is that an adaptation process can introduce new sources of error and uncertainty, particularly to attain the desired level of model robustness.

Another possible working direction toward robust occupant behaviour models was identified as introducing more powerful memory mechanisms. Wang, Jiang et al. (2022) presented a novel method based on the memory-augmented dynamic filter generator. It enables the generation of scenario-specific parameters in a dynamic manner for various scenarios. The memory bank part can be adopted to identify and reuse similar patterns learned in history, and the dynamic filter network part is used to encourage the model to learn to distinguish and generalize to diverse scenarios. This technique has shown good performance in human mobility behaviour modelling, even for unprecedented events. Similarly, for occupant behaviour modelling, memory mechanisms could be used to capture and incorporate information about past behaviour and experiences, as well as to adapt to changing conditions over time. For example, memory mechanisms could be used to capture information about how occupants have responded to extreme weather events in the past and to use that information to inform predictions about how they may behave in future similar events.

By combining the above-discussed approaches, it was possible to create occupant behaviour models that are more accurate, robust, and adaptable.

5.5. Digital tools for enabling occupant behaviour research

One of the objectives of Subtask 2 was to develop digital tools and platforms for enabling occupant behaviour research. That was achieved by creating an OB ecosystem of tools, datasets, guidelines, and methodologies that will result in a long-lasting contribution to this research community. Specifically, thanks to the activities described before, guidelines for OB data collection and clear and transparent documentation of OB models could be derived and published as a separate deliverable of the Annex. Furthermore, several OB datasets were collected, and after a quality assurance process, they were compiled in the ASHRAE Global Occupant Behaviour Database. Moreover, after gathering several OB models in GitHub, the Occupant Behaviour Library (OBLib) was created, and, finally, an evaluation web app was made for a standard evaluation of OB models. Both internet platforms are digital deliverables of the Annex. The Subtask 2 OB ecosystem is represented in Figure 5-4.

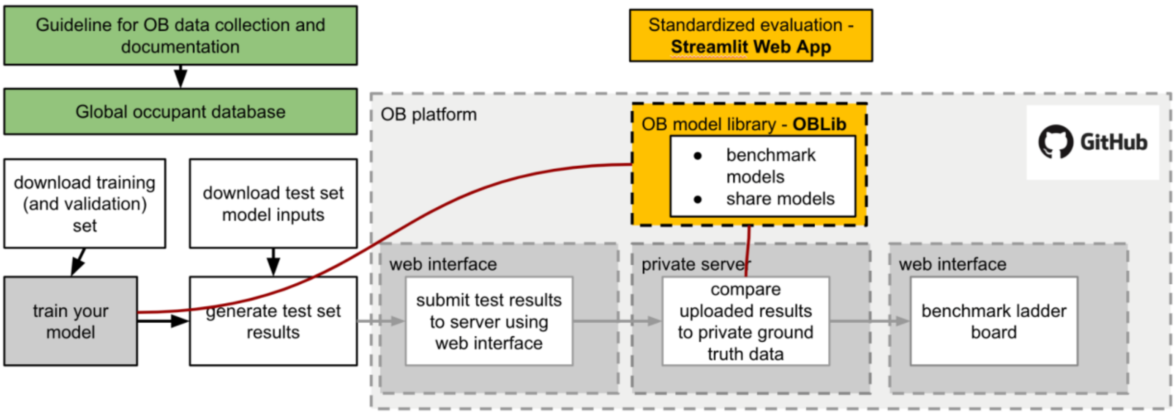

Figure 5-4: The Subtask 2 OB ecosystem

In the following sections, these components of the ecosystems are described in more detail.

5.5.1. The ASHRAE Global Occupant Behaviour Database

Over the past decade, numerous research studies have focused on modelling and simulating occupant behaviour in buildings, represented by initiatives such as IEA-EBC Annex 53, Annex 66, and Annex 79. These projects have explored the applications of occupant behaviour models in building design and operation, considering factors such as building types, climates, systems, and controls. However, each research study typically relies on its own datasets and represents a specific case, even though studies have been conducted across different countries. There has been a significant volume of research, with over 400 papers published on the topic of occupant behaviour over the last decade. Subsequently, there is an opportunity to consolidate these valuable datasets into a comprehensive repository. By establishing such a repository, researchers studying occupant behaviour will have access to a vast body of data, enabling them to conduct in-depth comparisons of occupant behaviours across diverse building types and nations. And yield valuable insights for energy-efficient building design and operations, facilitating the development of more effective strategies in this domain.

For this purpose, the ASHRAE Global Occupant Behaviour Database has been developed (as a part of the ASHRAE MTG.OBB research grant URP-1883), incorporating data contributions from researchers worldwide. This comprehensive database encompasses 34 field-measured datasets on different building occupant behaviours collected from 15 countries and 39 institutions across 10 climatic zones. The database covers various building types in both commercial and residential sectors (Dong, Liu et al., 2022). This extensive global database is multifaceted, encompassing occupancy patterns (presence and people count), occupant behaviours (including interactions with devices, equipment, and technical systems within buildings), as well as indoor and outdoor environmental measurements (e.g., temperature, relative humidity, carbon dioxide concentration, etc.). The database is publicly accessible, and a dedicated website has been developed to enable the users to interactively access, query, and download specific datasets or the entire database. To facilitate data retrieval, a Python package has been developed, incorporating a custom-made Application Programming Interface (API) for selecting and downloading data from the database.

The database covers field measurements from Asia, Australia, Europe, the Middle East, North America, and South America. Among those continents, about 36% of the data (by behaviour type) comes from Europe, and researchers from Asia contribute nearly 35% of the data (by behaviour type). In total, the datasets come from 35 cities all over the world. A query builder was created to assist users in selecting the desired dataset based on city and country. The datasets were collected between 2003 and 2020, and after rigorous data processing and quality control procedures the database amounts to approximately 3.81 GB of data records. It includes 24 in-situ datasets, one mixed-type dataset that combines sensor data with survey responses, and nine survey-type datasets. Data based on in-situ methods encompasses dynamic information and measurements within the study buildings, collected at regular and consistent intervals. In contrast, survey-based data comprises specific information gathered from studies, such as responses from occupant questionnaires, static details about the building's exteriors, floor layout, and measurements taken at selected intervals. Any datasets that lack a uniform and fixed time frame for sampling are categorized as survey-based data. Additionally, there was one dataset identified as a mixed type, as it incorporates elements of both survey-based and in-situ-based data collection. Importantly, the database covers ten distinct climate zones worldwide, as classified according to the Köppen-Geiger climate classification[3].

Three different types of buildings were identified in the database: educational, commercial, and residential. The reason to separate the educational building type from the commercial building type is due to the fact that all data contributors are university researchers who collected data in university/educational buildings. Commercial buildings include office rooms. Academic buildings include classrooms, educational offices, and study zones. Residential buildings include single-family

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[3] https://en.climate-data.org

houses, apartments, and dormitories. The occupant behaviour types captured in the database encompass a range of measurements, including door status (on/off), fan status (on/off), window status (on/off), shading status (on/off), lighting status (on/off), occupant number, occupant presence (occupied or not), appliance usage (in watts), indoor measurements, outdoor measurements, and other relevant study-specific parameters. To ensure consistency and standardization, each type of measurement is associated with a corresponding CSV template file. These templates guide the preprocessing of raw data, ensuring that the data adheres to standardized naming conventions, data types, and formats.

The ASHRAE Global Occupant Behaviour Database offers extensive support for various use cases in occupant behaviour research, including (i) gaining insights into actual occupant behaviours in buildings. (ii) comparing and understanding the diversity and dynamics of occupant behaviours. (iii) developing mathematical models of occupant behaviours at different spatial and temporal resolutions for different building types. (iv) benchmarking different approaches to modelling occupant behaviour. (v) generating typical occupant schedules and behaviour models for building performance simulations, as well as building energy codes and standards. The ASHRAE Global Occupant Behaviour Database is accessible through a data-sharing website[4] and is described in Dong, Liu et al. (2022) . All the raw datasets, together with pre-processed datasets, have been uploaded to a public repository hosted by Figshare[5].

5.5.2. The Occupant Behaviour Library

The Occupant Behaviour Library (OBLib) is a web-based platform for deciphering the details of the machine learning models trained from the data of the ASHRAE Global Occupant Behaviour Database. The significant advantage of OBLib is that it presents the testing results of various machine learning models in a simplified manner. Also, the metadata showing the model information can be easily accessed. These details and evaluation metrics of these models' predictions can be seen in the Streamlight Web Application URL[6]. The webpage also has an access link to the GitHub page[7] with detailed ML codes for all the models. This webpage provides an interactive user interface for selecting any OB model and viewing the corresponding evaluation results. The example snapshot of this interface is explained in Figure 5-5 and Figure 5-6. Any user can choose the desired type of OB in the first box, as shown in Figure 5-5. If there are any models available for this type of OB, they will show up in the second box. Once the model is selected, the description of the dataset on which the model is trained/tested pops up, along with detailed information about the parameters used for training this model (Figure 5-6).

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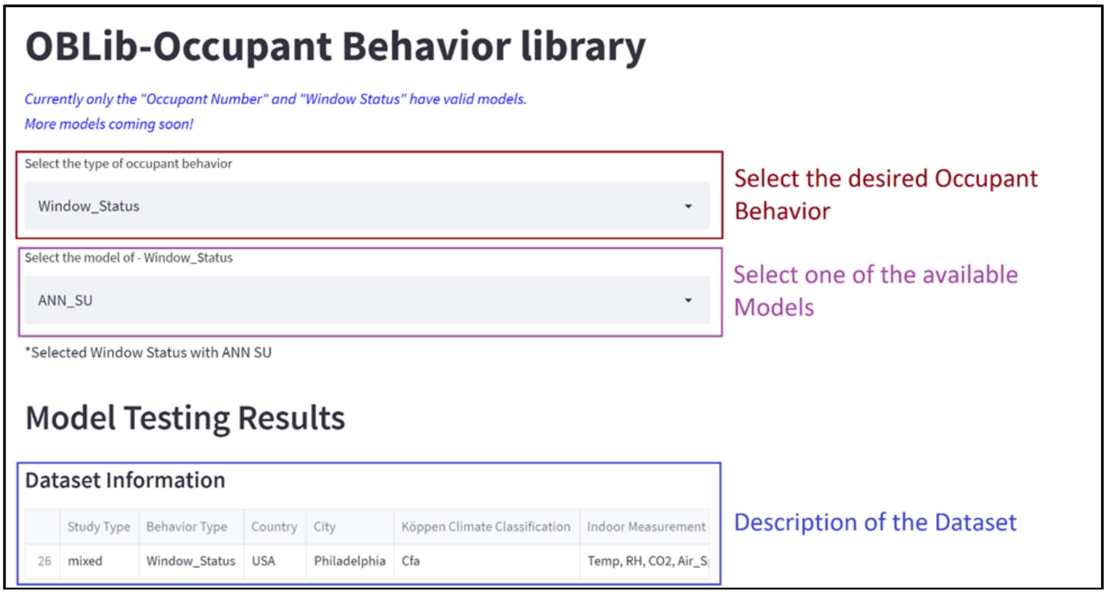
[4] https://ashraeobdatabase.com/#/export

[5] https://doi.org/10.6084/m9.figshare.16920118.v6

[6] https://yapanliu-oblib-streamlit-app-staging-4j4hur.streamlitapp.com/

[7] https://github.com/yapanliu/OBlib



OBLib-Occupant Behavior library

Currently only the "Occupant Number" and "Window Status" have valid models.
More models coming soon!

Select the type of occupant behavior
Window_Status

Select the desired Occupant Behavior

Select the model of - Window_Status
ANN_SU

Select one of the available Models

*Selected Window Status with ANN SU

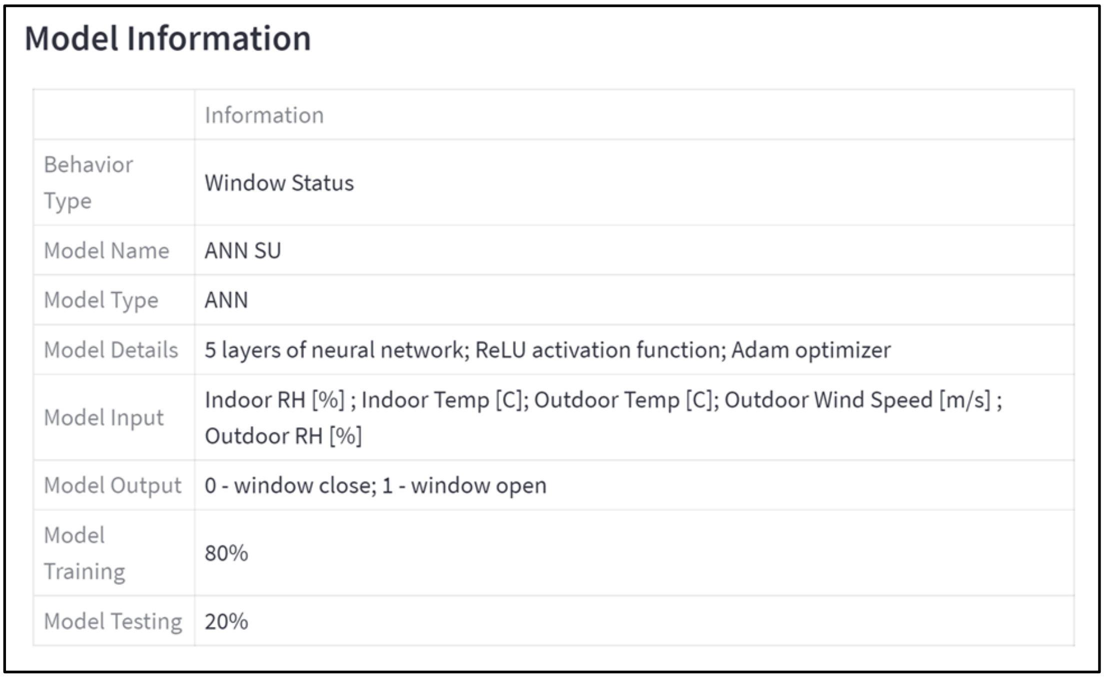
Model Testing Results

Dataset Information

Description of the Dataset

	Study Type	Behavior Type	Country	City	Köppen Climate Classification	Indoor Measurement
26	mixed	Window_Status	USA	Philadelphia	Cfa	Temp, RH, CO2, Air_S

Figure 5-5: OBLib user interface for selecting desired occupant behaviour



Model Information

	Information
Behavior Type	Window Status
Model Name	ANN SU
Model Type	ANN
Model Details	5 layers of neural network; ReLU activation function; Adam optimizer
Model Input	Indoor RH [%] ; Indoor Temp [C]; Outdoor Temp [C]; Outdoor Wind Speed [m/s] ; Outdoor RH [%]
Model Output	0 - window close; 1 - window open
Model Training	80%
Model Testing	20%

Figure 5-6: Model information and table for selected models

After specifying the details of the model, the prediction accuracies are presented using various types of charts, Accuracy, F1 score, or Confusion Matrix, depending on the nature of the OB the model is trying to predict. For example, if the problem is related to the prediction of window status, which is the classification problem, the proper evaluation metric is the Confusion Matrix. If an ML model is trying to do regression analysis, for example, plug load prediction, then the appropriate evaluation metric can be the mean absolute percentage error (MAPE), root mean square error (RMSE), or coefficient of variation of RMSE. Figure 5-7 shows the snip of Streamlight's user interface, where the actual versus predicted window operation values are shown in a diagram. Figure 5-7 also shows the evaluation results. The blue vertical lines in Figure 5-7 show actual changes in the window state, where '1' is 'OPEN' and '0' is 'CLOSED.' The red vertical lines at the bottom show the window state predicted by the selected model.

Testing Results

Model Resting Results

Evaluation Results

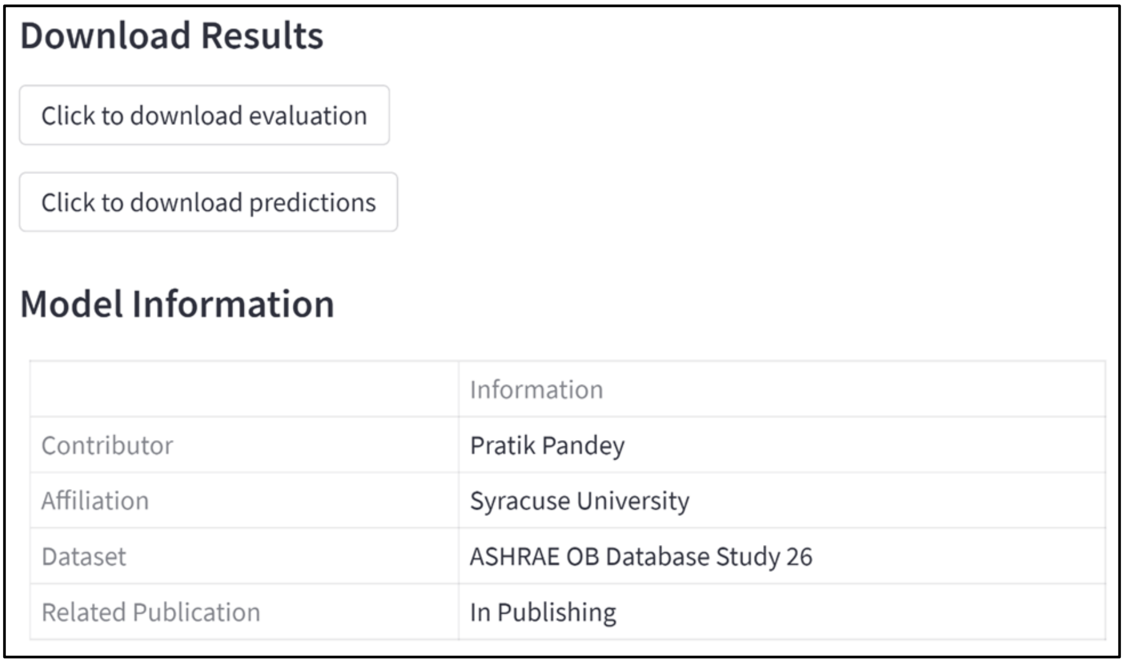
	Evaluation
Accuracy	98.45%
F1-Score	78.91%

Confusion Matrix

	0	1
0	51468	328
1	507	1562

Figure 5-7: Testing results and performance evaluation results of the submitted OB model

Finally, this user interface allows the download of the CSV files containing these evaluation metrics and the CSV file containing the real and predicted values, as shown in Figure 5-8. Also, in the end, some of the model's metadata, like the model's contributor, the contributor's affiliation, the dataset's name, and related publications, are shown.



Model Information

	Information
Contributor	Pratik Pandey
Affiliation	Syracuse University
Dataset	ASHRAE OB Database Study 26
Related Publication	In Publishing

Figure 5-8: Web interface for downloading the predicted values from the neural network along with the model's metadata

The 'Hamburger' button (☰) on the top right corner of the webpage allows access to additional features like changing display settings, recording the screencast, reporting a bug, and getting help to explore the website.

Since this project is in its earlier phase, there are currently just three models uploaded to this platform. Two models are for window state prediction, and one model is for occupancy prediction. The details of these models are presented in Table 5-3. The window operation models have very high accuracy, over 95%. The mismatch rate for the occupancy number prediction model is 30%.

Various types of plots have been used in OBLib to show actual versus predicted data. For example, the bar plot in Figure 5-7 shows the window state prediction. Figure 5-9 shows the actual versus predicted occupancy number.

Table 5-3: Model performance evaluation of three OB models

Model Name/Type	OB type	Developer	Model Input	Accuracy	F1 Score	TPR	Mismatch Rate
ANN_SU/ DNN	Window Operation	Pratik Pandey	Indoor/ Outdoor Temperature, Indoor/ Outdoor RH, Outdoor Wind Speed	98.45%	78.91%	0.755	-

SVM_E3D/ SVM	Window Operation	Andre Orth	Indoor/ Outdoor Temperature, Indoor/ Outdoor RH, Occupant Number	96.20%	46.36%	0.340	-
ANN_SU/ DNN	Occupant Count	Zixin Jiang	History of Occupant Count	-	-	-	30%

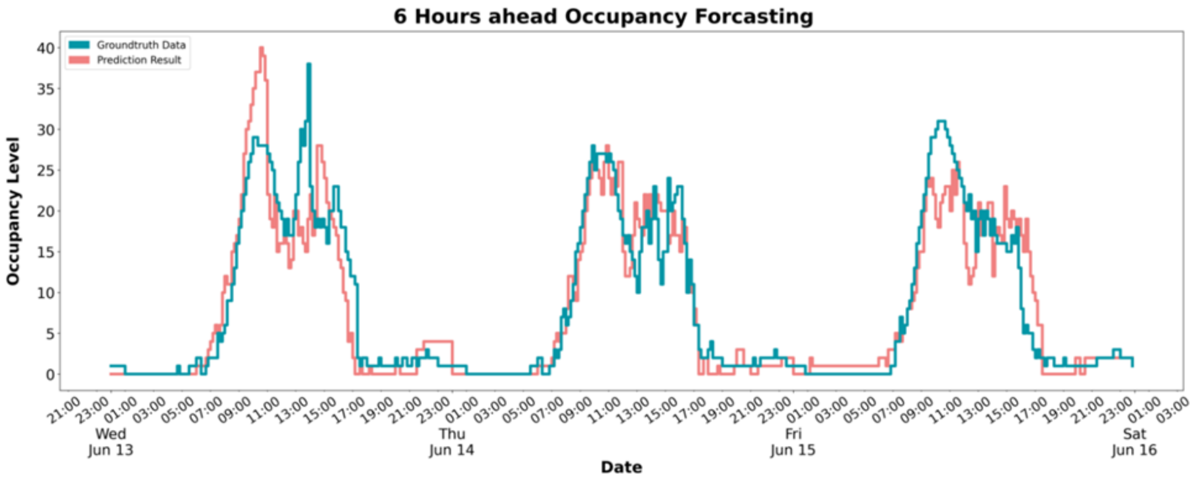


Figure 5-9: Occupancy count forecasting (mismatch rate = 30%)

5.5.3. Immersive virtual environments for understanding human-environmental perception

In addition, researchers explored the use of virtual reality (VR), especially immersive virtual environments (IVEs), as an alternative approach to studying human behaviour and indoor environmental perception (O'Brien, Wagner et al., 2020, Vittori, Pigliautile et al., 2021, Bellazzi, Bellia et al., 2022). Previous studies have highlighted the potential and challenges of the approach (Zhu, Saeidi et al., 2018), its limitation in experiments involving multiple domains and users (Alamirah, Schweiker et al., 2022), and the need to demonstrate sufficient ecological validity (Schweiker, Ampatzi et al., 2020). Essentially, existing virtual reality technology provides virtual stimuli at different levels of maturity, which can limit the application and potential of this alternative approach. Therefore, it is essential to carefully consider the design of virtual stimuli, experimental protocols, and data collection instruments. By doing so, researchers can ensure that virtual reality is used to its fullest potential in studying human-building interactions.

Recent studies have shown the effective use of mature virtual stimuli in human-building interaction studies. For example, visual stimuli have been applied to study lighting perception and behaviour (Heydarian and Becerik-Gerber, 2017) and assess visual quality and lighting perception (Bellazzi, Bellia et al., 2022). In addition, another line of research focused on improving analytic models by incorporating virtual reality-based “future” data using machine learning (ML) (Chokwitthaya, Zhu et al., 2019, Chokwitthaya, Zhu et al., 2020, Chokwitthaya, Zhu et al., 2021). This research argues that while predictive models based on historical data are helpful during the design stage, they often do not account for circumstances specific to a new design. Therefore, this research has developed a computational framework using virtual reality data by taking advantage of IVEs to generate “future” data about human building interactions and using ML to enhance predictive models. In addition, while some studies, e.g., Kang, Wu et al. (2022) , have explored the direct use of virtual reality data for behaviour analysis and modelling during design, more research is needed to understand the impact of differences in data embodiment between data collected from virtual and actual environments.

Virtual thermal stimuli were effectively created by combining IVEs with external heating or cooling sources to study thermal comfort and related behaviours, for example (Ozcelik and Becerik-Gerber, 2018, Yeom, Choi et al., 2019, Saeidi, Rentala et al., 2021, Vittori, Pigliautile et al., 2021). However, existing studies have applied different experimental protocols and data collection methods. For example, in one study (Yeom, Choi et al., 2019), participants’ thermal sensation, comfort, heart rate, and skin temperature were surveyed every 10 min while the temperature continuously changed between 20°C and 30°C. Other studies (e.g., Ozcelik and Becerik-Gerber, 2018, Saeidi, Rentala et al., 2021) collected similar types of data while the temperature stabilized at a particular temperature step. These two experimental protocols produced different ecological validity of IVE-based experiments. In addition, using IVEs to observe behaviour directly is sometimes difficult due to technological limitations. Instead, some studies proposed using behaviour intention as a proxy (Ozcelik and Becerik-Gerber, 2018, Saeidi, Rentala et al., 2021). However, using different instruments to collect intentional data may lead to different conclusions on the ecological validity of IVE-based experiments. These studies suggest reliable experimental protocols are yet to be developed.

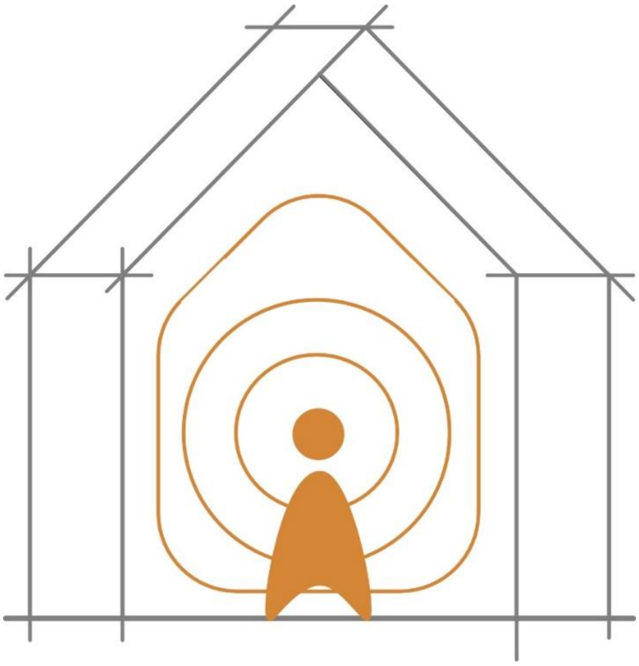
One approach to accelerate the development of IVE-based experimentation and data collection on human-building interactions is to share experimental protocols and results based on the principles of open science. For this purpose, an ontology (VHBIEO) has been developed to describe the experimentation of human-building interactions using virtual reality (Chokwitthaya, Zhu et al., 2023). The ontology refers to existing ontologies, data standards, and models, including the ontology of scientific experiments (Soldatova and King, 2006), the ontology to represent energy-related occupant behaviour in buildings (DNAs) (Hong, D'Oca et al., 2015), and a spatial-temporal event-driven (STED) model to guide the design of IVE-based data collection methods and experiments (Saeidi, Chokwitthaya et al., 2018).

5.6. Conclusion and future outlook

Subtask 2 of the IEA EBC Annex 79 has advanced the understanding of occupant behaviour and its integration into building performance modelling and simulation. By examining a broad spectrum of modelling approaches, including rule-based models, stochastic models, and data-driven methods, the work provides a comprehensive analysis of how occupants interact with building systems. This analysis highlights the need for models that accurately represent these interactions to improve energy efficiency and occupant comfort. One of the key findings is the importance of integrating occupant behaviour models into predictive building control systems. Such integration can lead to substantial energy savings, with reductions of up to 50% without compromising occupant comfort. This is particularly critical in light of the increasing focus on sustainable building practices and the need for energy-efficient solutions. The study also underscores the challenges associated with the current state of occupant behaviour modelling. These challenges include a lack of standardized documentation, insufficient guidelines for model development, and the need for comprehensive evaluation frameworks. Addressing these gaps is crucial for the advancement and broader application of occupant-centric models in real-world settings.

Looking forward, there are several areas where future research could make significant contributions. First, the development of a formal representation of occupant behaviour models using a unified schema and semantics is essential. Efforts like the Brick schema can be expanded to include more comprehensive datasets, enhancing the model's utility and transferability across different building types and climatic zones. Second, the creation of an open-source library for occupant behaviour model documentation would facilitate the sharing of best practices and enhance reproducibility in research. Such a library could also support the deployment of these models in practical building control applications, bridging the gap between theoretical research and practical implementation. Third, the integration of more sophisticated memory mechanisms and transfer learning techniques can enhance the robustness and adaptability of occupant behaviour models. These approaches can capture and utilize historical data to improve predictions under varying conditions, such as those posed by climate change and pandemics. Additionally, future research should explore the inclusion of personalized cooling and heating systems within occupant behaviour models. This would allow for more precise control strategies tailored to individual preferences, further enhancing both comfort and energy efficiency.

In conclusion, the continued development and refinement of occupant behaviour models are critical for the advancement of energy-efficient and sustainable building practices. By addressing the current challenges and leveraging emerging technologies, researchers can create more accurate, robust, and adaptable models that significantly improve building performance and occupant well-being.



6. Applying occupant behaviour models in a performance-based design process

6.1. Introduction

Focusing on integration of occupant information and application of occupant behaviour models in the building design process, IEA EBC Annex 79 Subtask 3 conducted the following research activities:

- Review of codes and standards involving performance-based design (Section 6.2);
- Review of simulation-based occupant-centric design procedures (Section 6.3);
- Development of a framework to integrate occupants in building design decision making (Section 6.4);
- Review the communication of occupant-related assumption between stakeholders (Section 6.5);
- Explore big data analytics for occupant behaviour research (Section 6.6);
- Development of synthetic population of behaviour data (Section 6.7);
- Development and examination of occupant-centric simulation-aided design methods (Section 6.8); and,
- Case studies involving occupant centric simulation-aided design (Section 6.9).

Figure 6-1 illustrates how these research activities have contributed to realize the aims of this subtask. A summary of these research activities is given in this report. Further details on these studies, along with several additional supporting investigations associated with occupant-centric simulation-aided building design can be found in the open access book resulting from IEA EBC Annex 79 research (O'Brien and Tahmasebi, 2023).

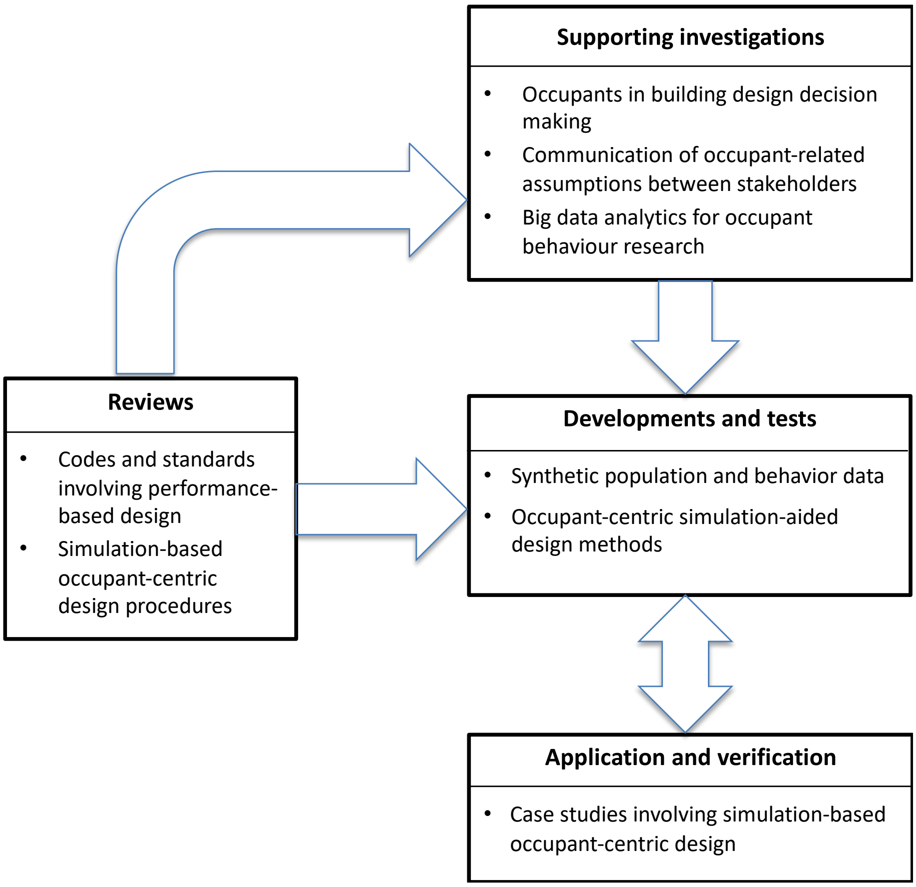


Figure 6-1: Research activities in IEA EBC Annex 79 Subtask 3

6.2. Review of codes and standards involving performance-based design

Building energy codes are among the most effective means to improve the energy performance of new buildings (Chirarattananon, Chaiwiwatworakul et al., 2010, Jacobsen and Kotchen, 2013, Evans, Roshchanka et al., 2017). Building codes have traditionally focused on physical attributes of buildings, such as building envelopes, lighting, heating, cooling, and ventilation systems, while often avoiding mention of occupants. This tendency stems from the uncertainty associated with occupants (i.e., ultimately it may be difficult to predict occupancy, let alone how occupants will use a building and affect its performance). However, as building performance improves due to increasing requirements for the above building traits, the role of occupants proportionately increases. We argue that even if occupancy has some uncertainty during the building design stage, we should still make an effort to predict occupancy and occupant behaviour. Inappropriate or simplistic assumptions about occupants (which are commonplace in existing building codes) run the risk of misleading designers about effective energy efficiency strategies (O'Brien and Gunay, 2019).

This work focuses on obtaining a global view of how occupants are incorporated into building codes. In all, we analyzed 23 regions' building codes or standards, as shown in the map in Figure 6-2. Our ultimate goal was to understand how different regions have "dealt" with the occupant issue in order to gain perspective, inspiration, and make recommendations based on this global perspective. We took a two-phased approach. The first phase is quantitative; we compared all occupant-related schedules, densities, and other values (e.g., thermostat setpoints and illuminance levels). In the second phase, we focused on qualitative requirements, such as the use of certain technologies that adjust to real-time occupancy levels. This work focuses on offices but should be extended to other building types in the future.

The dominant way that occupants are defined for performance paths of codes and standards is through schedules and corresponding densities or other values that correspond to the schedules. Selected results from the first phase are shown in

Figure 6-3,

Figure 6-4, and

Figure 6-5. The ranges for occupancy, lighting power, and office equipment power densities range by a factor of over two (and up to seven for equipment). While the schedules generally resemble each other, there is little consistency among them. In contrast to density values, we found significantly more consistency among setpoints; most countries specify between 24 and 26°C for cooling and 20 and 22°C for heating. In general, the sources for these values are not explicitly stated by the codes. Perhaps more importantly, the way in which these values are applied varies significantly. In some countries, these values must be used in the models used for performance-based code compliance. For others, consultants may replace them with customized values. Regardless, most codes state that the same occupant assumptions must be made for both the base model (code-compliant model) and proposed building model. That is, building design cannot be considered to affect occupant behaviour. This contrasts with our view that building design can in fact affect occupant behaviour. However, we note that this requires strict guidelines or else it would be subject to abuse (e.g., making overly optimistic assumptions about occupants in the proposed building model).

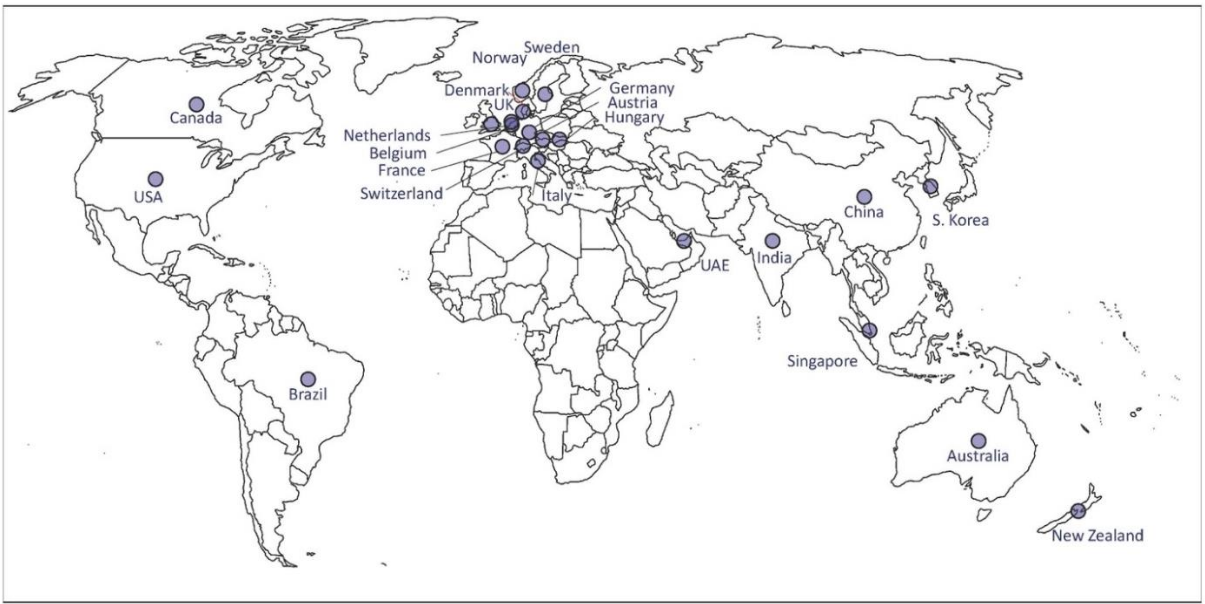


Figure 6-2: Map of the regions whose building codes or standards were analyzed in this study

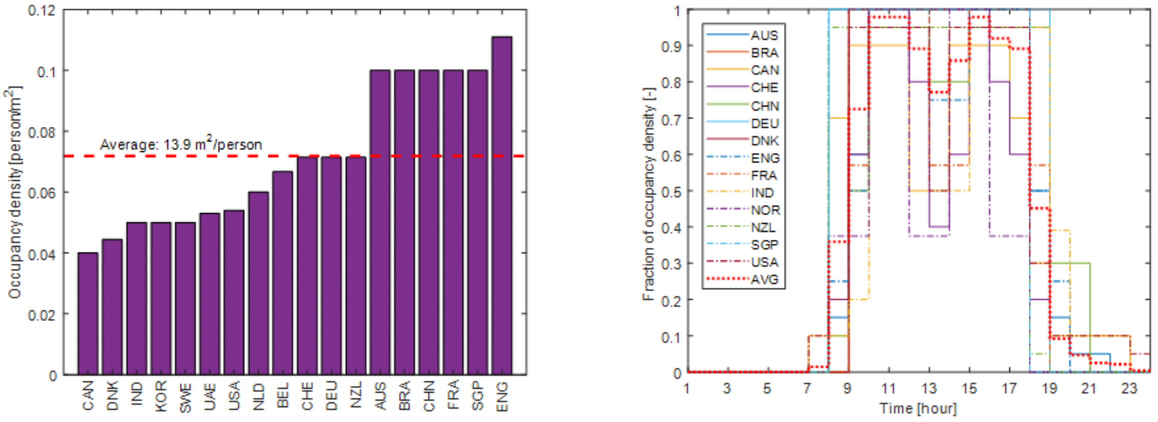


Figure 6-3: Office occupant density values and schedules provided by the reviewed codes

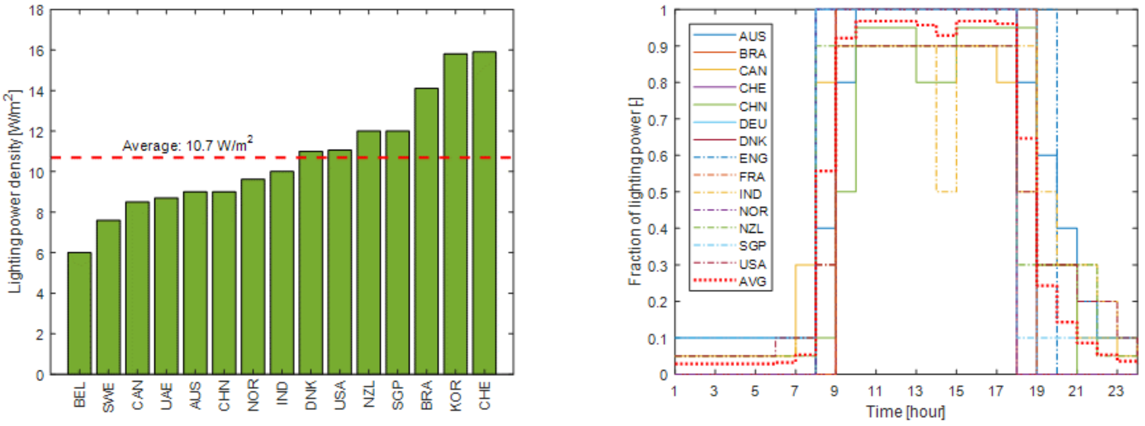


Figure 6-4: Office lighting power density values and schedules provided by the reviewed codes

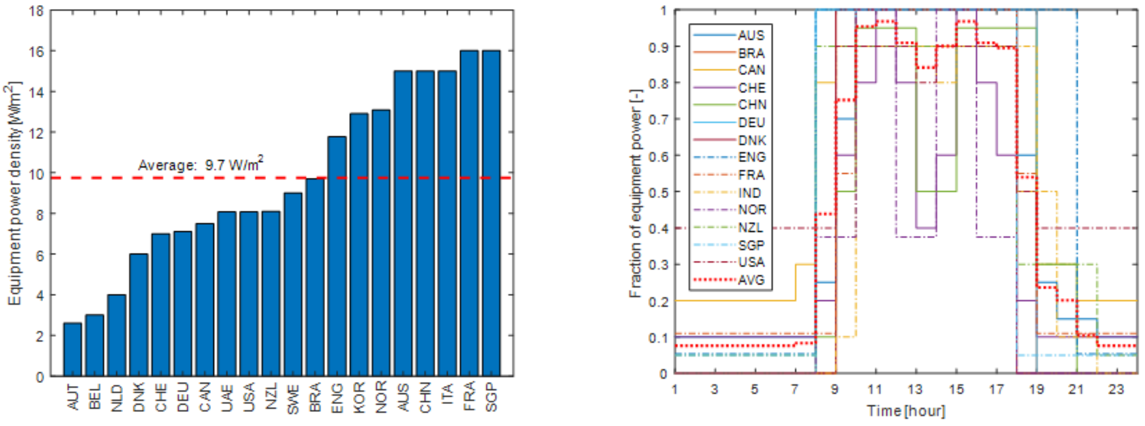


Figure 6-5: Office equipment power density values and schedules provided by the reviewed codes

The second phase of this study, on the qualitative aspects of the codes, revealed similarly difference between countries. In total, 167 requirements with references to occupants were uncovered. We note that often occupants are described in very implicit ways (e.g., reference to automated vs. manual systems). Several of the codes are very explicit that occupants cannot be assumed to use manual systems to save energy. However, other codes allow building systems (e.g., shades) to be used strategically by occupants (e.g., close when there are intense solar gains). The review found more than half of the codes require or give credit to occupancy-based lighting or demand-controlled ventilation. In general, the reviewed codes and standards rely on simple assumptions, with only a few allowing rule-based modelling.

From this review, the researchers identified several ways that building energy codes could be elevated without introducing significant contributions (e.g., stochastic results that require multiple simulations to develop a distribution). In order of simplest to more complex, our recommendations include the following.

1. Add prescriptive requirements that relate to occupancy (e.g., mandate demand-controlled ventilation in all commercial buildings).
2. Update schedules, densities, and other values based on recent field studies (e.g., thermostat schedules could be updated based on smart/Internet-of-Things-based thermostats that have yielded a large sample of data).
3. Require multiple occupancy scenarios to be modelled such that buildings with greater flexibility towards different occupancy schedules are incentivized.
4. Elevate occupant modelling requirements (e.g., rule-based behaviour models) to recognize that building design can influence occupant behaviour.

Finally, one notable finding from the review is the lack of requirements for usability of building systems (e.g., thermostats, window blinds, etc.). As investigated by several major Annex 79 efforts, building usability is critical for a building's energy performance, comfort, and perceived control. We recommend that additional usability requirements be investigated and ultimately incorporated into building codes and standards. This work is written up as an article in Building and Environment (O'Brien, Tahmasebi et al., 2020).

6.3. Review of simulation-based occupant-centric design procedures

Designing occupant-centric buildings requires adapting existing design workflows to capture occupants' needs, behaviours, and corresponding performance metrics. An essential part of the design workflow is using computer-based simulations to predict building performance and inform design choices. However, it was unclear if existing modelling tools and techniques are effectively leveraged to guide and promote occupant-centric building designs. This activity addressed the stated gap by investigating simulation-aided methods used to inform occupant-centric building design and involved a review of existing scholarly work to gain a systematic understanding of the state-of-the-art.

The full literature review was published in Azar, O'Brien et al. (2020) and covered occupant-centric (i) metrics, (ii) modelling/simulation tools, (iii) design methods and workflows, and (iv) mechanisms that can support an occupant-in-the-loop design approach. Starting with the metrics, we defined and detailed various performance metrics that could be considered occupant-centric: thermal, visual, and acoustic comfort; indoor air quality; well-being and productivity; energy; and space planning metrics. We found that while the metrics are mostly well-defined in the literature, guidelines on how best to integrate them into design workflows are lacking. We also observed a tendency to normalize metrics (e.g., per unit of floor area), minimizing the influence of individuals' attributes (e.g., physiological and social) on design outcomes.

In parallel, we reviewed simulation-based methods and tools that could support occupant-centric designs. These included existing Building performance simulation (BPS) software models, occupant behaviour modelling approaches (e.g., stochastics and probabilistic), and approaches to enable OB-BPS modelling integration (e.g., co-simulation). We found that despite advancements in modelling capabilities, OB-BPS integration is facing adoption barriers such as the lack of OB modelling expertise on design teams, unclear benefits to practitioners, and uncertain value proposition (i.e., is the added modelling complexity justified?).

Next, we reviewed previous studies that adopted occupant-centric design methods and tools. The content included occupant-centric design workflows, parametric design and optimization, and probabilistic design methods. We observed an apparent disconnect between OB research and design practices, confirmed by the small number of studies applying occupant-centric design workflows. Moreover, these studies were mainly at the proof-of-concept stage and lacked implementation and validation in actual buildings. Another shortcoming of the mentioned studies is their narrow scope of analysis, often limiting occupant-centric performance to a single metric (e.g., thermal comfort). Evaluating building performance across multiple occupant domains (e.g., energy, comfort, and space management) is gaining significant interest in academic circles. Still, it has not made it to the design workflows of buildings.

Finally, we reviewed mechanisms or practices that could enable wider adoption of occupant-centric design practices, namely building codes/standards and project delivery methods. We observed that in building codes, standards, and certifications, occupants' needs are mostly accounted for through indoor environmental condition requirements. As a result, occupant-building interactions are often overlooked, limiting any insights they may have on design decisions.

6.4. Development of a framework to integrate occupants in building design decision-making

This activity comprised the development of a framework to integrate considerations of building occupants and occupant behaviour into the decision-making process of building designers. Called 'occupant-centric design patterns' (OCDP), the framework was inspired by Alexander's 'Pattern

Language’ (Alexander, 1977) and developed to be compatible with building information management (BIM) systems and building performance simulation (BPS) tools. This is particularly important nowadays when documents issued by professional accreditation bodies have been revised and amended to fully embrace BIM and the new ISO standards together with building performance by extending design delivery stages up to buildings in operation.

Design and operation are now seen as a continuum, in which design targets are verified in the operation phase transferring joint responsibility for the client and the design team in terms of their needs and aspirations for the occupants. Translated into practice, this mean having information about occupants connected to or embedded in comprehensive digital models (BIM models) which, in theory, facilitate design for manufacturing assembly and can be constantly refined until they become asset management models. BIM models mirror the different disciplines involved in a building project, enabling information exchange and design decisions to be better controlled and coordinated by the design team.

Using BIM systems and the new ISO standards as a starting point and considering that building operation now needs to be part of design agendas, enabled us to examine different types of design aims, requirements, considerations and decisions related to the fundamental elements of BIM models which are affected by or affect occupants. To this end, we discussed first, the impact of decisions on occupants within built spaces considering that designers: (i) impose constraints (either consciously or unconsciously) on occupants by, for instance, defining how occupants can use spaces through fixed furniture; (ii) use persuasive strategies towards specific behaviours through, for instance, automation and ‘smart’ meters; (iii) design affordances (with intended or unintended effects) on how occupants use the building; and (iv) might keep adaptive opportunities in mind when designing spaces which are significantly shaped by the way people use them.

We then discussed how decisions related to the four main BIM objects namely ‘built spaces’, ‘construction entities’, ‘construction elements’ and ‘construction properties’ affect or are affected by occupants when interacting within (for ‘built spaces’ only) and with these objects as well as with the environment (natural and built) of the wider site. For example, when deciding about building orientation, designers might have to “Provide places for children to play in the sun” therefore influencing occupants’ interactions within the building. When deciding about evacuation routes, designers are likely to have to “Provide safe route to the outside” properly defining wayfinding for occupants’ to interact with the building in a safe way.

We noticed these interactions are complex and context-based but design decisions about the building and its spaces are surprisingly ‘typical’ because the design team has a finite number of ‘built spaces’, ‘construction entities’, ‘construction elements’ and ‘construction properties’ to manipulate towards achieving project goals. So, if a design team wants to integrate considerations about occupants to design practice, the design team needs to be prepared to record information about occupants throughout the design process in a structured way so this information can be easily recalled as design progresses.

We, therefore, proposed a template, ‘occupant-centric design patterns’ (OCDP), for producing occupant-centric design information which captures decisions and objects in their design contexts. The template was inspired by Alexander’s ‘Pattern language’ (Alexander, 1977) and intended to show designers how a current design ‘problem’ (and its solution) might affect occupants or is itself affected by them. These ‘problem-solution pairs’ are seen as a powerful way to transfer and share knowledge and quality control design solutions. They enable expert knowledge, normally deployed in a tacit form, to be formalized, stored, and accessed by novice designers or non-experts. Thus, OCDPs describe common situations where design decisions will affect or be affected by occupants and propose design solutions integrated to BPS that will take these into account.

The structure of OCDP encapsulates expert knowledge from building performance and is used to integrate relevant occupant-related information (e.g., models to be used, analytical processes), and to make them available in a 'user-friendly' way to building designers. Important parts of OCDP problem statements include: (i) the context in which the pattern is inserted in and, therefore, the context in which a decision needs to be made; (ii) a synthesis of the type of problem being dealt with; (iii) and an example showing where the pattern can be or was deployed considering its relationship with occupancy, building performance simulation and design practice. Important parts of OCDP solution statements include: (i) aims of the pattern from a BPS perspective; (ii) BPS model settings; (iii) and processes and analysis involved in BPS together with relevant outputs and interactions with a model that should be afforded in visualizations related to this pattern.

We presented the aforementioned rationale together with an illustrative OCDP on 'effects on building energy use of occupants in low energy co-housing apartment building' in Chapter 3 of the book 'Occupant-Centric Simulation-Aided Building Design: Theory, Application, and Case Studies' (O'Brien and Tahmasebi, 2023), proposing OCDP can form part of a library of patterns better connecting design decisions with different types of performance to be simulated and assessed.

In a nutshell, we proposed that information about occupants needs to be properly documented throughout the design process so that it is linked not just with BPS but also with BIM to fit within information exchange happening between team members with different disciplinary backgrounds, supporting collaborative initiatives from a technical perspective. For this to happen, we need to record and trace design decisions related to occupants in a single environment that is compatible with BIM models and BPS tools so that multiple assessment points can be scheduled throughout the design process and design decision-making can be evidence-based and better integrated with performance in-use. This proposal is effectively a 'Lego' of generic objects structured so it is sharable, easy to recall and exchange, opening the door for future work to implement this structure within common BIM tools to facilitate agility and distributivity in decision-making.

6.5. Review the communication of occupant-related assumptions between stakeholders

A fundamental requirement for performing occupant-centric building design is establishing an effective mechanism to communicate occupant-related assumptions among project stakeholders. Discrepancies in occupant-related assumptions made by designers can lead to suboptimal design solutions or lead to at least to overlooking design opportunities. However, observing current design practices, which typically follow the traditional linear process, yields that occurrence of discrepancies is not uncommon (Abuimara, O'Brien et al., 2020). Therefore, the objective was to assess the current status of communicating occupant-related assumptions, trying to identify the needs and challenges in this matter, and propose steps to be taken to improve the current practices. This activity consisted of three main stages: reviewing the needs and challenges of occupant-centric design, documenting the status quo and challenges, and then concluding our proposed ways to move forward in improving communicating occupant-related assumptions among design stakeholders.

First, we conducted a review of literature to document the different practices of communicating design assumptions including occupant-related assumptions during the design process. The review was published in a conference paper (Abuimara, Rajus et al., 2019). The review covered the following topics: Identification and definition of design stakeholders, the importance of occupants and occupant-related assumptions during building design, and the current state of sharing and communicating occupant-related assumptions. The study concluded that there is a lack of recognition of the importance of occupant-related assumption which resulted in overlooking the challenges and opportunities they pose. We also highlighted the need for a survey on the needs and challenges in incorporating occupant-related assumptions.

Next, we conducted semi-structured interviews with industry practitioners to document the challenges, and the opportunities in making and using occupant-related assumptions during building design. We published the findings of this survey study in a conference paper (Abuimara, Rajus et al., 2021). In this study, we interviewed several building design practitioners including architects, engineers, and energy modelers. The practitioners were from different countries and regions across the globe including Brazil, Canada, India, Palestine, and USA. Based on the interviews, we concluded that a linear design process was still widely adopted by design practitioners. The process typically lacked effective information exchange mechanisms leading to discrepancies in occupant-related assumptions. On the contrary, the integrated design process (IDP), with its high potential to mitigate the discrepancies in design assumptions including occupant-related assumptions, was found to be not as common as expected (Commission for Environmental Coopreration, 2015, Keeler and Vaidya, 2016, Abuimara, O'Brien et al., 2018).

Finally, based on the review and the interviews, we concluded this activity with following recommendations:

- Building designers need to develop/deploy an information exchange platform that is accessible to all design team members.
- IDP needs to be promoted among designers, owners, and all stakeholders to improve coordination and discussions and enhance information sharing.
- As the building design process is driven by policy, codes and standards need to require detailed occupant-related assumptions, documentation, and information exchange. Furthermore, codes and standards should outline the approach to implementing any occupant-related assumptions.

6.6. Explore big data analytics methods for occupant behaviour research

To understand and model occupant behaviour, data collection is the first essential step. Existing studies have proposed various approaches to monitor occupant behaviour and gain comparable datasets. The start-of-art data acquisition technologies to capture occupant behaviour in buildings primarily include in-situ monitoring measurements, questionnaires and surveys and laboratory experiments. In-situ measurements are usually conducted in several selected case study buildings or rooms using remote sensors (Yan, O'Brien et al., 2015). This method is effective to study specific occupant behaviours, including occupancy (Calì, Matthes et al., 2015, Arvidsson, Gullstrand et al., 2021) and occupant interactions in buildings (Ren, Yan et al., 2014, Heydarian, Pantazis et al., 2016, De Dear, Kim et al., 2018, Zhou, Ren et al., 2021), which can provide a long-term temporal-sequential data collection. Survey-based methods are widely applied to review the characteristics and nature of occupant behaviour (Andersen, Toftum et al., 2009), while the diversity caused by participants' subjective nature can hardly be avoided. Laboratory studies collect occupant behaviour under certain designed scenarios (Schweiker and Wagner, 2016), offering great flexibility and control, but this method is typically costly in establishment and operation.

With the advances of wireless communication technologies and online platforms, big data analytics methods offer a new perspective in occupant behaviour data collection (Fan, Yan et al., 2021). Considering volume, variety and veracity, big data has advantages regarding large-scale samples, comprehensive collected parameters, and high data quality, assisting researchers to acquire an overall knowledge of occupant behaviour in buildings. Scholars have investigated the potential of big data analytics in identifying occupancy profiles (Anand, Sekhar et al., 2017), establishing energy use models (Zou, Zhou et al., 2018), and controlling building systems (Zou, Zhou et al., 2018). Thus, big data analytics demonstrates great value in occupant behaviour research.

This activity investigates and provides an overview of big data analytics in occupant behaviour research. Considering that occupancy is one of the essential inputs of building performance simulation at design phase (Muroni, Gaetani et al., 2019) and helps to promote innovative control strategies at operation phase (Dong and Lam, 2014), this activity explores a systematic way to utilize big data in occupancy research. When exploring typical occupancy profiles, we use large-scale mobile positioning data and K-means clustering analysis to acquire weekly occupancy profiles for various public buildings, including railway stations, airports, commercial complexes, and hospitals. Based on the clustered occupancy profiles, a set of descriptive parameters are introduced to illustrate the features of profiles quantitatively regarding the daily peak value and daily total condition. In comparison with profiles from ASHRAE standards, there remains a significant gap difference from the measured occupancy profiles, leading to non-negligible differences in building energy performance simulation. The work suggests that typical weekly profiles can depict the deviations of occupancy between weekdays and weekends and among different buildings, implying that energy codes may need to update reference occupancy schedules according to building types and the different time periods. More comprehensive and realistic occupancy schedules can further help to improve the accuracy of building energy performance evaluation during the building design phase. Recent studies have shown that accurate knowledge of occupancy in buildings could provide predictive control strategies of building energy system, realizing great energy-saving potential (Kleiminger, Mattern et al., 2014). Based on bid data from occupant mobile positioning big data, we conducted research on occupancy forecasting in public buildings serving the purpose of optimizing building system controls at the operation phase (Jin, Yan et al., 2021). This work fully considers the temporal-sequential features of occupancy data and provides the temporal characteristics of building occupancy. Daily and weekly occupancy profiles are extracted to identify typical patterns, and seasonal decomposition is conducted to detect the high correlative time lags. Using the temporal analysis features combined with artificial neural network (ANN), the work proposes an innovative approach to forecast occupancy in one week for various public buildings. Based on the predicted results, traditional time-series prediction algorithms, such as Holt Winters, seasonal auto-regressive integrated moving average (SARIMA), and random forest are compared. The comparison confirms that the proposed novel method significantly improves the accuracy of occupancy forecasting according to the evaluation metric mean average error (MAE) and root mean squared error (RMSE). The work also prospected the applications of improved occupancy forecasting that the short-term control strategies of building systems can be predicted and optimized by utilizing the accurate forecasting results of occupancy, especially the flexible load and demand response strategies and operation of renewable energy systems and so on. Moreover, with the help of big data analytics, occupancy at urban scale can be investigated, captured, and simulated. Accordingly, data-driven algorithms including Bayesian neural network, recurrent neural network, and reinforcement learning have been proposed to model occupant behaviour at a community scale. This activity further conducted a systematic review on urban-scale occupant modelling, especially the emerging data-driven methods based on big data (Dong, Liu et al., 2021).

In general, big data analytics has demonstrated its advantages in the capability of acquiring occupant behaviour information at a large scale, covering plentiful parameters, which bring about various valuable opportunities for understanding occupant behaviour more comprehensively in the occupancy, thermal comfort, and operations of windows, shades and blinds, and the usage of building equipment. Simultaneously, a growing number of data-mining approaches are emerging. These approaches offer powerful techniques to describe occupant behaviour accurately based on big data. We can utilize methods from the fields of machine learning, pattern recognition (e.g., clustering), statistics, databases, and visualization, thus helping to acquire more reliable occupant behaviour models, occupancy schedules and distributions. With the rapid advancements in big data, increasing analytical and modelling methods, and simulation applications have provided insights into occupant behaviour research, leading to great energy saving potential and opportunities. The state-of-the-art big data analytics offer a promising platform for future researchers to measure the full effects of occupant behaviour in buildings more accurately. The progress in occupant behaviour research further helps to better building energy performance shaping, targeting, implementing, and evaluating.

6.7. Development of synthetic population and behaviour data

Generating and representing synthetic occupants from existing datasets are essential to enabling agent-based occupant modelling and its co-simulation with building performance modelling to capture occupants' activities and behaviours and their impact on building design and operations (Malik, Mahdavi et al., 2022). This activity developed an ontology to represent an occupant population's characteristics and their behaviours and developed a method to generate synthetic occupants from integrating and fusing existing datasets.

First, a literature review was conducted on synthetic population models from other disciplines (e.g., transportation), as well as methods to develop synthetic population models. Potential use cases of the synthetic population model across the building life cycle were identified. The existing DNAS (Drivers-

Needs-Actions-Systems) ontology (Hong, D'Oca et al., 2015) and obXML schema (Hong, D'Oca et al., 2015) were extended to represent the characteristics and behaviours of the occupant population (Putra, Hong et al., 2021). The extension introduces new elements to the ontology that fall into five categories, including socio-economic, geographical location, activities, subjective values, and individual and collective adaptive actions (Figure 6-6).

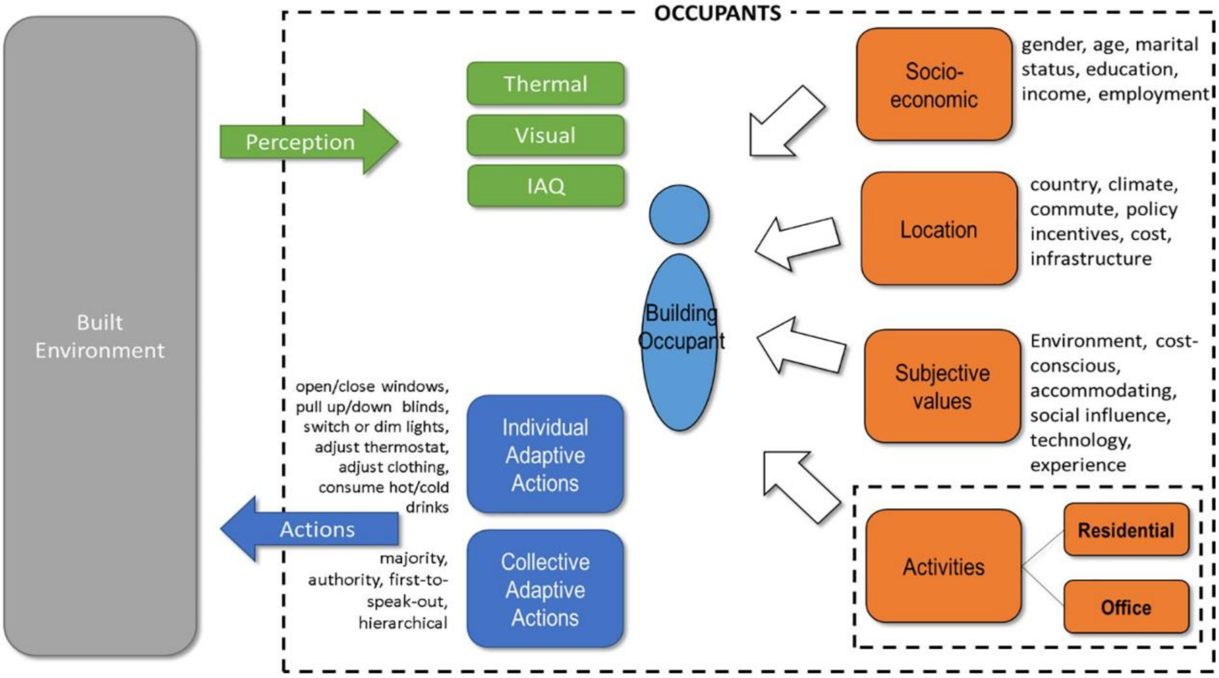


Figure 6-6: Conceptual interaction of components of the building occupant population ontology (Putra, Hong et al., 2021)

Existing datasets were identified that provide data of occupants concerning their socio-economic characteristics, comfort and indoor air quality perceptions and preferences, human-building interactions, activities, and group decision making. These include census survey, community survey, time-of-use survey, the occupant survey conducted by Annex 66 (D'Oca, Chen et al., 2017), the ASHRAE Global Thermal Comfort Database (Ličina, Cheung et al., 2018), the Annex 66 special issue for Nature Scientific Data (Huebner and Mahdavi, 2019), and the ASHRAE Global Occupant Behaviour Database (Dong, Liu et al., 2022).

Next, a method was developed and demonstrated to generate synthetic occupant population using existing datasets (Putra, Andrews et al., 2021). The Bayesian networks (BN) structural learning approach was adopted to synthesize populations of occupants in a multi-family housing case study. Two additional cases of office occupants and senior housing residents are considered as a cross-case comparison. We draw upon the extended DNAS ontology to guide the selection of variables and data imputation. Figure 6-7 illustrates the population synthesis workflow. Results show that the BN approach is powerful in learning the structure of data sets. The synthetic data sets successfully match the joint distributions of the underlying combined data sets. Experiments on the multi-family housing shows better performance than the office and senior housing cases.

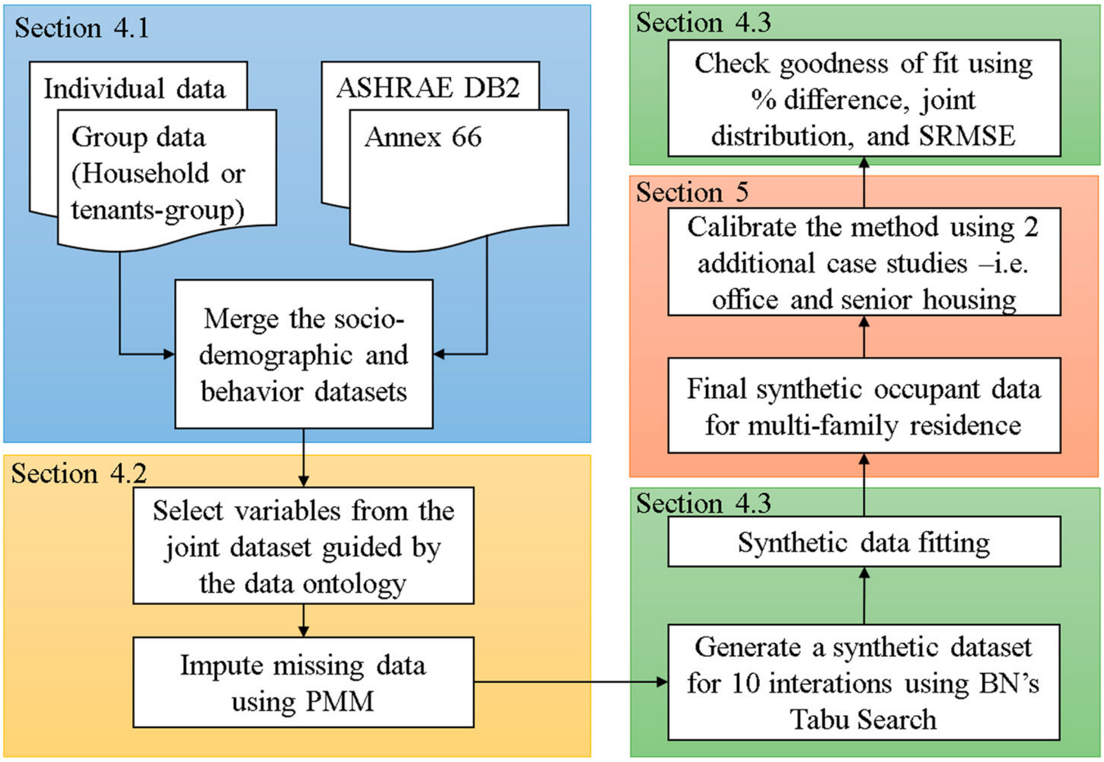


Figure 6-7: The population synthesis workflow (Putra, Andrews et al., 2021)

This activity advances the ABM of occupants with a standard ontology to represent occupant population and a method to synthesize occupant data from diverse datasets. This activity feeds to the Annex 79 cross task activity C2 ABM.

6.8. Development and examination of occupant-centric simulation-aided design methods

Over the last six decades, building performance simulation has increasingly served to assess how well buildings meet their functional requirements and the goals of the stakeholders. Performance quantification through simulation has been particularly advantageous to building design, as it can be applied to non-existent buildings in the design process, allows for testing design variants under identical conditions, and demands much less resources as compared to physical measurements. Consequently, use of building simulation in the design process has evolved to – amongst other things – establish and verify design performance, screen and optimize design parameters, and study design robustness in adverse conditions.

In this context and following the review of existing simulation-based occupant-centric design procedures (Section 6.3), this activity investigated how these procedures can specifically support an occupant-centric building design. To this end, we devised a general framework to better understand different ways in which occupants can be incorporated into simulation-aided design methods. The framework is based on two key questions about modelling occupants in the design process:

1. Do the occupant models respond to iterative changes in the building design, i.e., are the occupant models static or dynamic in relation to the changes in building design?
2. Are the occupant models themselves subjected to iterative changes in the design process, i.e., are occupant-related assumptions among the design's fixed or variable parameters?

Having considered the approaches to integrate occupant models in design process, we then investigated four common simulation-aided design methods used by different members of design teams to make design decisions factoring in occupancy behaviour: uncertainty and risk assessment, sensitivity analysis, parametric design, and optimization. Subsequently, a number of key simulation-aided design methods and objectives were explored with a focus on the role of occupants. Finally, a carefully described prototypical building model served to demonstrate and test the introduced occupant-centric simulation-aided design procedures. Figure 6-8 provides an overview of the process used to integrate stochastic occupant behaviour modelling within an optimization process using the GA algorithm. The full study can be found in Tahmasebi, Ouf et al. (2023) . Moreover, Chapter 8 of the book 'Occupant-Centric Simulation-Aided Building Design: Theory, Application, and Case Studies' (O'Brien and Tahmasebi, 2023) has a more comprehensive description and demonstrations of advanced design methods.

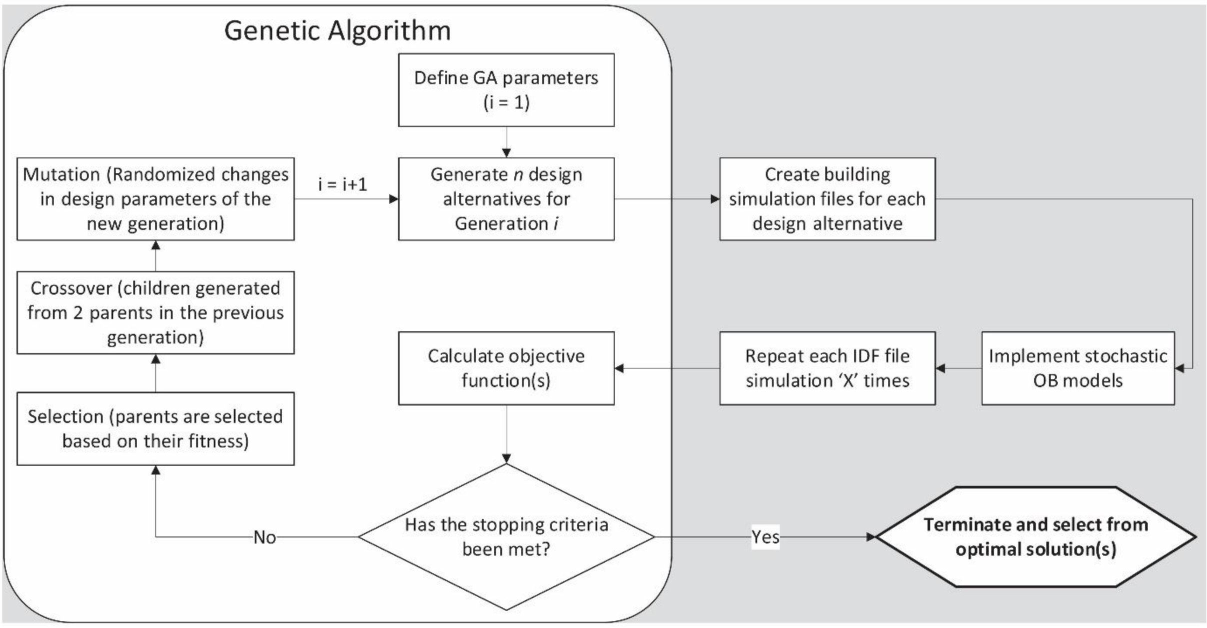


Figure 6-8: Overview of integrating stochastic occupant behaviour in optimization using the genetic algorithm (adapted from Ouf, O'Brien et al. (2020))

6.9. Case studies

In this activity we brought theory and principles of occupant-centric design to application through presenting seven real-world case studies. The seven case buildings are unique in many ways: geographic location, building type, project phase, and building size. Our main objective in this activity was to provide insights on how building design is affected by (1) occupant needs and preferences, and (2) occupant assumptions and modelling. We also aimed at demonstrating, through alternative design approaches, how considering occupants at the core of the design process could yield more efficient design alternatives and capture design opportunities.

We selected the seven case study buildings based on the availability of information about the case study, breadth of design/construction phases among case studies, and the useability of the analysis in advancing occupant-centric design. Table 6-1 summarizes the case studies information and in the following a brief description of the seven case studies is provided. Figure 6-9 shows photos or renderings of the buildings.

Table 6-1: A summary of the selected seven case study buildings

Case study	**Building type & size**	**Location**	**Project phase**	**Case study objectives**
Case study 1: Toronto	Mid-rise office building	Toronto, Canada	Design	● Document occupant modelling approaches during design. ● Develop a method for handling occupant-related uncertainty during design.
Case study 2: E-co-housing	Mid-rise multi-unit residential building	Budapest, Hungary	Design & construction	● Explore and leverage synergies between people and the built environment in all dimensions of sustainability. ● Bridge qualitative co-design methods and simulation for higher fidelity energy models.
Case study 3: Cité Verte	Mid-rise multi-unit residential building	Quebec, Canada	Post-occupancy	● Evaluate the feasibility of low-energy buildings. ● Assess the impact of occupants on achieving low-energy goals.
Case study 4: Gillies Hall	Mid-rise student residence	Melbourne, Australia	Post-occupancy	● Assess occupants’ comfort and well-being as well as energy saving potential from passive house strategies when coupled with performance-based modelling.

				● Assess the benefits of deploying low-cost sensing techniques in passive house design.
Case study 5: Stanford Redwood City	Mid-rise office building	Redwood city, California, USA	Post-occupancy	● Optimize building layouts to maximize occupants' productivity and collaboration while achieving energy efficiency.
Case study 6: Goblet Lavandier & Associésa HQ	Mid-rise office building	Niederanven City, Luxembourg	Post-occupancy	● Derive occupant-centric rules for optimal exterior shading design.
Case study 7: Samhällsbyggnad 1	Institutional office building	Gothenburg, Sweden	Post-occupancy	● Realize IEQ enhancement and energy saving potentials based on an evaluation of occupants' satisfaction in energy efficient buildings.

Toronto case study is a mid-rise office building located downtown Toronto, Canada. It is a commercial office building (core and shell). The analysis of this case study was focused on the design phase and followed qualitative and quantitative approaches. The analysis involved design parametric analysis, design optimization and comfort analysis.

E-co-housing is a multi-unit residential building that is located in Budapest, Hungary. Eco-housing analysis was focused on design and construction phases and was primarily focused on involving occupants in the design process (co-design).

Cité Verte is a multi-unit residential building that is located in Quebec City, Canada. The analysis of Cité Verte took place post-occupancy and is focused on assessing the impact of occupants on achieving building design low-energy goals.

Gillies Hall is a mid-rise student residence located in Melbourne, Australia. The analysis of Gillies Hall case study was focused on assessing occupants' comfort and well-being from passive house strategies implemented in the building and comparing that to the predicted/simulated performance.

Stanford Redwood City is a mid-rise office building in Redwood City, California, USA. The analysis of this case study took place post-occupancy and was focused on optimizing building layouts to enhance occupants' collaboration while achieving energy efficiency.

Goblet Lavandier & Associés headquarters is a mid-rise office building in Niederanven, Luxembourg. This case study analysis is during the post-occupancy phase and is focused on tracking the building automated shading design and operation from design documents including selection criteria to analyze occupants' interactions with the automated shading data.

Samhällsbyggnad 1 is a mid-rise institutional office building that is located in Gothenburg, Sweden. This case study analysis took place post-occupancy with the objective of tracking IEQ and energy use data to evaluate occupants' satisfaction in high-performing buildings.

Toronto, Canada Budapest, Hungary Quebec, Canada Melbourne, Australia

Redwood City, USA Niederanven, Luxembourg Gothenburg, Sweden

Figure 6-9: The seven case study buildings and corresponding locations

6.10. Summary and future work

Based on the studies carried out under Subtask 3 and, in particular, the analysis of case study buildings, we draw the following conclusions and recommendations for future research:

- Performing occupant-centric design requires information to be shared effectively among design stakeholders. The traditional design approach is troublesome, as it can lead to discrepancies in assumptions made by designers, suboptimal design solutions, and overlooking design opportunities.
- Occupant-related assumptions can influence the outcomes of simulation aided design processes. While obtaining highly accurate occupancy data at design stage is a challenge, intentional examination of different occupant-related assumptions can further inform the design process and lead to a range of energy savings obtained from implementing energy conservation measures.
- Occupant-related assumptions affect the levels of comfort in buildings. Current comfort metrics used in the industry overlook comfort at the occupant and building zone/space levels. Alternative occupant-centric comfort metrics should be developed and deployed.
- Occupant participation in the design process (i.e., co-design) can contribute largely to a better representation and catering for occupants in the design process. Co-design has shown promising results in reducing performance gap and improving overall performance of buildings.
- Raising the occupants’ awareness of energy-intensive behaviours is critical for achieving operational energy efficiency.
- The case study buildings analyses emphasized the importance of post-occupancy data collection through occupant surveys, sensing infrastructure, and interviews with building design stakeholders. Gathering post-occupancy occupant-related data proved to be useful to improve spatial design and energy efficiency, and to understanding building performance gaps.

7. Development and demonstration of occupant-centric building operation strategies

7.1. Introduction

Building operations management is a multidisciplinary field that encompasses a range of activities aimed at ensuring the optimal functioning of building systems (Abuimara, Hobson et al., 2021). This includes the maintenance and control of heating, ventilation, and air conditioning (HVAC) systems, energy management, safety and security systems, and other aspects of building performance. The ultimate goal is to provide a safe, comfortable, and productive environment for occupants while minimizing energy use and environmental impact. In recent years, the field has been undergoing a significant transformation, driven by the increasing integration of technology and the growing focus on sustainability and occupant comfort. Occupant-centric controls (OCC) have emerged as a key concept in this transformation, shifting the focus from traditional building-centric operations to a more occupant-focused approach.

The OCC approach is underpinned by a rich array of data, encompassing occupant behaviour, building performance, and environmental conditions. This data-driven approach enables more precise and responsive control strategies, which can significantly enhance energy efficiency, occupant comfort, and overall building performance. OCC has been extensively studied in the IEA EBC Annex 79 research project *Occupant-Centric Design and Operations of Buildings (O'Brien, Wagner et al., 2020)*. This report summarizes some of the key findings from its Subtask 4. While many topics in building design and control could be considered *occupant-centric*, e.g., equity and inclusion, privacy, trust, etc. (Becerik-Gerber, Lucas et al., 2022), in this report we will mainly focus on indoor environmental quality (IEQ) for our discussion.

This report delves into the core aspects of OCC, addressing ten critical questions that span the breadth of this field. We begin by defining OCC (S1) and its foundational data categories (S2), followed by an exploration of the evolving role of building operators in the OCC context (S3). We then discuss the simulation of OCC for building controls (S4) and its potential role in residential demand response programs (S5). The report also examines the impact of OCC on the recent paradigm shift in building occupancy and operations (S6) and presents a classification of occupant-centric operations case studies (S7). We further delve into the OCC strategies implemented and evaluated in these case studies (S8) and discuss the limits of occupant behaviour sensing and strategies to ensure occupant satisfaction (S9). Finally, we conclude with a forward-looking discussion on the future directions and trends in OCC research and development (S10).

7.2. Definition of occupant-centric controls and operation

Traditionally, control and operation of buildings' heating, ventilation, and air conditioning (HVAC) and lighting systems has been based on constant or steady-periodic setpoints and schedules (Gunay, 2016), which are often selected conservatively by designers to cater to unrealistically high occupancy and occupied durations. For example, it is commonplace for HVAC equipment to operate at full or near-full capacity during operating hours - which start and end many hours before and after occupants first arrive or last depart, respectively - as determined by a static daily or weekly schedule (Gunay, Ouf et al., 2019), regardless of when, where, or how many occupants are present, or what their preferred indoor environmental conditions are. Despite this traditional one-size-fits-all approach to operations, occupancy and the preferences of individual occupants in buildings are diverse; workplaces have been rapidly moving away from rigid 'nine-to-five' work schedules for almost a quarter of a century (Golden, 2001), while occupants have been shown to have individually preferred indoor air temperatures and illuminance levels (Gunay, O'Brien et al., 2017, Haldi, Calì et al., 2017), for example. Occupant preferences further extend to other aspects of how occupants experience and interact with the built environment (e.g., location and type of seating, olfactory sensitivities or preferences, access to views, flexible working hours, etc.) which ultimately impact their productivity and well-being. Any attempt to address this diversity with conservative setpoints and schedules is to provide services to buildings blindly, which ultimately wastes energy, affects indoor environmental quality (IEQ), and causes occupant discomfort. This problem is not limited to a single building type (i.e., commercial., or residential) nor to a single country, culture, or climate zone.

One potential antidote to the problems created by traditional control and operation strategies that has developed since the early 2000s (Nicol, 2001) is the concept of occupant-centric controls (OCC). The position paper published by IEA EBC Annex 79 defines OCC as an approach which involves "sensing indoor environmental quality, occupants' presence, and occupants' interactions with buildings" (O'Brien, Wagner et al., 2020). These data can then be used in control algorithms to adapt the sequences of operation in a manner that provides building services when and where they are needed, and in the amount that they are needed (Shen, Newsham et al., 2017) based on occupancy and occupant preferences, thus improving energy efficiency, IEQ, and occupant comfort without impacting usability and perceived control for the occupants. In parallel, this data could be used to reinforce human-building interaction by giving feedback to occupants about the IEQ and energy consequences of their behaviour and engaging them to energy efficient building systems control for a healthy environment. Park, Ouf et al. (2019) provides a review of over 35 published field studies which document the viability of various OCCs which attempt to derive setpoints and schedules for HVAC equipment and lighting controls based on occupancy and occupant preferences. They grouped these OCCs as either occupant behaviour- or occupancy-centric. The former adjusts the indoor environment based on occupants' preferences that are learned either actively or passively; active preference learning is achieved by soliciting occupants' feedback explicitly through an interface (e.g., smartphones or wearables), while passive preference learning is achieved by monitoring occupants' interactions with the buildings' environmental control systems (e.g., thermostats or lighting switches) and determining their preferred environmental conditions implicitly. Occupancy-centric controls, on the other hand, adjust the indoor environment based on either the presence/absence or number of occupants (e.g., turning off equipment or using a setback when spaces are unoccupied). In both cases, the data needed to inform the controls and the sequences of operation can be gathered from proprietary sensing technologies, leveraged from existing sensors already present in the building for other purposes, or determined using a collection of sensors and datatypes via sensor fusion. Additionally, data regarding occupant satisfaction and overall system performance can be gleaned from qualitative sources such as surveys and, increasingly, from emerging datasets like computerized maintenance management systems (CMMS).

Figure 7-1 proposes a framework for (OCC) by illustrating its contextual processes within the built environment. This model includes four types of energy, mass, and information transfers that take place between the indoor and outdoor environments, occupants, and various building systems, primarily heating, ventilation, and air conditioning (HVAC), windows, and lighting systems, as indicated by the colored arrows. These systems can actively transport mass, such as fresh air, and energy in the form of heat or light, or they can passively regulate the energy exchange between the indoor and outdoor environments, as with windows and blinds. In the former scenario, energy generation is required, while in the latter, the energy expenditure from the occupants is utilized. These processes could lead to energy/fuel consumption and impact the quality of the indoor environment. Along with the outdoor conditions, these factors act as stimuli that prompt the occupants' actions and perceptions (Schweiker, Ampatzi et al., 2020). Additional stimuli for occupants include interactions with other occupants and information regarding the building's operation, conveyed via visual displays (either fixed or app-based). The information necessary for OCC may be derived from four types of data, represented by the following sensing points: occupants' presence, movement, performance (physiological and psychological data), well-being, indoor environmental quality (IEQ) variables, human-interface interactions, and energy consumption. Moreover, OCC could benefit from actively involving the occupants in judicious control, achieved by sharing relevant information with them through, for instance, visual displays or well-designed interfaces (Day, McIlvennie et al., 2020). This could inspire the occupants to take action themselves by adapting their behaviours, such as changing their clothing or consuming cold/warm beverages, thereby expanding the range of thermal comfort conditions and reducing energy consumption (Nicol, Rijal et al., 2022).

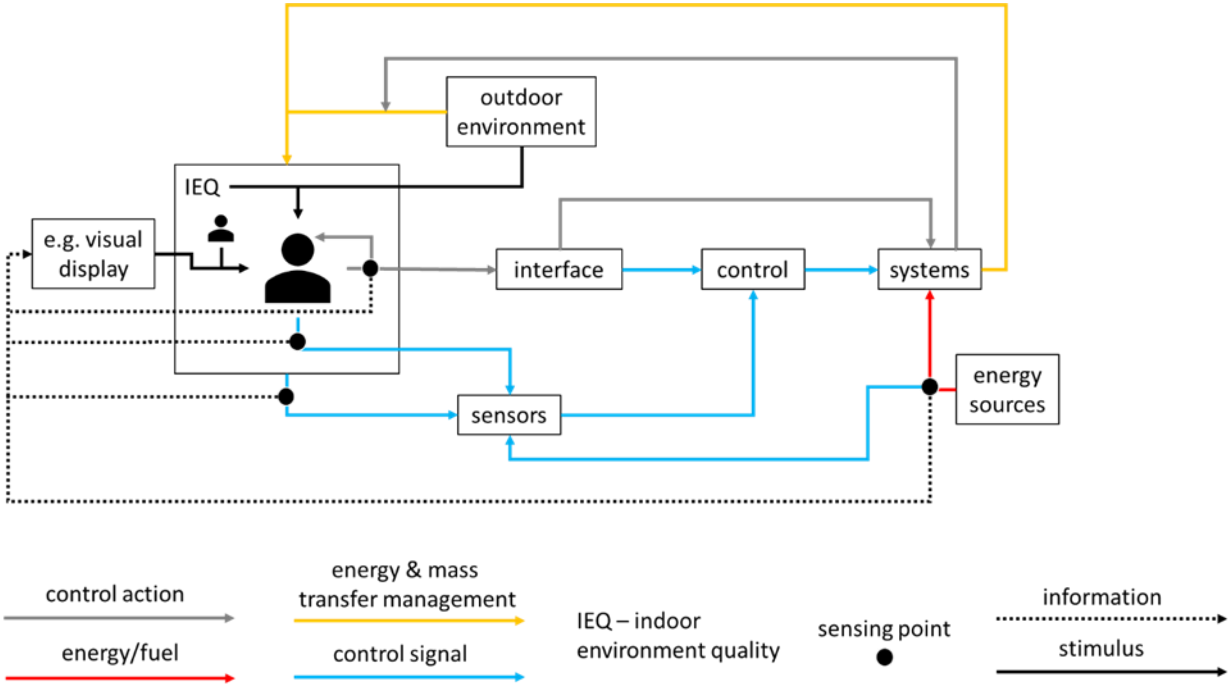


Figure 7-1: Framework for OCC implementation in built environment. OCC is based on systems control using data from sensing points and could also engage occupants by presenting them collected data in relevant way

By this definition, OCC covers a wide swath of interventions with a range of complexities that can be performed to improve the built environment for occupants. For example, it could be argued that an occupant simply opening a window to mitigate thermal discomfort is an occupant-centric operation. A ‘smart’ thermostat with integrated motion-detection capabilities can infer if a home is unoccupied and apply a temperature setback of several degrees to reduce energy use as a form of OCC. A single-occupant office may record illuminance readings and an occupant’s interactions with the light switch to determine what lighting level results in the lowest rate of interaction with the light switch and, implicitly, what lighting level the occupant prefers. Alternatively, an application on a smartwatch could periodically poll the occupant about their satisfaction with the lighting levels instantaneously to gather the same data explicitly. This would allow for artificial lighting to be reduced when natural light can meet or exceed the occupant’s preferred illuminance, increasing both occupant comfort and energy savings via this occupant behaviour-centric control (Gilani and O'Brien, 2018).

While some OCCs have become relatively commonplace (e.g., demand-controlled ventilation (DCV)), widespread adoption of OCC at scale has yet to be realized (Hobson, Huchuk et al., 2021). However, emerging software and hardware for sensing, data-archiving, and control, continued advancements in data mining tools and techniques, and demonstrable savings from a growing number of case studies have all contributed to an increased interest in OCC and operation by practitioners. For example, the ASHRAE Handbook of HVAC Applications (ASHRAE 2019) now includes a chapter devoted to OCC. At the same time, enterprise-grade commercial solutions for OCC applications have begun to emerge. It is likely that the rate of adoption of technologies and strategies that enable OCC will increase dramatically as the benefits to occupant comfort, productivity, and well-being become increasingly clear.

7.3. Occupant-centric controls taxonomy

As OCC is enabled largely by sensors and data, the categories of OCC can be related back to quantitative occupant-related data available in a building. Based on the framework introduced by Melfi, Rosenblum et al. (2011) , data relating to building occupants can be grouped into the occupant, spatial., and temporal resolutions. The occupant resolution can be further subdivided into four grades: presence, count, activity, and identity. Presence data enables learning binary patterns of space use, which can be used for scheduling the availability of building services (e.g., automatically turning lighting or HVAC equipment off when a space is empty and unlikely to be occupied in the immediate future). Occupant count data can enable modulation of available building services proportional to the space use intensity (e.g., occupancy-based demand-controlled ventilation, whereby ventilation is reduced or increased depending on how heavily occupied a space is) (Peng, Rysanek et al., 2017, Peng, Rysanek et al., 2018). Occupant activity data (e.g., thermostat use behaviour, comfort feedback solicited through Web, mobile, or wearable applications) enables customization of the delivery of building services for each space type (e.g., learned preferred indoor temperatures for a specific room) (Gunay, O'Brien et al., 2017, Park and Nagy, 2018, Park, Dougherty et al., 2019, Park, Ouf et al., 2019, Peng, Nagy et al., 2019, Park and Nagy, 2020). Occupant identity data can be of practical use if an occupants' location inside a building frequently changes to ensure that the services delivered at their given location match their activity and preferences (e.g., learned preferred indoor temperatures for a specific occupant). The identity grade of occupant data is not as useful in spaces with transient occupancy characteristics as individual occupants do not occupy these spaces frequently or long enough to establish individualized occupant behaviour-centric controls (e.g., airports, hotels, restaurants). It should be noted that there are privacy and security related implications associated with explicitly identifying individual occupants either directly or indirectly. In buildings or spaces that are occupied by the same occupant(s) (e.g., a residence, single- or multi-occupant office spaces with assigned seating, etc.), OCC can be tailored to individual occupants' preferences without the need for explicit identity data. Simply put, monitoring occupants' activities in such spaces yields individualized controls without the need for explicitly identifying the occupant or tracking their movements. These types of data are inherently pseudonymized per General Data Protection Regulation (GDPR, 2016): while the data in each individual building or space can be attributed to the same occupant(s) is not collected. For this reason, the identity grade of occupancy data has not been necessary for OCC in most applications to date (Park, Ouf et al., 2019). These types of data can, however, still be linked back to the individual occupant(s) explicitly using additional information (e.g., seating plans, office directories, etc.). Therefore, any OCC which uses the identify grade of occupant data either directly or indirectly should consider the sensitivity of the data being collected, best practices (e.g., anonymization, pseudonymization, or de-identification), and the prevailing legislation for the jurisdiction in which the OCC will be conducted. Further work on this topic as it relates to OCC should parallel the continually evolving landscape around data and privacy as a whole.

Occupant data grades can be acquired at different spatial resolutions and can broadly be categorized at the system/building-level and room/zone-level resolution. Depending on the building considered, system-level data may not apply to a whole building, but to a subset of zones that are controlled by a single unifying system (e.g., the zones controlled by a single air handling unit (AHU) in a building with multiple AHUs, where the AHU is the 'system' in this context). Similarly, it is not uncommon for multiple rooms to be grouped together as a zone (e.g., multiple rooms controlled by a single variable air volume (VAV) terminal unit, where the multiple rooms are collectively the ‘zone’ in this context). Therefore, when considering the spatial resolution of an OCC, consideration must be given to the granularity of the building’s HVAC systems and lighting equipment. This is why higher spatial resolution (e.g., down to the workstation or sub-room level), while a promising research topic, is not considered in this report; most buildings do not have infrastructure to support OCC at resolutions below the room/zone-level. Generally, because occupants and their preferences are so diverse, energy savings and occupant comfort increase as the spatial resolution of OCC becomes more granular (Gilani, O'Brien et al., 2018). However, occupant data at higher spatial resolutions requires denser sensing and data-collection/storage infrastructure, which increases installation and maintenance costs. The higher burden on controls-integrators that the increasing complexity of high-resolution OCCs brings cannot be discounted. This burden will likely decline as OCC and operation become standardized, such as recent efforts by O’Neill et al. (2017) to incorporate OCCs such as DCV directly into sequences of operation via codes and standards like ASHRAE Guideline 36 (ASHRAE, 2021) .

The temporal resolution at which occupant-related data are collected can vary. For example, monthly energy use data have been used to develop virtual meters for system-level equipment which enables the number of occupants within the system to be estimated (Darwazeh, Gunay et al., 2020). While this may be used to inform the occupancy-centric operation of these equipment, controls-oriented applications (i.e., those which modulate equipment in real- or near real-time based on occupancy and occupant behaviour) typically require data at a sub-hourly resolution for OCC. Similar to the spatial resolution, higher temporal resolution data will increase the burden on building automation systems (BAS) and building energy management systems (BEMS) as the sheer volume of data will increase network traffic and associated infrastructure requirements (e.g., data-collection and storage). Therefore, the selection of timesteps for the collection of occupant-related data should be done carefully. When developing OCCs, especially those that rely on data from multiple sensors or sources, consideration should be given to whether the data are collected concurrently, or if they are offset, how this can be accounted for during controls development.

Considering the above, the following categories can broadly be used to group OCC:

- Category 1 relates to presence/absence at the system/building level.
- Category 2 relates the same to the zone/room level.
- Categories 3 and 4 represent occupant counts at the system/building and zone/room levels, respectively.
- Categories 5 and 6 indicate occupant activities at the system/building and zone/room levels, respectively.

Even categories (2, 4, and 6) correspond to the higher spatial resolution of the zone/room level, while odd categories (1, 3, and 5) correspond to the system/building level. Occupant identity grades and lower spatial resolutions are omitted for the reasons previously discussed. These categories are summarized in Figure 7-2 which is adapted from Gunay, Hobson et al. (2023) .

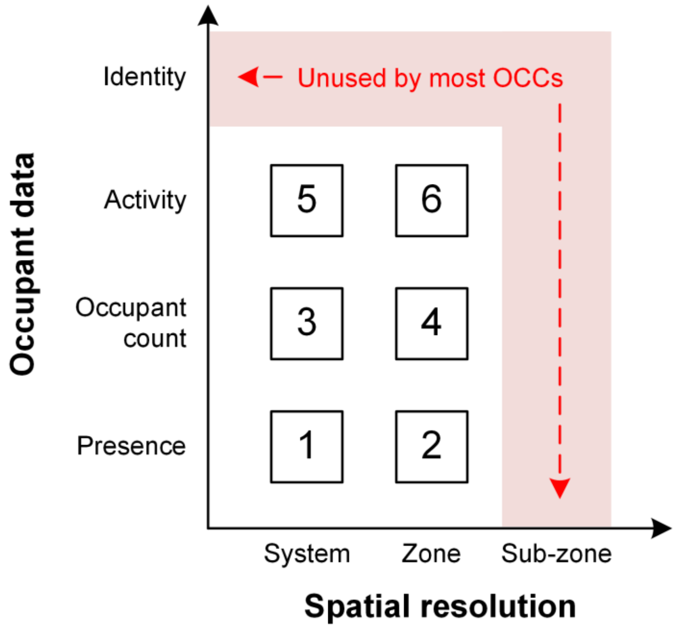


Figure 7-2: Categories of occupant-centric controls (OCCs) based on occupant-related data used and spatial resolution of controls

7.4. The role of building operators for occupant-centric controls

Building operators fulfill various roles and responsibilities covering crucial areas such as maintenance, efficiency, safety, sustainability, and satisfaction. For example, operators are responsible for assessing, scheduling, supervising, and sometimes conducting maintenance activities, including inspections, repairs, and replacements of systems and equipment such as HVAC, electrical., plumbing, and fire safety. In addition, operators strive to optimize energy and water consumption by monitoring usage, identifying areas of excess waste, and implementing reduction measures through upgrading equipment or automation. Furthermore, operators ensure compliance with safety regulations, conduct regular inspections and coordinate with security personnel to develop and implement effective security protocols. Increasingly, operators play a vital role in promoting sustainable practices. For example, they implement recycling programs, reduce waste, monitor water usage, and explore renewable energy options. More importantly, operators are responsible for fostering a pleasant environment for occupants by serving as a point of contact and addressing their needs as necessary.

The climate-adaptive operations movement has already significantly transformed the role of operators by increasing the focus on efficiency and sustainability. Implementing OCC will continue to transform the role by prioritizing customization and personalization of the built environment to meet occupants' specific needs and preferences. Successfully incorporating OCC requires operators to enhance their expertise in advanced technology integration, effective communication, and educational strategies. However, like all paradigm shifts, fundamentally changing the role of operators will be met with several challenges (Srivastava, Awojobi et al., 2020). The first major challenge for operators will be balancing historical quantitative measurements such as standards, cost, and efficiency with modern qualitative measurements, including comfort, productivity, and happiness. To prepare for their future as OCC operators, both tenured and new operators will need adequate training on integrating technology, state-of-the-art communication methods, and educating occupants. Overcoming these existing knowledge gaps will foster healthy operator and occupant relationships critical to transitioning from traditionally managed buildings to OCC buildings.

Technologies such as building information modelling (BIM), CMMS, and facility management systems (FMSs) provide operators with a wealth of fundamental support-related information that can then be collected, analyzed, and integrated into the larger building systems (Chen, Hong et al., 2020). However, training and knowledge is necessary to properly apply these technologies. It is also necessary that organizations value their use and understand the benefits they present in supporting operators' work. Studies show that the opportunity for occupant engagement is either neglected or hindered by the presence of organizational or structural factors despite the operational benefits these systems and the information provides (Valle, Verhulst et al., 2019). Often these factors include operational goals limited to quantitative metrics such as cost and emissions. When these technologies are affordable, durable, maintainable, and easily integrated, they help operators achieve these quantitative goals. Once these goals are met, operators can overcome structural barriers to dedicate more time and resources to the human-facing aspects of their job, such as fostering a healthy relationship with occupants while also meeting qualitative goals. However, for those technologies a key component of a healthy relationship is communication. Unfortunately, existing communication methods between operators and occupants are poorly implemented, resulting in broken information feedback loops leading to both poor building performance and occupant dissatisfaction (Arens and Brown, 2012). For occupants and operators, advanced communication systems and methods that promote regular, direct, and electronically tracked feedback mechanisms help foster a healthy relationship (Ruiz, Day et al., 2022). These systems include but are not limited to post-occupancy evaluations (Boissonneault and Peters, 2023), occupant voting (Khan, Kolarik et al., 2020), and occupant wearables (Gao, Marschall et al., 2022). As occupants provide feedback, operators can make decisions that benefit both occupants and operation without major detriment to one or the other.

However, communication is not limited to feedback. Operators must also provide occupants with adequate education by hosting training sessions and providing resources on technology and their built environment to encourage occupant autonomy without negative impacts on operation. For example, window signaling methods indicate when occupants can and cannot open windows in mixed-mode ventilation systems. Occupants who are educated about the window signaling system, as well as the personal and environmental benefits of following it, are more likely to participate in using it and using it properly (Ackerly, 2012). By proactively educating occupants on how to interact with the system positively, operators mitigate instances where occupants negatively interact with the system where they may cause discomfort to their peers, excess energy use, or harm to the system. Occupants and operators must work together for OCC to be successful.

Another challenge in changing the role of operators when adopting OCC is that there are an insufficient number of operators entering the field to account for the high rate of retirement that will occur in the next ten to fifteen years (Sullivan, Georgoulis et al., 2010). This can be attributed to the limited number of formal academic programs and training specifically aimed at training operators. Expanding access to certifications, training, and education is a critical component of adopting OCC and preparing operators for the changes OCC brings to the operator's role. However, the lack of training and education opportunities is also associated with a lack of guidelines and standards developed and tested to effectively help operators to implement OCC worldwide. Studies that demonstrate ways of implementing and overcoming barriers need to be expanded to create a consolidated knowledge base for these reference materials (André, Bandurski et al., 2023).

7.5. Simulation of occupant-centric controls for building controls

OCC performance is subject to several sources of uncertainty which include typical culprits, such as weather fluctuations and such impact to HVAC operations and envelope performance. However, occupant preferences and OCC configurational settings, especially the selection of hyperparameter values if machine learning models are used, can have a more significant effect on OCC performance (Ouf, Park et al., 2021). OCC hyperparameter tuning is typically done through trial-and-error at the expense of occupant comfort and energy savings potential., leading to loss of stakeholder confidence in OCC solutions (Naylor, Gillott et al., 2018, Park, Ouf et al., 2019). This is also constrained by other logistical and cost-related challenges, such as the limited number of rooms with near identical conditions in which OCC can be tested, as well as concerns and hesitation from facility operators towards adopting new control strategies (Xie, Li et al., 2020, Zadeh and Ouf, 2022). These are the main barriers to implement OCC for actual building systems (Park, Dougherty et al., 2019, Park, Ouf et al., 2019)

To this end, building performance simulation offers a flexible environment to investigate alternative OCC formulations and assess their impact on energy performance and indoor environmental quality (Yang, Bandyopadhyay et al., 2022). However, the integration of OCC in building simulations is not a straightforward process. While typical building simulation inputs with regards to building design parameters are relatively straightforward, the way in which occupancy, occupant behaviour and OCC is represented in building simulation is not trivial. Several approaches have been presented in the literature to achieve this integration, which are summarized in Figure 7-3. In general, OCC simulations can be categorized based on the way in which occupants and their interactions with building systems are integrated in the simulation. The first category relies on identifying occupant-related metrics offline by analyzing historical data which are then used as inputs for OCC simulations. The second category focuses on integrating models to represent occupancy and occupancy-building interactions, which influence OCC operations at each simulation time-step.

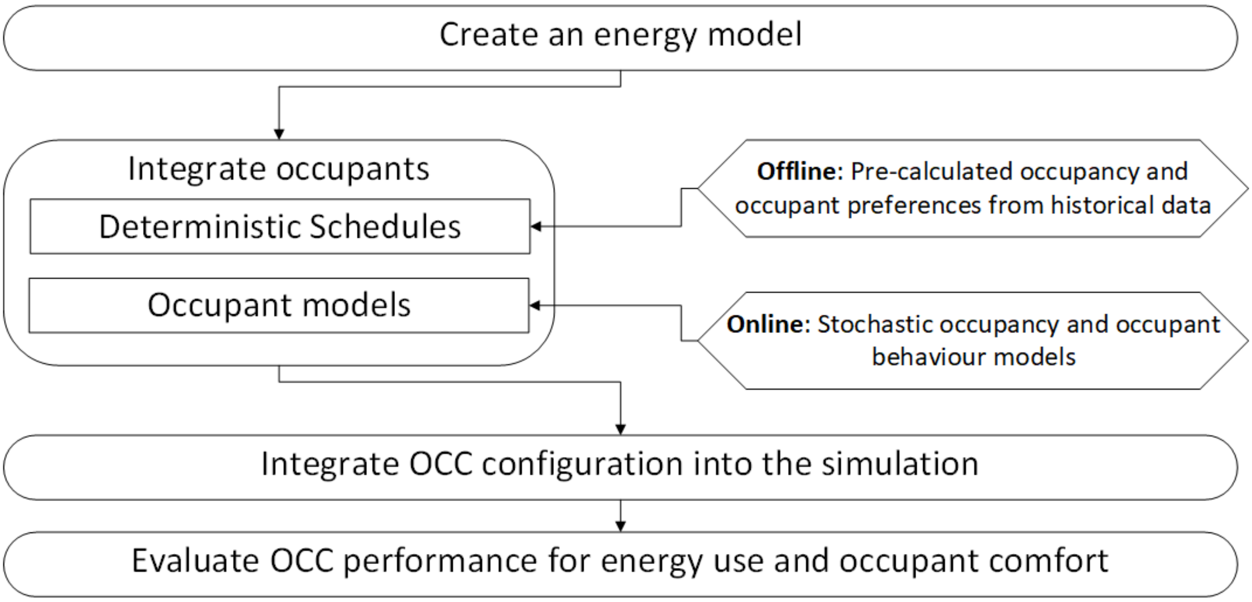


Figure 7-3: Overview of simulation-based approaches for OCC

The main advantage of the first simulation approach with offline occupant-related inputs is its practicality and relatively less complicated workflows. For example, Hobson, Huchuk et al. (2021) introduced a library of OCC functions in R, which leverage building sensor data to identify five different occupancy- and occupant behaviour-centric control-oriented metrics (e.g., presence/absence times at the building and zone levels), which were integrated into building simulations. This was demonstrated using BAS data collected from 29 private offices, then several OCC strategies were simulated, showing that the energy use and thermal discomfort could be reduced by up to 37% and 65%, respectively, when OCCs are implemented. An alternative approach for OCC simulation was also presented by Pang, Chen et al. (2021) , who quantified potential nationwide energy savings due to implementing occupant presence and occupant count sensing OCCs for ventilation in large hotels. They modified occupancy schedules in building simulations based on previous data on hotel occupancy patterns to provide a more realistic representation of hotel occupancy. Based on simulations in 19 different climate zones, they showed that HVAC energy savings varied between 24 – 58%, with occupant presence sensing, which increased by an additional 5 – 15% when using occupant counting sensors (Pang, Chen et al., 2021).

Since OCCs require human-building interactions, the second OCC simulation approach relies on coupling detailed occupant behaviour models with building simulations. These models may represent both adaptive and non-adaptive behaviours; the latter are mainly related to schedule factors (e.g., occupancy (absence/presence), and equipment usage). On the other hand, adaptive behaviours are defined as actual responses of internal or external stimuli (Zhao, Lam et al., 2016, Hong, Yan et al., 2017). For example, occupants who are adaptive to their indoor environments can control thermostats, light switches, and windows to adjust their environment (Gunay, O'Brien et al., 2016). To the best of our knowledge, few studies entailed coupling such adaptive occupant behaviour models in OCC simulation. Ouf, Park et al. (2021) introduced a workflow for such integration, which was tested in a case-study to simulate OCCs for lighting and heating/cooling setpoint adjustments in a single office under various occupant types, as well as OCC settings and design configurations. Zadeh and Ouf (2022) leveraged this workflow to optimize OCC hyperparameters then identify configurational settings and design parameters that minimize energy consumption and maximize occupant comfort under various occupant scenarios. de Vries, Loonen et al. (2021) used a different approach by mapping predicted occupant comfort to sensor measurements, which were represented in a simulation environment for lighting and blinds control to minimize glare discomfort as well as energy use. In a different study, Elehwany (2023) used the Python API within EnergyPlus to represent thermostat interactions and implement a reinforcement learning algorithm that identifies preferred set-points and adjusts them accordingly, thus reducing occupant interactions as well as energy use. Overall, these studies demonstrated the advantages of fully representing OCC operations in a simulation environment, which allows for exploring their full potential in ways that may not be feasible in field implementations.

7.6. The role of occupant-centric comfort in residential demand response programs

Traditional residential demand response (DR) programs aim to shed peak electric demand on the grid through direct-load control of home HVAC systems (Roth and Reyna, 2019). Despite some residential DR programs resulting in 30% occupant overrides and a 30% reduction in the program's energy savings capacity, DR programs currently do not include occupant behaviour or comfort models in their control strategy (Seiden, Olig et al., 2017). This lack of OCC-integrated DR control results in these programs failing to meet their peak shaving goals, threatens reliability of the grid, and places large financial penalties on the DR provider (Goetzler, Guernsey et al., 2019). When integrated with DR, and grid-interactive efficient buildings (GEBs) generally, the value of OCC is amplified from the scale of a single building to the scale of an entire regional power grid. This magnified value in turn magnifies the stakes for getting OCC right.

Recent research has attempted to understand underlying dynamics of occupant behaviour in pursuit of informing future OCC-integrated DR programs. Current occupant models have looked to understand DR occupant override behaviour based on the accumulation of thermal frustration, noting the significance of lagged occupant response to automated DR thermostat setbacks (Kane and Sharma, 2019). These data-driven models show that the time to occupant override is inversely and exponentially related to the magnitude of the setpoint override. These findings have the potential to improve the reliability of DR programs by aiding in the prediction of when and by how much occupants will override DR controls. Additionally, these findings can help inform the design of future DR programs to balance the occupants' need for a thermally satisfactory environment and the grid's need for increased magnitude and duration of load flexibility. In addition to developing DR behaviour models, the standard ASHRAE Standard 55 thermal comfort models have been analyzed to explore their potential application in the context of DR. This research has revealed that the wide spatial temperature variation common in residential buildings is a major barrier to using these existing models for DR. It was found that there was an average spatial temperature variation of approximately 2°C with a standard deviation of 1.2°C across the homes studied. Given that indoor temperature is an input parameter of both the Predicted Mean Vote model and the Adaptive Thermal Comfort model, this wide temperature range increases the uncertainty of the models' predictions as the actual temperature an occupant is experiencing remains unknown. This research further found that while the adaptive thermal comfort model is sufficiently good at predicting thermal satisfaction of occupants, it is not able to accurately predict thermal dissatisfaction. It was found that 84.8% of the dissatisfied votes occurred within the 80% acceptability range. This suggests that thermal dissatisfaction models, rather than satisfaction models may better suit the needs of DR controls. Another barrier to using the standard ASHRAE 55 thermal comfort models is related to the temporal variation of the temperature during DR. These models do not account for the psychophysiological phenomena of thermal overshoot and thermal alliesthesia affecting thermal comfort during the induced dynamic thermal conditions (Vellei, De Dear et al., 2021). As such, they do not provide any indication on how to better control DR for increasing occupant comfort and pleasure.

Thermal discomfort is not the only reason for unreliable DR programs. One study found that occupant routines related to thermostat interactions were the most important drivers of overrides, as occupants often manually changed their setpoint at the same time of day regardless of whether it coincided with a DR event or not (Sarran, Gunay et al., 2021). However, the study also showed that the likelihood to override a DR event decreased after participants had been exposed to several events. Another related study conducted with the same dataset highlighted the need to study occupant behaviour and OCC not only during the DR event but also before and after it. In the studied dataset, the occupants received a notification at least a day ahead informing them that the DR event was occurring. Approximately one in four users manually adjusted the setpoint temperature before the DR event, while only 13% of the DR events were interrupted by a user's adjustment. Among those DR events, different types of rebound effects in terms of intensity and durations were observed. These rebound effects could only be partially explained in terms of physical thermal aspects (Tomat, Vellei et al., 2022). Finally, studies have suggested that participants' lack of familiarity with DR programs and smart thermostats can result in program disengagement (Sarran, Gunay et al., 2021). At times, this lack of familiarity can also lead to diminished energy and financial savings as occupants may over-correct when manually overriding thermostat controls. These findings suggest that an important feature of OCC is not just intelligent control systems, but also the strategic sharing of information about these systems with building occupants.

While DR programs are inherently motivated by the periodic need for load reduction, understanding occupant behaviour is the key to deploying reliable DR programs. It has been shown that manual setpoint change behaviour of thermostats can differ significantly between homes in terms of setpoint change frequency, mean setpoint value and the spread of setpoint values. These findings suggest that the development of unique control strategies could be advantageous to the reliability of DR. Recent studies have suggested that personalized models could be tailored to a particular occupant behaviour pattern by clustering similar behaviour together. This clustering would allow for future DR control strategies to address the inherent diversity of occupant behaviour which is especially relevant when scaling the implementation of OCC DR at larger district or regional scales.

7.7. The role of occupant-centric controls during COVID-19

At the beginning of 2020, the world was thrust into an unprecedented crisis in the form of the global COVID-19 pandemic that has forever changed how we live, work, and play. Health and well-being were brought to the forefront of every aspect of life. Building operations were no exception as buildings - by their very nature - are spaces in which people congregate, which introduces potential for the spread of viruses via infectious aerosols. Consequently, indoor air quality (IAQ) has become pervasive in the minds of the general public in a way that has not been seen since the rise of sick building syndrome nearly five decades ago. This paradigm-shift has fundamentally changed the way buildings are used, with the line between home and work blurring as flexible work schedules and remote work options become increasingly prevalent. Although this transition away from rigid work schedules had been underway for the past two decades (Zeytinoglu, Cooke et al., 2009), the full momentum had not been realized until the COVID-19 pandemic. For example, over an eleven-year period between 2006 and 2017, the number of Canadian office workers who spent less than three days a week in their physical workplace rose to 47%; during the COVID-19 pandemic, the number of office workers working fully from home spiked to over 80% in a matter of weeks (Statistics Canada, 2021). While the return to work has varied across countries and industries, it is widely regarded that occupancy, especially in office buildings, will likely never return to pre-pandemic levels.

As a result of these changes in when and where people were working, the energy use patterns in buildings were expected to change. Intuitively, if an office building is unoccupied, energy use should decrease correspondingly, while residential energy use should increase. While the latter increase in residential energy use was observed, recent research has shown that energy use in many commercial buildings remained relatively unchanged in the early months and even over the course of the pandemic despite a drastic drop in occupancy in many jurisdictions. For example, the consumption of electricity and natural gas by the commercial building sector during the initial months of the pandemic in the United States fell by just 4.7% and 2.0%, respectively, compared to pre-pandemic levels (U.S. Energy Information Administration, 2020). This eye-opening experience has highlighted flaws in the way we traditionally operate our buildings, and many have adopted a new normal (i.e., hybrid, remote, and in-person work) for which current operational practices are still unprepared for.

As discussed in Question 1, OCC has revealed itself as a promising approach for controlling and operating buildings based on occupancy and occupant preferences. The benefits of such an operational approach in this new paradigm (i.e., with sparser and less-predictable occupancy) are self-evident. For example, Hobson, Abuimara et al. (2021) also found that an office building with a system-level occupancy-based ventilation OCC scheme was able to save 43% and 17% on heating and cooling energy, respectively, after the building was largely emptied in the initial months of the pandemic, compared to pre-pandemic energy use. In brief, buildings with OCC are inherently more adaptable to the variable occupancy that will be seen in many buildings moving forward as they can increase or decrease the services delivered to a space based on occupant-related data.

While few buildings currently have OCC implemented, OCC utilizes sensors and data that have been available in buildings pre-pandemic and continue to be available. The data streams that can be leveraged range from the most basic data available in all buildings (e.g., bulk-metered energy data for an entire building) to data from the most detailed and granular sensor networks (e.g., occupant-counting cameras in each zone), and from implicit sources (e.g., occupants' impact on data streams such as CO_2 concentrations, energy use data, thermostat interactions, etc.) to explicit sources (e.g., dedicated occupant counting/sensing technologies, prompting occupant feedback via wearables, etc.). OCC can be developed based on a single available data stream, as well as by combining data streams via various machine learning methods and sensor fusion (Dodier, Henze et al., 2006). The use of sensor fusion in particular can allow for occupancy and occupant-preference to be inferred by leveraging the implicit sources commonly available in existing buildings, allowing for low- or no-cost ‘opportunistic’ (Melfi, Rosenblum et al., 2011) approaches to acquiring these data for OCC purposes (Hobson, Lowcay et al., 2019). During the pandemic, these data became invaluable for estimating building occupancy levels to comply with public health requirements (e.g., social distancing, minimum ventilation rates, etc.). This represented perhaps the largest leap in practitioner interest in the field of sensor fusion and occupant-related data to date. With the increased knowledge of the potential power that these data hold, the importance of implementing OCC in buildings moving forward may begin to be realized. It should be noted that a lack of OCC adoption during the pandemic (and in general) may not be due to a lack of willingness on the part of building operations personnel, but rather due to limitations in the systems and/or controls of their buildings which prohibit such interventions.

Much of the benefit of OCC explored so far relates to saving energy when buildings are partially or fully unoccupied, however, OCC also benefits occupant comfort by providing services when, where, and in the amount that they are needed as tailored to occupants (Shen, Newsham et al., 2017). Such OCCs may even result in increased energy use where demands for service are high, such as in instances during the pandemic when increased outdoor airflow rates were mandated by ASHRAE (Schoen, 2020); this increase in energy use is undeniably justifiable for the purpose of safeguarding human health. While occupants have been shown to be satisfied in buildings with improved IEQ and IAQ (Newsham, Veitch et al., 2018) as provided by OCC, directly quantifying metrics such as well-being and productivity into the development and deployment of OCC is an area of research that is actively underway. The emphasis on this holistic understanding of OCC and operations that considers well-being explicitly likely represents the future of this topic within the research community.

7.8. Classification of occupant-centric controls case studies

Findings from the literature review conducted as part of the Annex 79 research program and briefly presented in the previous questions revealed various case studies on OCC in buildings (Park, Ouf et al., 2019). In an effort to classify the different types of OCC implementations found in the extant literature, we propose the classification categories illustrated in Figure 7-4. On the first level, a distinction is made between *observation* and *intervention-based* studies. An observation-based study is one that collects data in a case study and seeks to explore those data for general insights. No comparisons are made "within" the case study, but comparisons might be made with standards or other studies. An intervention-based study includes a comparison between a control/test group *or* a before/after condition. In both cases, the study can be centered around humans (occupants and/or operators) or systems (HVAC, sensors, lighting, interfaces, etc.).

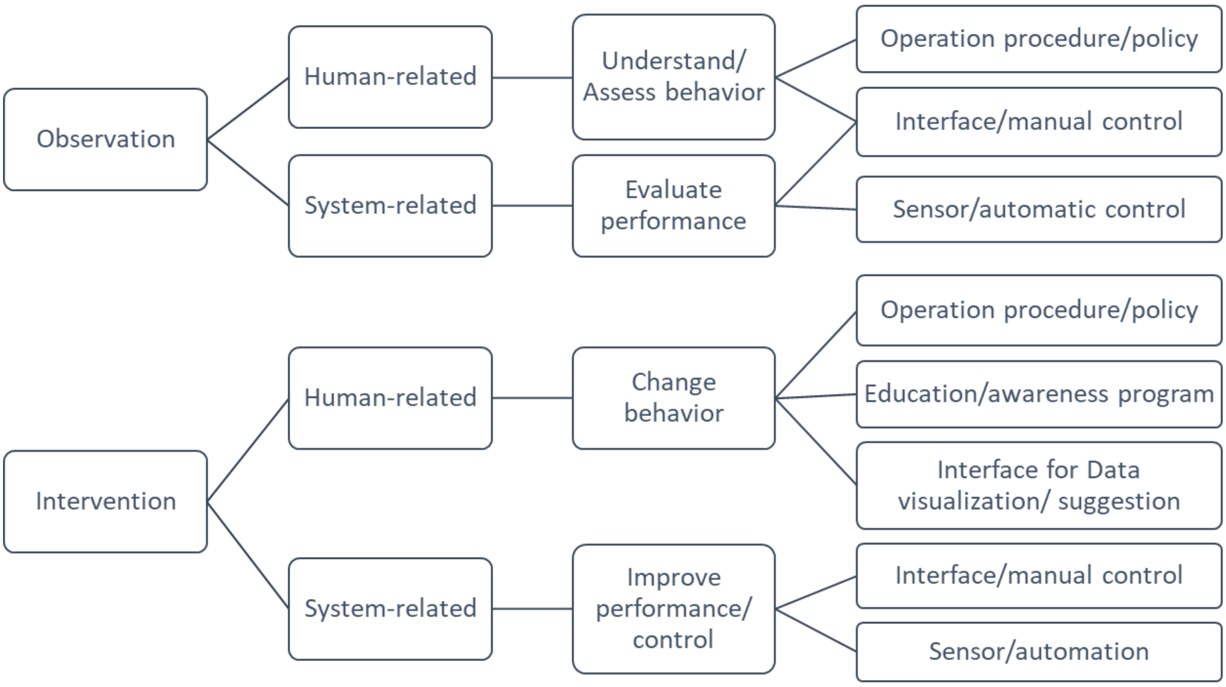


Figure 7-4: Classifications for OCC studies

On the second level, case studies can be *human-related* or *system-related*. In general., *human-related observation* studies try to understand human behaviour and assess its impact on building performance as well as the occupants' own responses, such as their satisfaction. *System-related observation studies* evaluate the effectiveness of available systems, controls, and interfaces. Two approaches are identified for *human-related observation* studies. Case studies may analyze either an existing operation procedure or policy, or an interface or manual control. In many cases, human interaction with the building happens through occupant-control interaction. Thus, depending on whether the study is more focused on the human side or the control side, evaluation and analysis of an interface or manual control may also be part of a *system-related observation* study. Next to this, *system-related observation studies* may evaluate the performance of an existing sensor-based automation control, another type of automation system, or even a manual control interface.

Intervention studies usually aim to characterize how a specific technology can improve performance. *Human-related intervention* studies commonly try to influence occupant behaviour to improve building operations. *System-related intervention* studies on the other hand, typically aim to achieve improvements by changing or optimizing the system (HVAC, lighting, etc.) or system control. Three approaches are identified for *human-related intervention* studies. Firstly, to achieve a behaviour change in operators or occupants, the policy or operation procedure may be changed. For example, control limitations may be imposed, and a schedule change or a new communication approach may be implemented. A second approach to achieving behaviour change is through an awareness campaign or other educational-based intervention to stimulate occupants to change their behaviour based on the information provided, and increase awareness of their impact on building performance (Jiang and Tovey, 2009). The third approach is through interface design, be it to provide information for occupants to make an informed decision, or to suggest behavioural changes through notifications. Examples are the use of notification to prompt/nudge occupants the best moment to open the windows (Li, Menassa et al., 2017) or real-time space distribution of occupants' thermal perception within a space to help operators to control the environment (Shahzad, Calautit et al., 2019).

For *system-related interventions*, two approaches were identified. Firstly, performance may be improved by changing the system or type of manual control implemented. Examples include case studies on improving a control or interface to make it easier to use, adding controls for occupants, like a personal conditioning system (André, De Vecchi et al., 2020), or imposing constraints on manual control such as resetting set-point temperatures. Secondly, *system-related intervention* studies may opt for an automation strategy, which may be schedule-based or include sensor feedback. For example, a lighting system may be installed that regulates the luminance flux of light bulbs based on available daylight measured through a daylight sensor (Bellia, Fragliasso et al., 2016). Automation strategies may either be reactive or predictive. Reactive control implements a change in system control following an event or sensor measurement. Alternatively, control may be predictive, and this means that a system control algorithm adapts to a predicted event or outcome based on sensor information collected in real-time. Examples include model predictive control algorithms (Drgoňa, Arroyo et al., 2020).

A variety of approaches to OCC have been evaluated in simulation- or field-based studies. The impact of such approaches varies depending on building and occupant characteristics, and the baseline to which they are compared (Park, Ouf et al., 2019). Knowledge of available systems, interfaces, procedures and space characteristics is therefore crucial to understanding the study conditions. In research, this knowledge is usually built by analyzing collected data. Observational studies are important in that sense, as they can help with understanding occupant patterns or identifying issues related to the implemented system. Therefore, observation studies can underline improvement opportunities that can later be tested in an intervention study, showing a behaviour or system diagnostic. The other important application of observation studies is the development of better models to represent occupant behaviour in a space with OCC, which sometimes differs from ideal simulation conditions or expected relations. The last branch of Figure 4 provides an overview of possible strategies depending on the study focus. Compared to observation studies, intervention studies are typically more challenging to set up, as a new system or control may need to be implemented, and occupants and operators need to agree to the testing conditions, which may affect building use and the evaluation of the environment. These types of studies are, however, necessary for the validation of OCC strategies, as they allow for pre-post performance comparison. Because of the differences in building and occupant characteristics, baselines used in the comparisons, and differences in study objectives and results, determining the best-case study approaches is difficult, and case dependent. It is not possible to rank the strategies, as each of them will be applicable to a given situation. Furthermore, the above-noted approaches may also be combined and emerge as complementary. Therefore, the aim of the study should be clearly defined so the applicable approach that will bring the expected outcomes can be identified. In this sense, with the objective of further providing useful references on implemented OCC approaches, an online survey was disseminated to collect case studies and compose a reference library. An overview is presented in the next section.

7.9. Case studies of occupant-centric controls

An online survey has been designed and distributed among the research community with the aim of creating a comprehensive library of case studies that can serve as a reference for future research. A case study in this context is defined as “a deployment of a single set of occupant-centric technologies, techniques, and/or policies across a real-world spatial context (single zone all the way up to a campus of buildings) for a certain period of time”. The survey questions were developed to be able to cover both observation and intervention studies. The information was grouped by a) building type, occupant demographic, operators and policies, b) the building system that is being controlled, c) the type of data that is being collected, d) the type of strategy, which may be focused on occupant-, operator-, or building automation-based solutions, e) machine learning deployments, and f) the degree of occupant centeredness. Figure 7-5 shows the results of four main questions: S1) location, S2) the focus of study and data gathered, Q3) occupant types and Q4) building type. As of January 2023, the library includes 54 case studies from around the world.

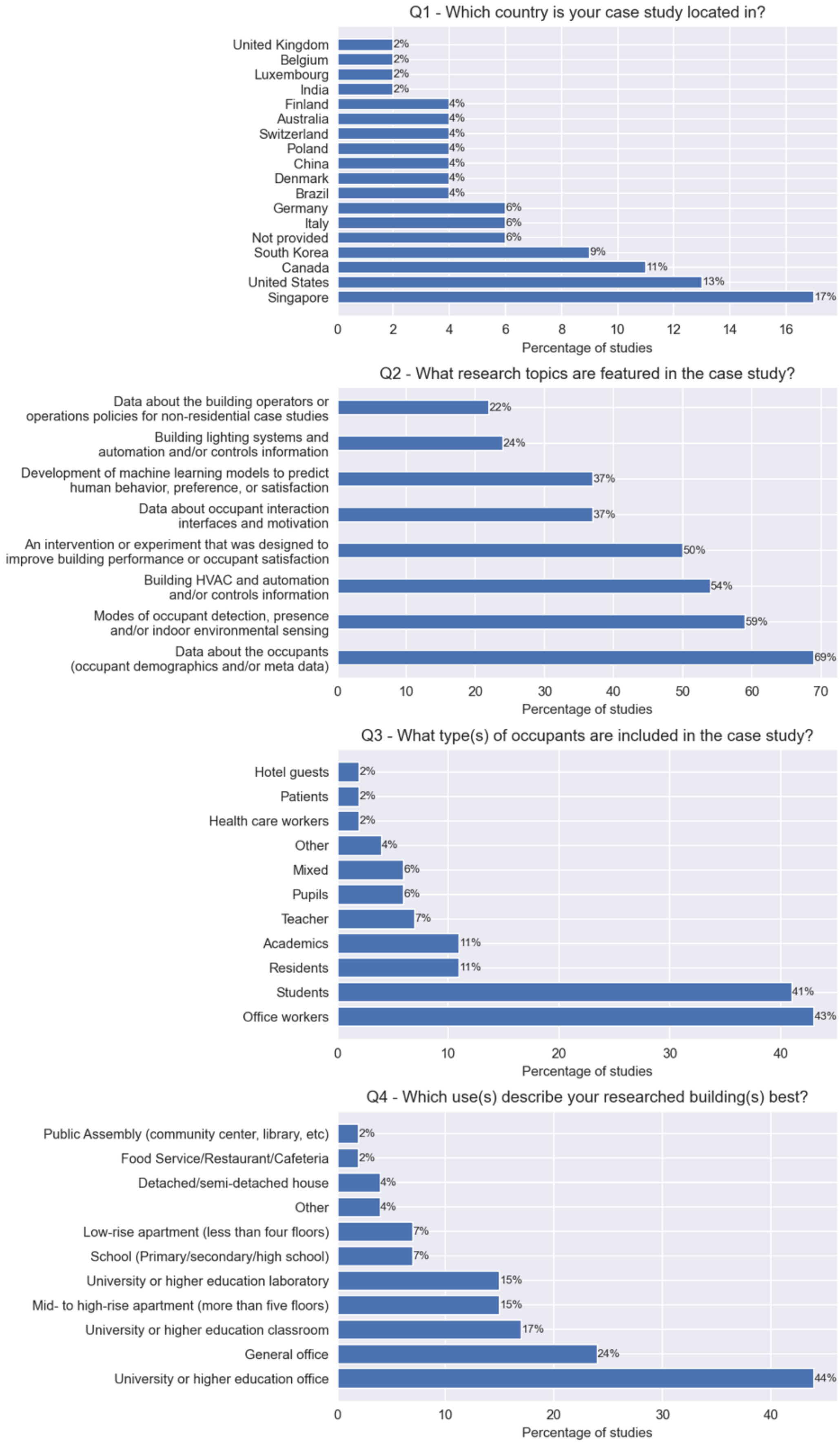


Figure 7-5: Library case study characteristics

The Q1 listed in Figure 7-5 shows the database includes data from worldwide, which indicates OCC is being researched in field studies all over the world. The studies that are featured in this survey are mostly distributed among Europe (31%), Asia (31%) and North America (24%), with additional studies from Oceania and South America (4% each). The high number of Singaporean studies stems from one of the survey planners being located at the National University of Singapore (NUS).

Q2 listed in Figure 7-5 deals with the type of data that is being collected and the methods that are being implemented in the case studies. The recorded studies in this survey are evenly split between intervention and observation studies. Among collected observational studies, 66% can be classified as human-focused as opposed to only 19% of interventional studies (a study was classified as human-focused when it did not include data on either HVAC or lighting systems). Building HVAC systems are much more commonly researched in interventional studies (81%) compared to observational studies (26%), revealing that interventional studies tend to be more system focused.

User interaction interfaces are featured in 37% of all recorded studies, while HVAC systems are investigated in 54% of all studies. This indicates that although most studies collect data on their users (69%), the user's actions to influence the IEQ are often not tracked and are under-represented compared to HVAC systems.

Out of the recorded studies that include residential buildings, only 45% stated that they feature data about the occupant compared to 74% in non-residential studies. This indicates that occupant data is harder to obtain in residential contexts than in public/office settings. The most likely reason for this difference is privacy concerns, which are stricter in private homes.

Q4 listed in Figure 7-5 indicates most of the non-residential studies are university buildings, therefore, university facilities (including different space usage) are the most common typology at which OCC case studies are applied. This probably stems from the ease of access for researchers and also for allowing the test of not ready to use solutions. Although having these benefits, the concentration of case studies in an academic context creates some bias. First, university staff which mostly consists of Ph.D. candidates, postdocs and students are usually concentrated in a limited age range, which is relevant for IEQ perception and behaviour (Wang, de Dear et al., 2018, Mitra, Steinmetz et al., 2020). Second, university staff and students might be more familiar with the research topics of these field studies compared to the general public. This may affect their attitudes, willingness to participate, and prior knowledge. These characteristics of the occupants need to be accounted for when applying research results to different settings.

These initial results highlight some trends in current OCC field study characteristics worldwide. By the inclusion of additional case studies, we expect this database to contribute to future studies, allowing comparisons and giving examples of possible approaches as it becomes public.

7.10. Limits of occupant behaviour sensing and occupant-centric strategies

As we continue to advance and advocate for OCC, it is important to reflect on the intrinsic limits of OCCs in accurately capturing and addressing occupants' needs, as well as to consider the way occupants will understand, perceive, and interact with these new control systems.

7.10.1. The challenges of predicting IEQ perception

IEQ perception does not only depend on environmental variables which can be easily measured. A number of personal (psychological and physiological) and contextual factors also have a determining influence on human perception and needs and are reflected in occupant-building interaction (Hellwig, Teli et al., 2019, Schweiker, Ampatzi et al., 2020). Examples include availability and accessibility of control options, occupants' cultural background, their mental stress level and their opinion of the building management (Hellwig, 2015, Schweiker, Ampatzi et al., 2020). The behavioural uncertainty associated with these factors contributes to an already existing performance gap of modern control systems resulting from the difficulty of creating reliable models of occupant preferences and behaviour. In a recent study, a framework was developed for analyzing anecdotes of occupants' behaviours and experiences from international research projects. It was found that occupants' priorities related to their comfort and personal control in real buildings were not always understood by the researchers, building designers or operators, potentially leading to discomfort and poor energy performance (Sarran, Brackley et al., 2023).

To advance researchers' understanding of occupants' needs, qualitative methodologies such as occupant surveys, open-ended questions, interviews and story collection should be more widely applied in building and energy research, as they constitute a very useful addition to quantitative data collection. They enable a deeper understanding of building occupants and description of the drivers of their behaviour, increasing the chance of success of future occupant-centric building operation strategies (Sovacool, 2014, Bavaresco, D'Oca et al., 2020). Besides, qualitative data can also be collected directly for the purposes of building operation. For instance, such qualitative methodologies have been included in occupant feedback systems in real building operation (Khan, Kolarik et al., 2020, Lassen, 2021). Research has also shown that incorporating qualitative elements in post-occupancy evaluations is essential to improve the building operators' understanding of occupants' preferences and address the discrepancy between intended purpose of building controls and actual usage (Day and O'Brien, 2017). Researchers planning to implement OCCs in real buildings are encouraged to assess their performance via a combination of objective measurements and subjective investigations among occupants and operators.

7.10.2. Automation vs personal control

An important question to be raised when addressing OCCs is whether occupants actually expect specific personalized environments, which can be delivered by a self-learning proactive control system, or rather require more options to reactively control their surroundings in an easy and effective way (Karjalainen, 2013). Control systems can be fully automated, based on a 'human-in-the-loop' approach (Jung and

Jazizadeh, 2019), or provide occupants with control for the purposes of an algorithm tuning process, after which human-in-the-loop control will be bypassed. In the late 1990s, the scholars behind the PROBE post-occupancy evaluation studies already warned researchers and building managers against the temptation of highly complex automated building control strategies for IEQ optimization. They argued that "users are satisficers not optimisers" (Leaman and Bordass, 2001) and that it was more important for them to retain a degree of control on the environment than to achieve optimal conditions thanks to advanced building controls, which according to the study rarely achieved this goal anyways.

In systems that lean more towards automation, or where occupant information is used for algorithm tuning rather than direct control, occupants can also be granted "secondary" control, when they, for example, provide feedback via an interface or address complaints to the facility manager (Hellwig, 2015). As already mentioned in this article, this requires good communication and a trust relationship between occupants and operators. However, such secondary control has the potential to be more stressful than primary control (Johnson, 1974), e.g., an occupant using a thermostat directly. The reason is the time lag between requested change and successful adjustment which is due to the need to rely on others (e.g., facility manager) or algorithms (e.g., OCC). Therefore, the experience of success in the control action might be diminished, leading to a lower level of perceived control and therefore of satisfaction (Hellwig, 2015).

In addition, it is important to address the challenges in serving a diversity of occupants in the same space using an OCC approach. As shown by Schweiker and Wagner (2016) higher numbers of people in rooms decrease perceived control over the indoor environment. On the other hand, among others, higher perceived control reinforces occupants' intention to conform to the norms of sharing environmental control features (Chen, Hong et al., 2020). Some solutions for this situation seem to be Personal Comfort Systems (PCS) (Rawal, Schweiker et al., 2020), which provide control diversification however require additional investment. There is still a need for research to develop guidance for user control in the built environment, e.g., (Hobson, Abuimara et al., 2022) and the development of technology for integrating local manual control to the environment system when they are complementary (André, De Vecchi et al., 2020). IEQ standards include little information about user control requirements, as for example on operable windows (European Committee for Standardization, 2019). However, it has been demanded to include personal control as a design goal into standards (Boerstra, 2010, Hellwig, 2015, Hellwig, Teli et al., 2022).

Personal control over the indoor conditions remains an important driver of occupant satisfaction (Kwon, Remøy et al., 2019, Hellwig, Schweiker et al., 2020, Tamas, Ouf et al., 2020). It is therefore important that future OCCs do not fully take this possibility away from occupants. As stressed in S1 of this article, OCCs should not aim at removing occupants from the decision loop, but rather at modulating operation around their inputs to reduce energy waste and dissatisfaction.

7.10.3. Occupant education, control transparency, and the importance of interfaces

The current literature points to several more areas that are crucial to the success of advanced control strategies (Sarran, Brackley et al., 2023), including information, education and the human-building interface. For instance, providing training to occupants on building systems and controls was shown to increase their satisfaction with IEQ, both in offices (e.g., Day and Gunderson (2015)) and in homes (van der Grijp, van der Woerd et al., 2019). The transparency of the control algorithm is also an important factor of occupants' acceptance: research showed that occupants are more tolerant of automated controls if they know what to expect from them (Karjalainen, 2013).

The building interfaces are particularly crucial., as they are the primary link between users and the building. Day and Heschong (2016) developed a framework to critically analyze building interfaces and controls in a consistent way to evaluate their design, selection, and operation. These ideas were considered in the context of resiliency, unexpected events, and equity in which it is argued that designers must think carefully about interface selection to ensure the health and safety of occupants under extreme conditions such as rolling blackouts, wildfires, and more (Heschong and Day, 2022).

Well-designed interfaces have the potential to increase transparency of the control systems in buildings, and can provide users with the information they need to effectively use their systems (Karjalainen, 2010, Brackley, O'Brien et al., 2021). Furthermore, Hellwig, Teli et al. (2022) proposed a design process for adaptive opportunities for occupants that approaches building design and operation planning through the lens of occupants and takes into account how occupants would want to adapt themselves in case they feel discomfort (Hellwig, Teli et al., 2022). Solutions with redundancy in adaptive opportunities, e.g., sensing and communication interfaces and operable windows, serving diversity among occupants due to their different backgrounds, experiences and capabilities are preferable.

Such human-centric measures could therefore complement sensor-based OCC strategies in order to take into consideration the agency required by occupants to feel in control of their environment, thereby avoiding discomfort and unintended interventions by occupants. This research therefore argues in favour of a stronger focus on detailing the modalities of building operation in the planning phase. Planning for building operation should not only encompass the design of building controls but also the definition of operational strategies that ensure the success of these controls, including training of operators, interface design and information of occupants (Hellwig, Teli et al., 2019).

7.11. Conclusion and outlook for future work

Subtask 4 of the IEA EBC Annex 79 was engaged in assessment of the state of art as well as knowledge generation and dissemination with regard to occupant-centric building control and operation. The literature reviews synthesized key findings from OCC case studies in the residential and commercial sector. The findings overall highlight major methodological inconsistencies in the real-world OCC implementations, particularly their measurement and verification approaches. Subtask 4 also conducted an international survey of building operators to document the current state in OCC use in the field and how building operations staff handle uncertainty regarding occupancy and occupant behaviour in their operational decisions. The group also made significant contributions towards the simulation-aided design and assessment of OCC technology. Various building performance simulation-based OCC implementation workflows have been developed and demonstrated. Subtask 4 worked towards the standardization of the nomenclature and taxonomy of OCC technology as well. A case study descriptors survey was conducted, which documented methodological, algorithmic, and taxonomic commonalities across OCC case studies.

The subtask activities identified a number of potential future research directions. Specifically, the significant growth of Information and Communication Technologies has been the catalyst for OCC development and pilot deployment in existing buildings. Therefore, future research trends will focus on using these advancements to develop more advanced OCC algorithms, especially in applications that enhance buildings' energy flexibility such as DR, as well as storage capabilities that could rely on widespread electric vehicles' adoption for example. While OCC developments generally aim to reduce energy consumption while improving occupant comfort, future research directions will take a more comprehensive approach to comfort that includes occupants' health and well-being, (including mental wellbeing), as well as productivity to improve occupants' overall experience within buildings. Other research trends also investigate different ways of collecting direct occupant feedback, such as using smart phone or watch applications for continuous and real-time data collection instead of making inferences from historical building automation systems' data, which has been the typical approach.

Nevertheless, previous studies show OCC development is not just a technical matter, the comprehension of the relationship between humans and buildings is crucial. The new knowledge from future research should be based on a multidisciplinary approach, joining at least engineering, medicine and social science, as OCC is a kind of socio-technical transition. For successful implementation of promising OCC technologies appropriate standards and design procedures have to be developed to make this approach used worldwide efficiently. Finally, standardized quantitative and qualitative performance metrics should be developed for evaluating any new OCC developments with respect to energy efficiency as well as improving occupant comfort, health, well-being and acceptance of these technologies represents one of the main research directions on this topic.

8. Further outputs and findings

8.1. Cross-subtask activities

Recognizing the importance of multidisciplinary research on specific topic and overlapping themes between the single subtasks, various "cross-subtask activities" were initiated during the working period of Annex 79 which are shortly described in the following sections.

8.1.1. Accounting for occupants in building design and operation practice

Literature suggests that there is inconclusive evidence of the contribution of occupants' behaviour to the energy performance gap, and a potential energy conservation of about 20% by changed occupant behaviour. Based on conclusions from various interviews with building operators, the aim of this activity was to gather information on how occupants are considered in building design and operation and get insights on practitioner's perspective on occupant behaviour consideration in practice.

An online survey among practitioners in different countries was conducted consisting of three parts: (1) background information on the respondents' role (question 1-6), (2) integration of occupant information in the planning process (question 7-25), and (3) use of simulation tools and occupant models (question 26-33). The survey was translated into different languages to be distributed in 12 countries. Overall, 880 surveys were returned of which 440 remained after removing the observations that did not provide any answer to the second section of the survey.

About one third of the respondents saw their expertise in architecture, about one fifth each in building physics and HVAC design, 7% in building information modelling and simulation. About one third worked in companies with less than 10 employees and one quarter in companies with 10 to 49 employees. Typical projects those companies were involved in include new buildings (mentioned by one quarter) and building retrofits (mentioned by one quarter). Simulation services were mentioned by 8%, HVAC design by 12%, architectural design by 18%, facility management by 5% and energy audits by 8%.

Two thirds of the respondents received information about the future occupants from the client or project manager in more than half of the cases, with one fifth stating that they always receive such information and 55% stating that they use simulation tools to evaluate indoor environmental parameters. In case simulation was used, it was for evaluating thermal (42%), visual (31%), acoustic (12%) environment and indoor air quality (15%). If the professional received information about the occupants, the project description contained information regarding requirements on thermal (N=114), visual (N=111), acoustical (N=90) environment and indoor air quality (N=78). The data provided useful insights about role, available information and tools used. Descriptive results were presented and discussed in an interactive session in a workshop at CLIMA2022 conference on 24th May 2022 and the final results were published as a conference paper (Hellwig, Gauthier et al., 2024).

8.1.2. Agent-based modelling

This activity intended to advance agent-based modelling (ABM) for integration with building performance simulation to evaluate the impact of occupants on building design and operation and vice versa. The first part of this activity focused on identifying and integrating behavioural theories into ABM to improve the modelling of occupant decision-making in terms of their activities, comfort preferences, and human-building interactions. A literature review on the current trends and approaches of representing occupants in ABM for buildings' energy and indoor environment-related applications identified that occupant-centric ABM applications frequently rely on sparse domain knowledge and limited theoretical foundation and there exists a paucity of empirically validated knowledge concerning processes related to occupants' perception, evaluation, and behaviour. Further, an examination of instances of behavioural theory applications for energy performance within buildings was conducted to synthesize multiple theories as a basis for a common ontology of occupant behaviour in buildings. However, the past applications of behavioural theories in building-related inquiries have not resulted in comprehensive, consistent, and versatile ontologies toward shared representations of building occupants.

This knowledge gap led to the development of a high-level theory to provide a general explanatory framework toward a more suitable perspective of occupants' control-oriented actions in indoor environments. The key elements of the theory are represented in form of a schema, illustrated in Figure 8-1, and act as the reference framework for the agent-based occupant representation. The pragmatic theory can systematically guide the formulation of occupant-related ontologies and their instantiation in computational applications related to building design, operation, and evaluation. The outcomes of this effort were two journal articles and three peer-reviewed conference papers. The journal articles include a review paper on current trends and approaches for representing occupants in ABM (Berger and Mahdavi, 2020) and a paper on the exploration of behavioural models as the potential knowledge base for the definition of ontologically streamlined behavioural patterns (Mahdavi, Bochukova et al., 2021). The conference papers expand upon possible paths for developing an occupant-centric ontology for OB representation (Mahdavi, Bochukova et al., 2021), review findings focusing on the methods used in ABM for the representation of occupants' behaviour and their environment (Berger and Mahdavi, 2021), and an illustrative case study to explore the potential and current challenges of ABM in building performance simulation (Berger, Regnath et al., 2022).

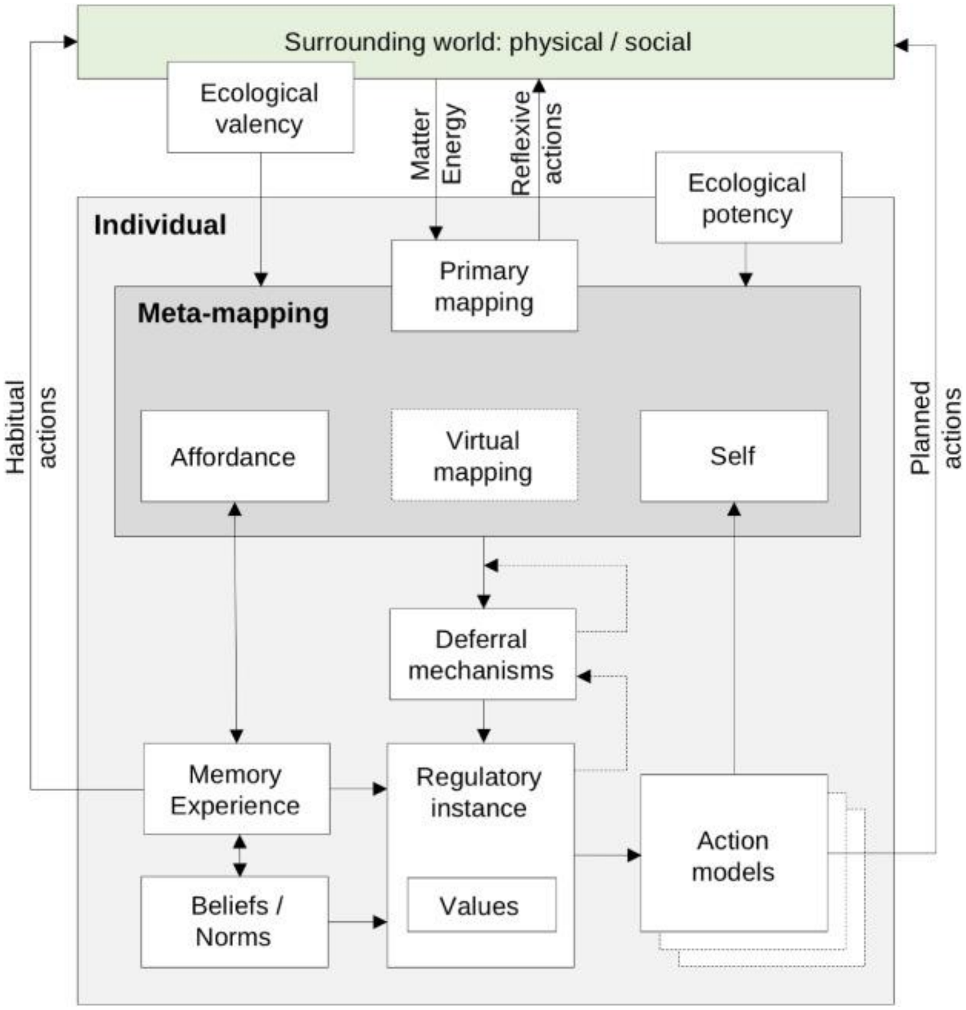


Figure 8-1: Schematic representation of the constituent elements of the pragmatic theory of occupants' control-oriented actions in buildings (Mahdavi, Wolosiuk et al., 2023)

8.1.3. Framework for occupant behaviour models documentation

This activity provided a framework to document occupant behaviour models that were developed for building performance simulation. The framework was intended to help modelers, practitioners and stakeholders to better comprehend the utility of OB models, as well as to select and adopt the most suitable model for their design application. A literature review revealed that in most papers occupant models were provided without specifying their purpose and without providing any information about their implementation. The two aspects appear to be related and indicate that occupant models have been so far developed without any specific building performance simulation application in mind. The activity resulted in a guideline for occupant behaviour models documentation as separate deliverable of Annex 79 where more detailed information can be found (see also Section 0).

8.1.4. ASHRAE Database

This activity focused on developing a database of well-documented occupant behaviour data containing 34 field-measured occupant behaviour datasets. These datasets are sourced from 39 institutions spanning 15 countries and 10 climatic zones, encompassing a variety of building types in both the commercial and residential sectors. For public accessibility, a website was launched, allowing users to interactively browse, query, and download specific datasets or the entire database. The web platform is one of the digital deliverables of Annex 79 and more detailed information can be found in Section 8.3.1.

8.1.5. Human Factors and Ergonomics for the Built Environment

This cross-subtask activity focused on employing human factors and ergonomics (HF/E) methods that are well established in other interactive system domains, to design buildings that meet the physical, physiological, and psychological needs of human operators. This activity had a particular focus on HF/E subdomains of human-computer interaction (HCI), systems engineering, and human-centered design (HCD). As a first step, an editorial that framed HF/E opportunities in the built environment was published (Agee, O'Brien et al., 2020).

In a next activity, a database of consumer-focused building control interfaces was developed, based on Day et al., 2020's review of select building interfaces. This study used a human factors approach to perform a summative evaluation on a sample of residential thermostats. Specifically, the work employed Human Information Process (HIP) theory to evaluate the visual perception of thermostat fixed visual displays (FVD) and their respective phone/tablet applications. The variables analyzed impact human-building interactions through the human visual sensory system and building controls including visual clutter, color, contrast, target/background colors, and consistency across FVD and app-based controls. The activity summarized best practices for design and evaluation criteria for building interfaces.

8.1.6. Dynamic glossary of IEA EBC Annex 79

As the Annex 79 members stemmed from a quite diverse collection of disciplines, the connotation and denomination of terms was often encountered to be slightly different, depending on which scientific disciplines persons came from. Therefore, the idea for a dynamic glossary developed among the Annex participants. First templates of how this glossary could look like (including key term definitions from various disciplines and the accompanying discussions of terms) have been created and posted on the Open Science Framework: https://osf.io/suhdj/. The Dynamic Glossary was intended to collect and discuss discipline-specific definitions and connotations in order to facilitate interdisciplinary exchange and to avoid misunderstandings by using key terms that are interpreted differently. Although it was not possible to gain enough momentum and augment the collection substantially, the initiative could be continued in a future Annex.

8.1.7. Human-System Interfaces for occupant-centric controls

This activity was focused on providing guidance on occupant-centric controls (OCC) based on field observations to close the gap between predicted and measured performance and user satisfaction. Among the main investigated success factors were occupants' acceptance of automated systems, the usability of interfaces, and the communication and training of occupants and operators. Additionally, a survey was piloted to understand how people perceive different features (e.g., colors, symbols, layouts) of thermostats. Preliminary findings suggest a lack of interface standardization in icons and spatial layouts as well as visual clutter. The manuscript from this work is ~90% and targeting a special issue on OCC.

8.2. Further deliverables of Annex 79

8.2.1. Book on Occupant-Centric Simulation-Aided Building Design

One of the major efforts of Annex 79, particularly Subtask 3, was the writing and edition of a book on 'Occupant-Centric Simulation-Aided Building Design' which is one of the further deliverables of the Annex besides this report. It addresses building designers and researchers and provides theoretical and practical means to bring occupants and their needs into the center of the building design process. Many of the Annex participants from all Subtasks contributed to the different chapters of the book which reach from indoor environment and human factors over selecting and applying models for simulation-aided building design to detailed case studies.

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Chapter 5 Occupant-centric performance metrics and performance targets

Chapter 6 Introduction to occupant modelling

Chapter 7 Fit-for-purpose occupant modelling: Choosing the right approach

Chapter 8 Advanced simulation methods for occupant-centric building design

Chapter 9 Building interfaces: Design and considerations for simulation

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Chapter 11 Detailed case studies

The book was published by Taylor and Francis Group as an open-access title in May 2023 (ISBN 9781032420028; https://www.routledge.com/Occupant-Centric-Simulation-Aided-Building-Design-Theory-Application/OBrien-Tahmasebi/p/book/9781032420028).

8.2.2. A Comprehensive Guideline for Documenting and Implementing Occupant Behaviour Models in Building Performance Simulation and Advanced Building Controls

Another deliverable of Annex 79 is a guideline on occupant model documentation. As already introduced as one of the cross-subtask-activities in Section 8.1, this endeavor aimed to establish a comprehensive and standardized guideline for documenting occupant behaviour models.

There have been many occupant behaviour models developed for building design and controls, yet without a comprehensive framework or standard showing how those models are documented and implemented in fields. This document aims to fill this gap through:

- developing a framework to document occupancy and occupant behaviour models for building performance simulation to emphasize the importance of capturing the multidimensional aspects of human behaviour. It consists of four blocks (description, development, evaluation, and implementation) and can be also regarded as a guideline to help researchers in the development, testing, implementation and transparent communication of their models.
- developing a guideline to document occupant behaviour models for advanced building controls by detailing how well-documented OB models can be operationalized to enhance building performance in real-time. It presents a model-evaluation schema that enables benchmarking of different models in field settings as well as recommendations on how OB models can be integrated with the building system.

The guideline is available online:

https://annex79.iea-ebc.org/Data/publications/OB_Guideline_final_version.pdf.

8.3. Digital deliverables of Annex 79

As stated in the introduction of this report, one of the objectives of Annex 79 was deploying ‘big data’ (e.g., data mining and machine learning) for the building sector. This consequently resulted in three internet platforms to support occupant behaviour modelling as well as insight into practical application of occupant-centric controls through case studies.

8.3.1. ASHRAE Global Occupant Behaviour Database

Occupant Behaviour (OB) is one of the most neglected parameters in Building Energy Simulation (BES). Many studies have been published in the past have suggested that neglecting OB in the building simulation can cause up to 50%-150% discrepancies between actual and simulation data (Wang and Greenberg, 2015, Delzendeh, Wu et al., 2017, Muroni, Gaetani et al., 2019). The initial Heating, Ventilation and Air Conditioning (HVAC) sizing during design phase of a building is depended on this simulation data. If the building simulation figures are incorrect, it might risk over or under-sizing of these systems. Given that HVAC system consume significant portion of the building’s overall energy usage (Huang, Zaheeruddin et al., 2006, Pérez-Lombard, Ortiz et al., 2008, Payne and McGowan, 2012), the inappropriate sizing will exacerbate the building energy consumption. The discrepancies in simulation that originate due to OB can be attributed to the use of 'constant' or 'standardized' schedules. These 'Occupancy and Equipment Schedules' are generally based on ASHRAE Standards (ASHRAE, 2022).

In past decades, there has been a significant development in modelling OB using different data driven models (Rijal, Tuohy et al., 2007, Haldi and Robinson, 2009, Hong, 2013, Li, Li et al., 2015, Markovic, Wolf et al., 2017, Yao and Zhao, 2017, Markovic, Grintal et al., 2018, Pandey, Sharifi et al., 2023). These models were possible to create because of advent of new sensor technologies that are portable, with years of battery life and most importantly, cost-effective. The volume of data from these sensors have exploded in recent years. The demand for this type of data is also high among researchers as new types of models based on AI and machine learning have emerged in recent years. Particularly, after the invention of low-cost GPUs and user-friendly Python-based machine learning algorithms like Tensor-Flow and PyTorch, the creation and use of these models have increased exponentially. However, no portals existed that could acquire and disseminate data and be used by building scientists across the globe to create the data-driven models for OB and replace those 'constant' schedules.

To bridge this gap, a new portal named 'ASHRAE Global Occupant Behaviour Database' (developed as a part of the ASHRAE MTG.OBB research grant URP-1883) to collect the data contributions from researchers across the globe (Dong, Liu et al., 2022). The database covers various building types in both commercial and residential sectors (Dong, Liu, et al. 2022). It is multifaceted, encompassing occupancy patterns (presence and people count), occupant behaviours (including interactions with devices, equipment, and technical systems within buildings), as well as indoor and outdoor environmental measurements (e.g., temperature, relative humidity, carbon dioxide concentration, etc.). Currently, this database includes 10 different types of occupant behaviour measurements like (1) occupant presence; (2) occupant number; (3) opening/Closing of windows; (4) opening/closing window blinds; (5) turning on/off lights; (6) adjusting thermostats; (7) turning on/off air-conditioners; (8) HVAC sizing and thermal comfort; (9) crowd control and security; and (10) circulation design. Currently, the OB database contains about 34 datasets from 39 different educational institutions spread across 15 countries and 10 climate zones. The datasets were collected between 2003 and 2020, and the database amounts to approximately 3.81 GB of data records. This includes 24 in-situ datasets, one mixed-type dataset that combines sensor data with survey responses, and nine survey-type datasets. Data based on in-situ methods encompasses dynamic information and measurements within the study buildings, collected at regular and consistent intervals. In contrast, survey-based data comprises specific information gathered from studies, such as responses from occupant questionnaires, static details about the building's exteriors, floor layout, and measurements taken at selected intervals. Any datasets that lack a uniform and fixed time frame for sampling are categorized as survey-based data.

The database will be a valuable asset for researchers across the globe to compare and understand the human behaviour of interactions with building systems and create the model that is realistic. To elaborate further, the OB database can help researchers in different domains. Apart from understanding the OB in real buildings, the database can help to compare and understand the diversity and dynamics of OB. The database can also help to develop mathematical models of OB at different spatial and temporal resolutions in different types of buildings. It can help in benchmarking various OB models and given the volume of data, can help to create various generative models. The database is publicly accessible, and a dedicated website has been developed to enable the users to interactively access, query, and download specific datasets or the entire database.

The Global Occupant Behaviour Database can be accessed via https://ashraeobdatabase.com/#/.

8.3.2. Platform for sharing and evaluating occupant behaviour models (OBLib)

The Occupant Behaviour Library (OBLib) is a web-based platform for deciphering the details of the machine learning models trained from the data of the ASHRAE Global Occupant Behaviour Database. OBLib presents the testing results of various machine learning models in a simplified manner. Also, the metadata showing the model information can be easily accessed. These details and evaluation metrics of these models' predictions can be seen in the Streamlight Web Application URL. The webpage also has an access link to the GitHub page with detailed machine learning codes for all the models. This webpage provides an interactive user interface for selecting any OB model and viewing the corresponding evaluation results. Any user can choose a desired type of OB and if there are any models available for this type of OB, they will show up. Once the model is selected, the description of the dataset on which the model is trained/tested pops up, along with detailed information about the parameters used for training this model.

The Occupant Behaviour Library can be accessed via https://annex79-oblib.streamlit.app/.

8.3.3. Online library of case studies on occupant-centric controls projects

Occupant-centric controls (OCC) and operations have emerged as a key concept in shifting the focus from conventional building- (or better system-) centric operations to a more occupant-centric approach. Despite the potential of OCC to meet occupants’ demands and bridge buildings’ energy performance gap, its implementation in real-world settings has been limited. In addition, there is a lack of standardization in methodologies and terms to facilitate meaningful comparisons among case studies. Therefore, a repository of OCC case studies was set up, offering a platform for presenting key information about practical implementations of these strategies in real-world scenarios. To accomplish this, descriptors, terms, and concepts pertaining to OCC case studies were discerned through a case study descriptors survey conducted with researchers and advanced practitioners implementing various OCC algorithms in the real-world. The survey has been designed with input from subtask 4 participants and it was aimed to capture methodological and algorithmic details of OCCs and the field performance levels of these case studies. This meta-study thus enabled a broad cross-sectional performance comparison of OCC technology with various occupant data forms, in different climates, and building typologies. By publishing the case study repository, standard categories for OCC strategies were established and a database through which practitioners and researchers can understand trends and possibilities for implementing OCC strategies is generated. The survey elements were systematically integrated to capture comprehensive information on OCC field study implementations. The survey includes approximately 90 questions for each case study. It was distributed widely to research and industry communities for a year starting April 2022. 58 valid responses (and case studies) were collected from five continents. The majority of the buildings are university buildings, offices, or residential buildings. The scope of the case study analysis includes building and occupant metadata, systems and controls, sensing technologies, occupant interactions with interfaces, machine learning applications, and interventions. The case study repository is intended to offer researchers and practitioners a reference point to understand trends and possibilities for implementing OCC strategies. Of the 58 case studies, fewer than half involved occupant interactions with interfaces; most of these focused on passively learning occupant preferences. Just over half of the case studies focused on HVAC, and a quarter focused on lighting. The authors noted a major void in OCC that incorporates wearable devices (e.g., smart watches). The study results highlight a lack of studies on OCC concerning electric lighting systems and building operators. OCCs were found to be more commonly implemented as responsive/reactive controls, highlighting a gap at the intersection of OCCs and model-free and model-based predictive controls.

The paper describing the database is: Lorenz, C.-L., et al. (2023). "A repository of occupant-centric control case studies: Survey development and database overview." Energy and Buildings: 113649. https://doi.org/10.1016/j.enbuild.2023.113649

The Online Library of Case Studies on OCC Projects can be accessed via https://github.com/RWTH-E3D/OCC-Case-Studies.

9. Conclusions

Introduction and Objectives

Occupant behaviour shows a strong influence on building performance and energy consumption. Therefore, it has been in the focus of scientific research for many years. IEA EBC Annex 66 (2014-2017) provided a sound framework for experimentally studying and modelling different behavioural actions, including the implementation of these models into simulation platforms. However, design and building operation practice shows that many of the models do not represent the manifold human interactions with a building appropriately enough, and that there is no guidance for designers and building managers on how to apply occupant behaviour models in standard practice.

Consequently, IEA EBC Annex 79 put a greater emphasis on these aspects by formulating the following objectives:

- Improvement of knowledge about occupants' interactions with building technologies. A specific focus was on comfort-driven actions caused by multiple and interdependent environmental influences which were not yet covered by existing models.
- Deployment of 'big data' for the building sector as the availability of various data related to occupants' behaviour in buildings increases rapidly. A special focus was on new modelling strategies to represent occupant behaviour in an improved manner.
- Standardized and commonplace implementation of occupant behaviour models in building practice by developing guidelines and preparing strategies for applying occupant behaviour models during building design and operation. Focused case studies should demonstrate the implementation of new models in different design and operation phases.

Key Findings

Subtask 1 of Annex 79 was engaged in the assessment of the state of art as well as knowledge generation and dissemination with regard to multi-aspect environmental exposure, building interfaces, and human behaviour. The findings of the subtask clearly confirm that occupants' expectations regarding the indoor-environmental conditions do influence their interactions with buildings and their systems, and such interactions influence, in turn, the energy performance of the built environment. There are a number of gaps in the state of knowledge in occupant-related topics, specifically in the theoretical foundations of i) human behaviour in buildings, ii) buildings' user interfaces, and iii) ontologies for representation of occupants in computational applications. They were confirmed via state-of-the-art reviews and resulted in development and publications of related high-level theories. Likewise, common views on the role of occupants in buildings' energy performance gap was critically reviewed, resulting in a strong need of more consistent studies with regard to approach and scope of buildings, comprehensiveness and quality of collected data, and robustness of the conclusions.

It also became obvious that a truly interdisciplinary approach involving representatives of physical and human sciences is necessary to cover the complexity of the topic, and a concerted effort should be taken to more actively involve professionals (engineers, architects, building operation specialists) in future research and development.

Subtask 2 showed that data-driven models have gained prominence in recent years and become the most widely utilized modelling approach, possibly due to the abundance of sensor-generated data and the availability of thorough statistical and machine learning software environments and programming languages. A noteworthy trend is a growing interest in adopting deep learning to model various aspects of occupants' presence and actions, and also predict their interactions with specific building devices for the development of adaptive controls. In light of maximizing the potential of data-driven models by utilizing current and future datasets, the establishment of a common data collection vocabulary or ontology is proposed, promoting data reuse and facilitating meta-analysis across different building types, sample sizes, and countries of origin. Additionally, providing occupant-related data in a standardized data model creates the opportunity to apply different methods to prepare the data as inputs into the energy simulation tools. As occupant-related models include deterministic rule-based, statistical/ stochastic, and data-driven models, the data preprocessing has to be specified for each approach.

To organize various data sources, an extended Brick schema provided a standardized data structure. It provides a semantic framework to describe the various aspects of a building's structure, systems, and operations and, with the extension, contextual, demographic, and behavioural details of occupants, along with their relevant data. For incorporating occupant-related data models into urban models, the Energy Application Domain Extension (ADE) is used. It expands upon the CityGML standard by incorporating energy-related features necessary for simulating the energy consumption of either an individual building or an entire city.

An important aspect is the availability of open data for modelling and simulation. In this view, separating data collection from data usage for research has to be considered due to the complexity of open data processes, as well as developing policies and guidelines to protect data providers. Finally, a variety of different modelling approaches were applied and tested for understanding and predicting occupant behaviour in building simulation, as well as for occupant-centric control. By combining different approaches, it was possible to create occupant behaviour models that are more accurate, robust, and adaptable.

Subtask 3 focused on integration of occupant information and application of occupant behaviour models in the building design process. An investigation of modelling tools and techniques with regard to guiding and promoting occupant-centric building designs revealed that, despite advancements in modelling capabilities, occupant behaviour integration into building performance simulation is facing adoption barriers such as the lack of occupant behaviour modelling expertise on design teams, unclear benefits to practitioners, and uncertain value proposition. Previous studies that adopted occupant-centric design methods and tools showed an apparent disconnect between occupant behaviour research and design practices. Studies were mainly at the proof-of-concept stage and lacked implementation and validation in actual buildings. Although building performance evaluation across multiple occupant domains is gaining significant interest in academic circles, it still has not made it to the design workflows of buildings. More real-world quantification is necessary to show the impact of occupant-centric design approaches.

A fundamental requirement for performing occupant-centric building design is establishing an effective mechanism to communicate occupant-related assumptions among project stakeholders. However, current design practices, which typically follow the traditional linear process, yields discrepancies in occupant-related assumptions made by designers which can lead to suboptimal design solutions and performance shortcomings. Based on a review and interviews, it was found that building designers need to deploy an information exchange platform that is accessible to all design team members in order to establish an integrated design process. As the building design process is driven by policy, codes and standards require updating regarding occupant-related assumptions, documentation, and information exchange. Furthermore, codes and standards should outline the approach to implementing any occupant-related assumptions.

Theory and principles of occupant-centric design were brought to application through the presentation of seven real-world case studies. Major findings were that performing occupant-centric design requires information to be shared effectively among design stakeholders as occupant-related assumptions can influence the outcomes of design parametric analysis and affect the levels of comfort in buildings. Occupant participation in the design process is useful in accurately representing occupants' presence and behaviour. The case studies also emphasized the importance of post-occupancy data collection through occupant surveys, sensing infrastructure, and interviews with building design stakeholders.

Subtask 4 focused on real world implementations of occupant-centric control and operation (OCC) which involves the sensing of indoor environmental quality, occupants' presence, and their interaction with the building, and feeding this information directly back to the control system to optimize for both operational efficiency and occupant comfort. For a systematic approach with regard to data collection and control strategies, a categorization is suggested relating to presence/absence of occupants, to occupant counts, and to occupant activities – all at system/building and zone/room levels, respectively.

The inclusion of OCC will result in a fundamental role change for building operators, including expanding their expertise into advanced technology integration, communication, and education. However, training and knowledge is necessary to properly apply these technologies. It is also necessary that organizations value their use and understand the benefits they present in supporting operators' work. Operators themselves must provide occupants with adequate education by hosting training sessions and providing resources on technology. Occupants and operators must work together for OCC to be successful. Moreover, it is critical that OCC not take controls completely away from occupants, given the importance of occupants having real and perceived control over the indoor environment.

Another topic was the role of OCC in current and future residential demand response programs where personalized models could be tailored to a particular occupant behaviour pattern by clustering similar behaviours together. This clustering would allow for future control strategies to address the inherent diversity of occupant behaviour which is especially relevant when scaling the implementation of OCC demand response at larger district or regional scales. Regarding the role of OCC in the recent pandemic-caused paradigm shift in building occupancy and operations, a change towards the recognition of occupants' comfort and well-being can be stated. While occupants have been shown to be satisfied in buildings with improved IEQ and IAQ as provided by OCC, the implementation of quantifying metrics for well-being and productivity into the OCC is an area of research that is actively underway. Open questions are – among others – about appropriate metrics and standardization.

While OCC developments generally aim to reduce energy consumption while improving occupant comfort, future research directions will take a more comprehensive approach to comfort that includes occupants' health and well-being, as well as productivity to improve occupants' overall experience within buildings. Other research trends also investigate different ways of collecting direct occupant feedback, such as using smart phone or watch applications for continuous and real-time data collection instead of making inferences from historical building automation systems' data, which has been the typical approach. At the same time, there are limits of occupant behaviour sensing and OCC strategies which include the challenges of predicting IEQ perception regarding psychological and societal influences, the question of automation versus personal control, and aspects like occupant education, control transparency, and the importance of interfaces.

In a cross-subtask activity an international survey investigated how occupants are accounted for in building design and operation practice. The data provided useful insights about available information and tools used, e.g. that information about the future occupants of a building is received from the client or project manager in more than half of the cases, and 55% of the respondents stated that they use simulation tools to evaluate indoor environmental parameters. If the professional received information about the occupants, the project description contained information regarding requirements on thermal, visual, acoustical environment, and indoor air quality.

Another cross-subtask activity on human-system interfaces for OCC was focused on providing guidance on occupant-centric controls (OCC) based on field observations to close the gap between predicted and measured performance and user satisfaction. Among the main investigated success factors were occupants' acceptance of automated systems, the usability of interfaces, and the communication and training of occupants and operators.

Main outputs

As an important output, Subtask 1 presented a comprehensive reflection of the state-of-the-art of occupant behaviour in buildings but also provided a robust and useful foundation for continued research and education in this essential area. The quest for a deeper understanding of the impact of multi-domain exposure situations on buildings' occupants is essential for a next generation of occupant representations to be integrated in computational applications (building information modelling, building performance simulation). Further, more intuitive and effective user interfaces for buildings and their systems, ideally tailored for different target groups, are needed to support successful comfort-driven occupants' interactions and thus reach their satisfaction with building performance. These are unconditional prerequisites for ensuring an improved energy and comfort performance of buildings.

One of the objectives of Subtask 2 was to develop digital tools and platforms for enabling occupant behaviour research. That was achieved by creating an occupant behaviour (OB) ecosystem of tools, datasets, guidelines, and methodologies that will result in a long-lasting contribution to the research community. Specifically, a guideline for OB data collection and clear and transparent documentation of OB models was derived and published as a separate deliverable of the Annex. Furthermore, several OB datasets were collected, and after a quality assurance process, they were compiled in the ASHRAE Global Occupant Behaviour Database. The database contains 34 field-measured datasets on different building occupant behaviours collected from 15 countries and 39 institutions across 10 climatic zones. It covers various building types in both commercial and residential sectors and it is multifaceted, encompassing occupancy patterns, occupant behaviours, as well as indoor and outdoor environmental measurements. A query builder was created to assist users in selecting the desired dataset based on city and country. The database includes 24 in-situ datasets, one mixed-type dataset that combines sensor data with survey responses, and nine survey-type datasets.

Moreover, after gathering several OB models in GitHub, the Occupant Behaviour Library (OBLib) was created. OBLib is a web-based platform for deciphering the details of the machine learning models trained from the data of the ASHRAE Global Occupant Behaviour Database. It presents the testing results of various machine learning models in a simplified manner. Also, the metadata showing the model information can be easily accessed. The webpage also has an access link to the GitHub page with detailed machine learning codes for all the models. It provides an interactive user interface for selecting any OB model and viewing the corresponding evaluation results. A desired type of OB can be chosen and the description of the dataset on which the model is trained/tested pops up, along with detailed information about the parameters used for training this model. Both internet platforms are digital deliverables of the Annex.

From a review of codes and standards involving performance-based design, Subtask 3 identified several ways that building energy codes could be elevated with regard to occupant behaviour by (i) adding prescriptive requirements that relate to occupancy, (ii) updating schedules, densities, and other values based on recent field studies, (iii) incentivizing buildings with greater flexibility towards different occupancy schedules by providing multiple occupancy scenarios, and (iv) introducing occupant modelling requirements to recognize that building design can influence occupant behaviour. As investigated by several major Annex 79 efforts, building usability is critical for a building's energy performance, comfort, and perceived control. Therefore, additional usability requirements are also recommended to be investigated and ultimately incorporated into building codes and standards.

To integrate considerations of building occupants and occupant behaviour into the decision-making process of building designers, a framework called 'occupant-centric design patterns' (OCDP) was developed which is compatible with building information management (BIM) systems and building performance simulation (BPS) tools. By linking with BPS and BIM it is integrated into the information exchange happening between team members with different disciplinary backgrounds, supporting collaborative initiatives from a technical perspective. With that design decisions related to occupants can be recorded and traced in a single environment. This proposal is effectively a 'Lego' of generic objects structured so it is sharable, easy to recall and exchange, opening the door for future work to implement this structure within common BIM tools to facilitate agility and distributivity in decision-making.

In order to generate synthetic occupant population using existing datasets, a Bayesian networks (BN) structural learning approach was adopted to synthesize populations of occupants in a multi-family housing case study. Results show that the BN approach is powerful in learning the structure of data sets. The synthetic data sets successfully match the joint distributions of the underlying combined data sets.

Subtask 4 provided a classification for occupant-centric operations case studies. On a first level, a distinction is made between observation (collecting data and seeking to explore those data for general insights) and intervention-based (including a comparison between a control/test group or a before/after condition) studies. On a second level, case studies can be human-related (trying to understand human behaviour and assess its impact on building performance as well as the occupants' own responses), or system-related (evaluating the effectiveness of available systems, controls, and interfaces). Further sub-categories served for differentiating occupant actions or system occurrences.

Further, a repository of OCC case studies was set up, offering a platform for presenting key information about practical implementations of these strategies in real-world scenarios. To accomplish this, descriptors, terms, and concepts pertaining to OCC case studies were discerned through a literature review. These elements were systematically integrated into a structured survey to capture comprehensive information on OCC field study implementations. 58 valid responses (and case studies) were collected from five continents. The majority of the buildings are university buildings, offices, or residential buildings. The scope of the case study analysis includes building and occupant metadata, systems and controls, sensing technologies, occupant interactions with interfaces, machine learning applications, and interventions. The case study repository is intended to offer researchers and practitioners a reference point to understand trends and possibilities for implementing OCC strategies.

A cross-subtask activity intended to advance agent-based modelling (ABM) for integration with building performance simulation to evaluate the impact of occupants on building design and operation and vice versa. The first part of this activity focused on identifying and integrating behavioural theories into ABM to improve the modelling of occupant decision-making in terms of their activities, comfort preferences, and human-building interactions. A high-level theory was then developed to provide a general explanatory framework toward a more suitable perspective of occupants' control-oriented actions in indoor environments. The pragmatic theory can systematically guide the formulation of occupant-related ontologies and their instantiation in computational applications related to building design, operation, and evaluation. This could help to improve the understanding of occupant behaviour in buildings under specific conditions and lead to more consistent occupant-centric design decisions.

Another cross-subtask activity on human factors and ergonomics (HF/E) focused on employing methods that are well established in other interactive system domains, to design buildings which meet the physical, physiological, and psychological needs of human operators. This activity had a particular focus on subdomains of human-computer interaction, systems engineering, and human-centered design. Further, a database of consumer-focused building control interfaces was developed. Best practices for design and evaluation criteria for building interfaces were summarized.

One of the major efforts of Annex 79 was the writing and edition of a book on 'Occupant-Centric Simulation-Aided Building Design'. It addresses building designers and researchers and provides theoretical and practical means to bring occupants and their needs into the center of the building design process. Many of the Annex participants from all Subtasks contributed to the different chapters of the book which reach from indoor environment and human factors over selecting and applying models for simulation-aided building design to detailed case studies. This also summarizes well the achievements of Annex 79 which not only contributed to new fundamental scientific knowledge in the field of multi-domain environmental exposure and the impact on buildings' occupants but also to new data-driven modelling approaches based on machine learning to integrate occupant behaviour in building performance simulation and occupant-centric controls. Further, strong advancements in implementing occupant behaviour into the design practice were demonstrated by suggesting the enhancement of standards, to review the design process itself, and to integrate models into the digital design and simulation environment. And finally, the consideration of occupants in building operation and control as a further approach to implement occupant behaviour in building practice was successfully shown with different activities.

10. List of authors and contributors

Many participants contributed to the writing of the final report. See Table 10-1 for a complete list of authors and contributors for each chapter of the final report.

Table 10-1: List of authors and key contributors of the subtask reports

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12. Appendices

12.1. Activities of Annex 79

The research work of Annex 79 was organized in four different subtasks with each having a specific topical focus. In addition, several cross-subtask activities brought together researchers from the four groups for investigating questions which either related to overlapping topics of more than one subtask or which were of general interest of the Annex and did not specifically fit into a subtask.

12.1.1. Subtask 1: Multi-aspect environmental exposure, building interfaces, and human behaviour

The focus of Subtask 1 was to better understand and develop research techniques to study energy-related occupant perception and behaviour in the context of multiple aspects of indoor environmental exposure. A closely related focus was to understand how occupants interact with building interfaces and the potential to affect real and perceived control and building energy performance. The following activities were conducted.

12.1.1.1. Review on multi-domain comfort and behaviour

The objective of this activity was to review existing research related to human comfort perception and behaviour dealing with interactions between single domain (e.g., thermal, visual, aural) environmental exposure circumstances. There was a need for a comprehensive and systematic overview of the state of the knowledge regarding multi-aspect exposure situations. An international literature review was performed for this purpose (Schweiker, Ampatzi et al., 2020).

12.1.1.2. Review on theories of perception and behaviour

Research in the social sciences suggests that different psychological factors may drive human behaviour and interactions with the surrounding environment. Bringing that perspective into buildings, occupant behaviour and interactions with building systems can be motivated by different psychological factors, resulting in how different systems (e.g., lighting, temperature, shading, etc.) may operate and impact the overall building energy consumption. The objective of this activity was to review literature related to theories from psychology and economy looking at human-building interaction (Heydarian, McIlvennie et al., 2020).

12.1.1.3. A review of the studies on the role of building occupants in the energy performance gap

In many instances, buildings' expected performance does not match actual observations. Whereas many factors can contribute to this performance gap, building occupants have increasingly attracted attention. However, there is still a need for identification of studies that objectively document the influence of occupants on buildings' energy and environmental performance. The focus of this activity was on studies that clearly establish that other factors cannot explain the gap between expected and observed performance, such that occupant behaviour remains the only viable explanation (Mahdavi, Berger et al., 2021).

12.1.1.4. Necessary conditions for a new generation of multi-domain indoor environmental quality standards

The activity entailed the writing and publication of a position paper with regard to the current state and future directions of multi-aspect building evaluation and rating systems (Mahdavi, Berger et al., 2020).

12.1.1.5. Quality criteria for multi-domain studies in the indoor environment: critical review towards research guidelines and recommendations

This study critically reviewed the literature on multi-domain studies and proposed research guidelines and recommendations for future multi-domain investigations. Several quality criteria were considered in the review and in the guidelines and recommendations, encompassing study set-up, study deployment and analysis, and study outcome. One of the main strengths of this contribution is stressing the importance of adopting a consistent terminology and result reporting style in future studies. More than 100 multi-domain studies were analyzed to extract the quality criteria and critically reviewed. The paper has received the best paper award 2022 of the journal (Chinazzo, Andersen et al., 2022).

12.1.1.6. Influence of pro-environmental values on thermal expectations in energy-saving buildings

The aim of this activity was to understand the influence of personal norms and hope on expectations about indoor conditions in sustainable buildings. Participants were exposed to description/depiction of sustainable vs. conventional buildings, asked questions about anticipated emotions about working in the building, expectations of indoor environmental conditions, and anticipated needs to interact with building systems (Arpan, Rissetto et al., 2022).

12.1.1.7. Exploring indoor environmental quality standards' evidentiary basis

This activity examined IEQ (indoor environmental quality) standards in view of the robustness of their underlying reasoning and evidentiary basis. As such, the activity targeted a critical examination of major standards in the IEQ domain and the technical evidence therein. The activity entailed five parallel streams, addressing multiple IEQ domains. These covered the thermal, visual, acoustic, indoor air quality, and user control aspects in indoor environments. A large number of standards in these domains were reviewed to explore if and to which extend the standard-based requirements are supported by direct or indirect references to relevant technical literature (Berger, Mahdavi et al., 2022, Berger, Mahdavi et al., 2023, Mahdavi, Cappelletti et al., 2023)

12.1.1.8. Review on interfaces and human behaviour

To encourage user behaviour patterns that are desirable from the operational standpoint, a better understanding of interfaces to control-relevant building features and systems is needed. Behavioural interventions will only work to the extent that the building interface allows. The objective of this activity was to identify how occupants interact with different types of building interfaces to better understand opportunities for energy savings and occupant comfort (Day, McIlvennie et al., 2020).

12.1.1.9. Facilities for multi-domain experimental studies

12.1.1.9.1. Test room-like wellbeing experimental facilities, review study

This activity investigated various existing test room facilities for comfort and energy efficiency studies. Besides the description of technical features, a strong focus was put on the suitability of the facilities for experiments with human subjects in the different comfort domains. Additionally, the amount of performed experiments in the different domains was reviewed. The findings have been compiled for a review paper (Pisello, Pigliautile et al., 2021).

12.1.1.9.2. Living-lab for wellbeing analysis, review study

This activity aimed at underlying potentials of living-lab studies, as an intermediate experimental procedure in-between test rooms and in-field studies. A review about living-lab facilities for comfort, productivity, and energy saving studies was compiled for a paper (Cureau, Pigliautile et al., 2022).

12.1.1.9.3. Round robin large scale experiments

A large-scale experiment was performed in “similar” test rooms for multi-domain comfort investigations. Particular interest was on investigating physiological responses of occupants exposed to multi-domain environmental stimuli. The protocol had been finalized and the first series of experiments were performed in summer 2022 and winter 2022/23. Intermediate results were analyzed, and the goal was to continue with more experiments until after the end of the Annex.

12.1.1.10. Ways forward for collecting information in multi-domain studies

Multi-domain studies of human-building interaction are key to understand occupant needs and requirements in an indoor environment for suitable building design and operation. However, performing this type of research is challenging in terms of data collection due to the number of variables involved. Moreover, findings are impacted by methodological approaches, and its diversity makes meta-analysis less effective. Therefore, a review of multi-domain studies of human-building interaction was done to analyze their methodological approach and data collection strategies. Key findings of this activity were, firstly, that the most popular are objective methods, which are not able to fully explain complex processes of human-building interaction. Secondly, the lack of a framework of methodological approach in multi-domain studies was recognized. It manifested by difficulties in the reviewing process: incomplete methodological data in papers (tools specification, cost) and misunderstanding between reviewers (even under standardized parameters, different interpretations of variables/domains). The activity findings are important feedback for the scientific community about the state-of-the-art in data collection methods and tools, and gaps in current approaches. It also calls for establishing a data collection framework to improve research quality and enable the future synthesis of research work realized across the world.

12.1.1.11. Occupants’ willingness to share information

Human perception and occupant behaviour are driven by a multitude of factors, including demographics, preferences, etc. The amount of information/data has increased manifold in recent times, including very personal data. Benefits may arise in getting access to such information/data for research and operation/control purposes. However, the question arises: which personal information are occupants willing to share and under which conditions? This activity developed a questionnaire in different languages assessing these questions and revealing insides into occupant's willingness to share information, depending on their “cultural” background, and in relation to (perceived) benefits. Data analysis and discussion of results continued after the end of the Annex.

12.1.1.12. Generational building resilience: learning about buildings and interface use

The goal of this pilot project was to meet with seniors from around the world to learn from their generational knowledge and their stories surrounding their experiences with and in the built environment. The study implemented qualitative and narrative methods to interview and observe older adults in buildings (homes and senior/assisted living facilities) to better understand how the passing of time has changed their relationship with and their interactions within the built environment. Qualitative data about well-being, health, socialization, building interfaces, lifestyles across lifetimes, adaptive comfort strategies etc. were collected in the United States. Preliminary results were presented in August 2022 at ACEEE Summer Study as well as virtually at the BECC webinar series in the fall of 2022. More data from Denmark, Canada, and Australia were planned to be collected and analyzed until after the end of the Annex.

12.1.1.13. Educational studies: influence of availability of indoor air quality information on user behaviour

This activity included a multi-national and multi-disciplinary CO2 monitoring campaign with students. The main goal of this activity was to monitor the IAQ in student dwellings (temperature, RH, CO_2) and evaluate whether having access to data characterizing IAQ from the meter interface could be an effective way to alter occupant behaviour and improve IAQ. The data collection efforts were significantly affected in 2020 and 2021 due to the COVID-19 pandemic, but nevertheless three researchers managed to carry on the data collection. This work was published as Bastien, Licina et al. (2024) .

12.1.1.14. New research on multi-domain influences: occupant behaviour in residential buildings

The goal of this activity was to assess how members of a household interact regarding building controls. What are the sociological drivers for adaptive actions in residential buildings? This activity was split up into two groups. One group focused on qualitative aspects. Another group focused on quantitative aspects. A survey was developed, based on the interdisciplinary framework for investigating building-user interaction in office spaces, as developed in Annex 66. The activity was revived after a COVID-19 hiatus and a pre-questionnaire and script for the qualitative online interviews were finalized. First pilot interviews were conducted and it was planned to continue the activity until after the end of the Annex.

12.1.1.15. Examining the impact of working from home (during a pandemic) on occupant health, well-being and productivity

12.1.1.15.1. Global indoor environmental quality work-from-home survey

The goal of this activity was to gather information about how individuals perceive their home workplace and whether they feel the environmental quality and the design of their workplace affects their productivity, health and well-being. A questionnaire was deployed via Qualtrics, in English and ten additional languages. Answers were collected during the Fall of 2022 and data analysis and publishing continued until after the end of the Annex.

12.1.1.15.2. Review of multi-domain indoor environmental quality studies in residential buildings and work-from-home settings

The goal of this activity was to assess the kind of evaluations that have been done around work-from-home (WFH) settings, best-practice methods for evaluating the dependent variables in WFH field studies and the kind of instrumentation used for such studies. As a starting point, a literature review based on 85 papers that ranged from non-IEQ studies related to WFH context to multi-domain IEQ studies in WFH and residential settings. The latter comprised monitoring- as well as questionnaire-based studies. Literature search for this review was completed in two phases, starting from several thousands of abstracts related to research on different aspects of WFH domain and narrowed down to 31 records related to IEQ research in WFH settings finalized for inclusion.

12.1.2. Subtask 2: Data-driven occupant modelling and digital tools

The overall goal of Subtask 2 was advancing methodologies, tools and platforms for fostering data-driven modelling and research on occupant presence and actions (OPA). This objective was pursued by initiating three main activities: (i) developing a novel occupant data collection approach for OPA, (ii) investigating stochastic and data-driven methods for OPA, and (iii) developing a platform for sharing data-driven methods and occupant data. In order to fulfill the Subtask's objective following activities were conducted:

12.1.2.1. Big Data Collection, Curation and Modelling Methods for Occupant-centric Data

12.1.2.1.1. Review existing big data source for occupant behaviour

In this activity, a comprehensive review of different sources of occupant-centric urban data was conducted that are useful for data-driven modelling. The range of applications and recent data-driven modelling techniques for urban behaviour and energy modelling was categorized, along with the traditional stochastic and simulation-based approaches. Finally, a set of recommendations for future directions in data-driven modelling of occupant behaviour and energy in buildings at the urban scale was presented (Dong, Liu et al., 2021).

12.1.2.1.2. Development and study collection and curation methods with big data

In this activity, a review was conducted for occupant behaviour modelling within and beyond building science. The goal was to bridge the data sources and methodology gap between building science and beyond. In order to achieve this goal, different research questions were addressed like modelling requirements of occupant behaviour at a community level, data sources which have been used in other domains, current modelling methods of occupant behaviour, modelling methods that have been used in other domains and could potentially enhance the modelling capabilities for building domain applications, as well as potential future research directions. Results were compiled in a review paper (Dong, Liu et al., 2021).

12.1.2.1.3. Develop a data sharing platform for occupant behaviour

In this activity, the efforts from ASHRAE Global Occupant Behaviour database were leveraged and a web-based data sharing platform was developed. This data sharing platform includes data sets from 32 data contributors from 15 countries. It covers a wide range of occupant behaviour including presence and number of occupants in a room or whole building, appliance usages, window opening, shading behaviour, lighting operation, etc. The website is open to the public now at www.ashraeobdatabase.com and is described in a publication (Dong, Liu et al., 2022).

12.1.2.2. Data-driven modelling for occupant behaviour

12.1.2.2.1. Systematic literature review on existing application of methods for occupant behavioural modelling

The systematic and data-driven literature review of existing methods for modelling occupant presence and actions in buildings was published in the special issue in the Building and Environment journal. It scrutinized a large set of publications collected from scientific databases (Scopus and Web of Science). The research question was composed using the Context-Intervention-Mechanism-Outcome (CIMO) scheme, and document search was structured according to the PRISMA flow diagram (Carlucci, De Simone et al., 2020).

12.1.2.2.2. Towards a standardized evaluation protocol and benchmark for occupant behaviour modelling

The aim of this activity was to propose a guideline for a thorough and standardized occupant-behaviour model documentation. For that purpose, a literature screening for existing occupant behaviour models in building control was conducted, and occupant behaviour modelling processes were studied to extract practices and gaps for each of the following phases: problem statement, data collection and preprocessing, model development, model evaluation, and model implementation. The literature screening pointed out that the current state-of-the-art on model documentation shows little unification, which poses a particular burden for the model application and replication in field studies. In addition to the standardized model documentation, this work presented a model-evaluation schema that enabled benchmarking of different models in field settings as well as the recommendations on how OB models are integrated with the building system (Dong, Markovic et al., 2022).

12.1.2.2.3. Investigation of metadata schemas for occupants' presence and actions data

The objective of this activity was to explore and develop possible metadata schemas in order to properly describe occupant presence and action datasets in a way that the research community can understand and use them. The existing metadata schemas were reviewed and the Subtask 2 deliverables were aligned with the state of the research, namely Brick schema extended by the occupant-related information (Luo, Fierro et al., 2022).

12.1.2.3. Platform for sharing data-driven methods

12.1.2.3.1. Review of open data principles, open data availability, usage of open data and software support for sharing

A literature review on this topic was completed and published as a paper as part of the special issue of Building and Environment (Kjærgaard, Ardakanian et al., 2020).

12.1.2.3.2. Approaches for data-driven occupant-centric modelling based on big data

This activity collected different approaches of machine learning techniques to OPA databases to identify potentialities, limitations, new opportunities. A paper on occupant-oriented model predictive control for demand response in buildings was published (Frahm, Zwickel et al., 2022).

12.1.2.3.3. Community building for data-driven methods on occupant-centric data

In this activity, the creation of a community was fostered by organizing and conducting the 1st ACM International Workshop on Big Data and Machine Learning for Smart Buildings and Cities (ACM BALANCES) at the BuildSys international conference in Coimbra Portugal on 17-18/11/2021. The workshop included 2 keynote speakers, 8 paper presentations with 46 participants and more than 400 visualizations on YouTube. Furthermore, a PhD forum was organized with two speakers and 18 participants. A second ACM BALANCES workshop was held in conjunction with ACM BuildSys 2022 on 9 November 2022, with 12 submissions and 8 accepted papers.

12.1.2.3.4. Anonymization methods for handling privacy of occupant data

This activity was investigating cases of privacy risks and possible anonymization methods to protect different typologies of datasets. The screening for the case study data sets was initiated in April 2021. As part of this activity, a framework of "privacy by design" versus "privacy preprocessing layer" was included in the planned platform of OB sharing. The current version of the tool is available under http://privacyrisktoolchain.tek.sdu.dk.

12.1.2.3.5. Open source ObLib project

This activity created an open-source occupant behaviour library and benchmarked model performance based on the same data sources, which were from the Global Occupant Behaviour Database. The goal of this ObLib project was to have ready to use occupant behaviour models for presence, occupant numbering, window opening, lighting operation and thermostat behaviours. The current version of the tool is available under: https://github.com/yapanliu/OBlib.

12.1.3. Subtask 3: Applying occupant behaviour models in a performance-based design process

Subtask 3 focused on applying occupant behaviour models in performance-based design process. The following briefly explains the different research activities in this Subtask.

12.1.3.1. Review of codes and standards involving performance-based design

This activity conducted an international review of occupant representation in building energy codes, covering 22 countries' building energy codes) and a paper was published in the Building and Environment special issue (O'Brien, Tahmasebi et al., 2020).

12.1.3.2. Develop, test, and document simulation-based occupant-centric design procedures

This activity successfully concluded an exploration of computational design support methods (such as robust design, parametric design and optimization) with a focus on occupant-centric design metrics and modelling/simulation approaches. The outcome of this effort was published as a journal paper (Azar, O'Brien et al., 2020).

12.1.3.3. Develop methods and guidelines to choose fit-for-purpose occupant modelling approaches

Subtask 3 researchers prepared a report on this activity as a chapter in the subtask-led book titled 'Occupant-centric simulation-aided building design'. This chapter was peer reviewed by Annex 79 participants, went through external peer review, and is published by Taylor & Francis Group as an open-access chapter of Annex 79 book (O'Brien and Tahmasebi, 2023).

12.1.3.4. Develop standard ways for communicating occupant-related assumptions between stakeholders

Finalizing a literature review of challenges, barriers and needs to develop effective communication mechanisms of the occupant-related assumptions among the building design stakeholders, a conference paper was published in Building Simulation conference in Belgium in 2021, which documented the common practice and challenges in communicating occupant-related assumptions during design through practitioners' interviews. This activity concluded by providing recommendations for best practices in communicating occupant-related assumptions among design stakeholders.

12.1.3.5. Development of synthetic occupant models

A literature review as completed on synthetic population models for other disciplines (e.g., transportation), as well as on methods to develop synthetic population models. Potential use cases of the synthetic population model across the building life cycle were identified. The existing DNAS ontology and obXML schema were extended and existing datasets have been identified to be used for the model development and verification, including the occupant survey conducted by Annex 66, the ASHRAE Global Thermal Comfort Database, the Annex 66 special issue for Nature Scientific Data, and the ASHRAE Global Occupant Database. Papers on the review and extension of DNAS ontology (Putra, Hong et al., 2021) and on methods to generate synthetic occupants from existing datasets (Putra, Andrews et al., 2021) were published.

12.1.3.6. Big data analytics for occupant behaviour research

This activity has concluded a dataset of occupancy at building scale and three articles concerning typical occupancy patterns and occupancy forecasting research (Jin, Yan et al., 2021, Kang, Yan et al., 2021) including typical clustering patterns, modelling and forecasting methods through big data analytics, and evaluation results. The activity also finished two joint review articles in collaboration with Subtask

2 (Salim, Dong et al., 2020, Dong, Liu et al., 2021). The papers were structured to address the modelling requirements and data sources, occupant modelling methodologies at urban scale and opportunities for future resilient building design, operation, and policy at community level. The activity also analyzed the role of occupant behaviour research in energy policy concluded in another journal paper.

12.1.3.7. Case studies

Annex 79 researchers peer-reviewed the case studies book chapter and the authors addressed the comments to improve the quality of the work. The chapter is published as open-access chapter of the book by Taylor & Francis Group.

12.1.4. Subtask 4: Development and demonstration of occupant-centric building operation strategies

The overall goal of Subtask 4 was to advance building operations and controls by exploiting new data sources and on-line learning methods to adapt to occupancy and occupant preferences and with this to provide more comfortable environments using less energy.

12.1.4.1. State-of-the art in real-world implementations of occupant-centric controls

The objective of this activity was to review the real-world implementations of occupant-centric control algorithms in the scientific literature. Two journal papers were published. Of them, one focused on commercial and institutional buildings (Park, Ouf et al., 2019), and the second one on residential buildings (Stopps, Huchuk et al., 2021).

12.1.4.2. Operator interviews for occupant-centric control

This activity focused on interviewing operations professionals from real-world case studies to collect information regarding standards, common practices, and needs. The interviews were led by 33 researchers from 16 different institutions. This activity completed and parsed 72 interviews from seven countries and four climate zones. All of them were imported into nVivo on a virtual machine for analysis. The researchers involved “coded”, i.e., pulled out quotes on themes relating to the original research questions. A paper was finalized that describes the methods and overall results. Another paper on international differences in building operation was also published.

12.1.4.3. Case study descriptors

The objective of this activity was re-targeted as a method of creating a set of descriptors and a framework for collecting data about case study buildings. A sub-team developed a survey using the Qualtrics platform that included over 120 questions capturing the various attributes of an occupant-centric operations case study. There were several categories of questions related to building meta data, data about occupants, operators and operations policies, building HVAC and lighting information, occupant interaction and motivation, and interventions related to occupant or operator behaviour change. The survey and data collection from the Annex and beyond was completed and a magazine article introducing base occupant-centric control categories with illustrative examples to HVAC practitioners was published. Survey results were analyzed as part of further activities of this subtask.

12.1.4.4. Simulation-based investigation of occupant-centric controls

The objective of this activity was to develop a simulation environment for the development and assessment of occupant-centric control algorithms. This simulation environment was implemented in the building performance simulation tool EnergyPlus. The capabilities of this environment were demonstrated through simulations with archetypical building energy models. Three journal articles were published addressing barriers regarding the simulation of occupant-centric controls. Progress of several case studies was discussed including an in-depth implementation of fine-tuning OCC using optimization. A journal special issue at Journal of Building Performance Simulation including seven original research contributions and an editorial has been published in early 2022. Research in this topic was completed with publications introducing OCC algorithms, presenting novel machine learning techniques such as reinforcement learning, and providing recommendations for ideal sensor configurations for OCC deployments by using building performance simulation.

12.1.4.5. Occupant-centric operations for demand-response

This activity focused on the analysis of occupant-centric building operations in the context of residential and non-residential demand-response. The objective of this activity was to improve the acceptability of demand-responsive sequences of operation that involves short-term curtailment of various building services. This involves sending personalized demand response signals and prioritizing the curtailment of services to unoccupied spaces. One journal paper was published. Large scale field implementation involving 30 residential buildings with forced-air heating and cooling systems in three climates in the United States was realized. While first findings were included in this report (Section 7), the project completion went beyond the end of the Annex.

12.1.4.6. Occupant-centric longitudinal intensive methodologies

This activity focused on the implementation of longitudinally intensive methodologies to collect data from occupants in buildings. Several projects using smart-watches and smart-phones formed the foundation for this activity. Publications were produced that represent best-practice use cases of longitudinal occupant feedback data collection mechanisms. While the findings were included in the final report, the project completion went beyond the end of the Annex.

12.1.4.7. Implementation of occupant-centric control strategies case study buildings

This activity entailed the integration of occupant-centric control algorithms to the building automation systems of the case study buildings. Technical and non-technical obstacles emerging at this phase were carefully documented from more than 50 case studies for future reference.

12.1.4.8. Testing of the case studies

This activity involved measurement and verification of the aforementioned case study results by individual research groups. On top of this, Subtask 4 set and reported standards to measure and verify energy and comfort performance benefits of occupant-centric controls. Comfort and energy performance indicators reported from more than 50 case studies were compared.

12.1.4.9. Synthesis of the case study findings

The objective of this activity was to summarize the results of the entire subtask to make the "lessons learned" available for others and to highlight promising types of algorithms. Besides the documentation in the report, a guideline document for the implementation of occupant centric controls was developed. This activity was discussed in detail regarding the methods of compilation of case studies. We are currently working on a journal paper synthesizing the main findings. While early findings from this activity were included in the final report (Section 7), the work will continue beyond the current Annex.

12.1.5. Cross subtask activities

12.1.5.1. Survey on the availability and quality of occupant data in the early design phase

The aim of this activity was to gather information on how occupants are considered in building design and operation and get insights on practitioner's perspective and OB consideration in practice. An online survey among practitioners in different countries was conducted consisting of three parts: (1) background information on the respondents' role (2) integration of occupant information in the planning process, and (3) use of simulation tools and occupant models. The survey was translated into different languages to be distributed in 12 countries. Overall, 880 surveys were returned of which 440 remained after removing the observations that did not provide any answer to the second section of the survey. Descriptive results were presented and discussed in an interactive session in a workshop at CLIMA2022 conference on 24th May 2022.

12.1.5.2. Agent-based modelling

This activity aimed to advance agent-based modelling for integration with building performance simulation to evaluate impact of occupants on building design and operation and vice versa. One task focused on identifying and integrating behavioural theories into ABM to improve modelling of occupant decision making in terms of their activities, comfort preferences, and human-building interactions. The second task focused on understanding, defining, and demonstrating various levels of detail of ABM to support their use across the building life cycle. Further, behavioural models were explored as the potential knowledge base for the definition of ontologically streamlined behavioural patterns suitable for inclusion in ABM. A literature review summarized use cases and their modelling details for ABM, leading to the development and publication of a ten-question paper to provide an overview and in-depth discussion on ABM focusing on level of details and applications. In addition, a framework to define ABM LoDs was published a related journal article. Finally, five simulation-based case studies using the developed ABM LoD framework were published.

12.1.5.3. Framework for occupant behaviour models documentation

This activity provided a framework to document occupant behaviour models that are developed for building performance simulation. It should help modelers, practitioners and stakeholders to better comprehend the utility of OB models, as well as to select and adopt the most suitable model for their design application. An overview of the state-of-the-art of occupant behaviour model documentation was also provided by systematically reviewing to which degree existing academic papers on occupant models meet the framework. It was found that most of the papers provide occupant models without specifying their purpose and without providing any information about their implementation. The two aspects appeared to be related and indicated that occupant models have been so far developed without any specific BPS application in mind. This further indicated the need for such a framework. An article outlining the documentation framework and the result of the review was published (Vellei, Azar et al., 2022).

12.1.5.4. ASHRAE Global Occupant Behaviour Database

This activity focused on developing a database of well-documented occupant behaviour data; following the precedent set by the thermal comfort community. The activity was linked to a funded ASHRAE project, with Annex 79 members leading. Datasets were sourced from 39 institutions spanning 15 countries and 10 climatic zones, encompassing a variety of building types in both the commercial and residential sectors. For public accessibility, a website was launched, allowing users to interactively browse, query, and download specific datasets or the entire database.

12.1.5.5. Human factors and ergonomics for the built environment

This activity focused on characterizing and employing human factors and ergonomics (HF/E) methods that are well established in other interactive system domains to design buildings that meet the physical, physiological, and psychological needs of human operators. This activity had a particular focus on HF/E subdomains of human-computer interaction (HCI), systems engineering, and human-centered design (HCD). In a first step, an editorial was developed that framed the problem space. Next, a mapping of building interfaces was conducted using an artifact analysis approach. This activity yielded best practices for interface design and evaluation criteria for building interfaces. Specifically, the work employed Human Information Process (HIP) theory to evaluate the visual perception of thermostat fixed visual displays (FVD) and their respective phone/tablet applications.

12.1.5.6. Dynamic glossary of IEA EBC Annex 79

As the connotation and denomination of terms strongly depend on the scientific disciplines of persons, the idea for a dynamic glossary developed among the Annex participants. First templates of how this glossary could look like (including key term definitions from various disciplines and the accompanying discussions of terms) were created and posted on the Open Science Framework: https://osf.io/suhdj/. The Dynamic Glossary was intended to collect and discuss discipline-specific definitions and connotations in order to facilitate interdisciplinary exchange and to avoid misunderstandings by using key terms that are interpreted differently. Although it was not possible to gain enough momentum and augment the collection substantially, the initiative could be continued in a future Annex.

12.1.5.7. Human-system interfaces for occupant-centric control

This activity was focused on providing guidance on occupant-centric controls (OCC) based on field observations to close the gap between predicted and measured performance and user satisfaction. Among the main investigated success factors were occupants' acceptance of automated systems, the usability of interfaces, and the communication and training of occupants and operators. A pilot story collection study and analysis were carried out based on the field studies of Annex 79 members, and an article presenting this proof of concept was accepted at the ASHRAE-AIVC IAQ joint conference in Athens. Additionally, a survey was piloted to understand how people perceive different features (e.g., colors, symbols, layouts) of thermostats and the results were published in the special issue on OCC.

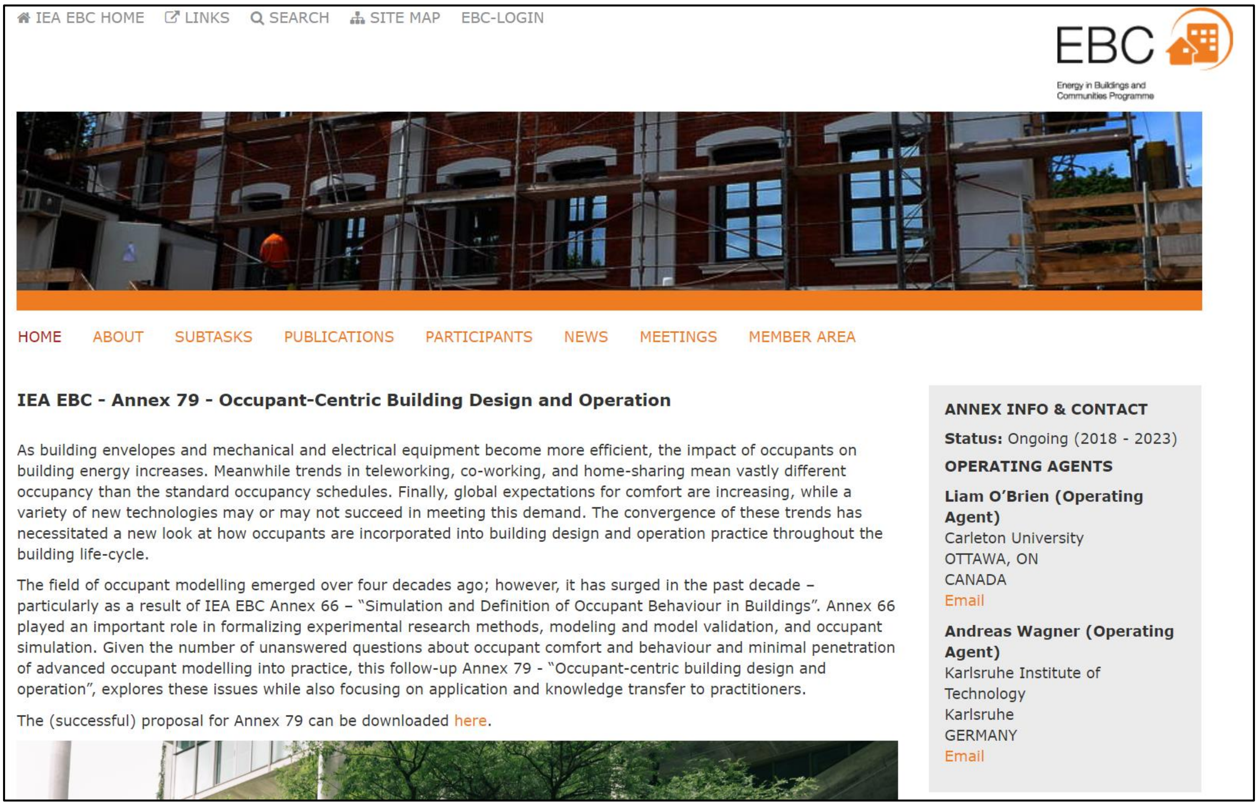
12.2. Publicity

Annex 79 used various channels to communicate the project research goals, methods, and outcomes to the public, as well as to reach out to related events and stakeholders, including:

1. Website, https://annex79.iea-ebc.org/
2. 4 newsletters
3. 6 symposia, organized by the Annex for young scientists and PhD students
4. 2 panel discussions with different stakeholders (architects and planners, experts from the area of data-driven building management and control)
   37 workshops and seminars
5. 3 topical issues for three journals
6. 113 journal articles on occupant behaviour research and applications

12.2.1. Website

https://annex79.iea-ebc.org/



IEA EBC - Annex 79 - Occupant-Centric Building Design and Operation

As building envelopes and mechanical and electrical equipment become more efficient, the impact of occupants on building energy increases. Meanwhile trends in teleworking, co-working, and home-sharing mean vastly different occupancy than the standard occupancy schedules. Finally, global expectations for comfort are increasing, while a variety of new technologies may or may not succeed in meeting this demand. The convergence of these trends has necessitated a new look at how occupants are incorporated into building design and operation practice throughout the building life-cycle.

The field of occupant modelling emerged over four decades ago; however, it has surged in the past decade – particularly as a result of IEA EBC Annex 66 – "Simulation and Definition of Occupant Behaviour in Buildings". Annex 66 played an important role in formalizing experimental research methods, modeling and model validation, and occupant simulation. Given the number of unanswered questions about occupant comfort and behaviour and minimal penetration of advanced occupant modelling into practice, this follow-up Annex 79 - "Occupant-centric building design and operation", explores these issues while also focusing on application and knowledge transfer to practitioners.

The (successful) proposal for Annex 79 can be downloaded here.

ANNEX INFO & CONTACT

Status: Ongoing (2018 - 2023)

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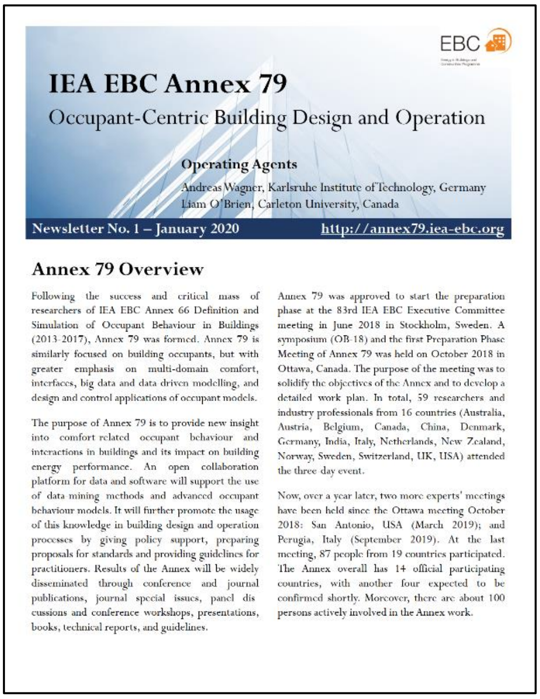
12.2.2. Newsletters



IEA EBC Annex 79

Occupant-Centric Building Design and Operation

Operating Agents

Andreas Wagner, Karlsruhe Institute of Technology, Germany
Liam O'Brien, Carleton University, Canada

Newsletter No. 1 – January 2020 http://annex79.iea-ebc.org

Annex 79 Overview

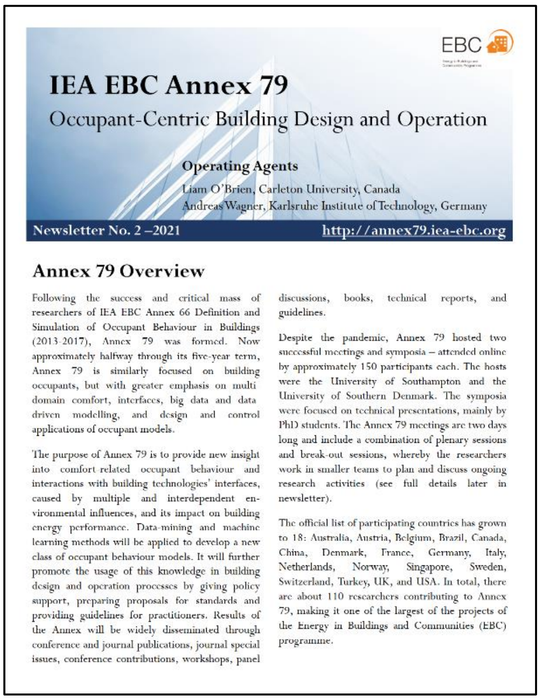
Following the success and critical mass of researchers of IEA EBC Annex 66 Definition and Simulation of Occupant Behaviour in Buildings (2013-2017), Annex 79 was formed. Annex 79 is similarly focused on building occupants, but with greater emphasis on multi-domain comfort, interfaces, big data and data driven modelling, and design and control applications of occupant models.

The purpose of Annex 79 is to provide new insight into comfort related occupant behaviour and interactions in buildings and its impact on building energy performance. An open collaboration platform for data and software will support the use of data mining methods and advanced occupant behaviour models. It will further promote the usage of this knowledge in building design and operation processes by giving policy support, preparing proposals for standards and providing guidelines for practitioners. Results of the Annex will be widely disseminated through conference and journal publications, journal special issues, panel discussions and conference workshops, presentations, books, technical reports, and guidelines.

Annex 79 was approved to start the preparation phase at the 83rd IEA EBC Executive Committee meeting in June 2018 in Stockholm, Sweden. A symposium (OB-18) and the first Preparation Phase Meeting of Annex 79 was held on October 2018 in Ottawa, Canada. The purpose of the meeting was to solidify the objectives of the Annex and to develop a detailed work plan. In total, 59 researchers and industry professionals from 16 countries (Australia, Austria, Belgium, Canada, China, Denmark, Germany, India, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, UK, USA) attended the three day event.

Now, over a year later, two more experts' meetings have been held since the Ottawa meeting October 2018: San Antonio, USA (March 2019); and Perugia, Italy (September 2019). At the last meeting, 87 people from 19 countries participated. The Annex overall has 14 official participating countries, with another four expected to be confirmed shortly. Moreover, there are about 100 persons actively involved in the Annex work.

2020



IEA EBC Annex 79

Occupant-Centric Building Design and Operation

Operating Agents

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Newsletter No. 2 –2021 http://annex79.iea-ebc.org

Annex 79 Overview

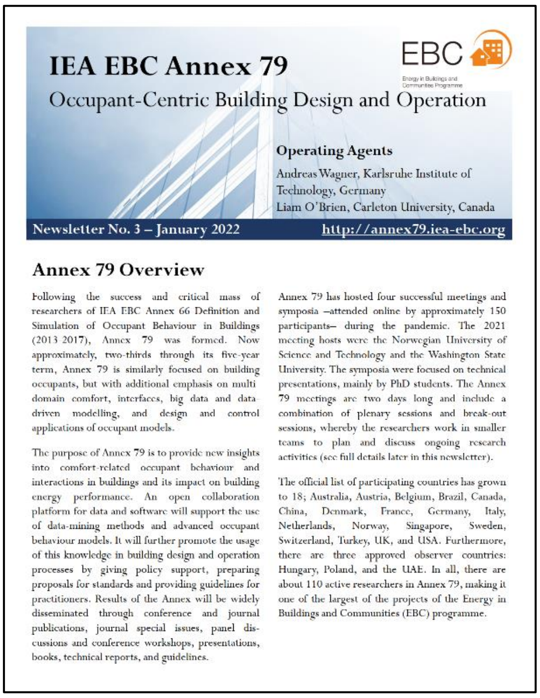
Following the success and critical mass of researchers of IEA EBC Annex 66 Definition and Simulation of Occupant Behaviour in Buildings (2013-2017), Annex 79 was formed. Now approximately halfway through its five-year term, Annex 79 is similarly focused on building occupants, but with greater emphasis on multi domain comfort, interfaces, big data and data driven modelling, and design and control applications of occupant models.

The purpose of Annex 79 is to provide new insight into comfort related occupant behaviour and interactions with building technologies' interfaces, caused by multiple and interdependent environmental influences, and its impact on building energy performance. Data-mining and machine learning methods will be applied to develop a new class of occupant behaviour models. It will further promote the usage of this knowledge in building design and operation processes by giving policy support, preparing proposals for standards and providing guidelines for practitioners. Results of the Annex will be widely disseminated through conference and journal publications, journal special issues, conference contributions, workshops, panel discussions, books, technical reports, and guidelines.

Despite the pandemic, Annex 79 hosted two successful meetings and symposia – attended online by approximately 150 participants each. The hosts were the University of Southampton and the University of Southern Denmark. The symposia were focused on technical presentations, mainly by PhD students. The Annex 79 meetings are two days long and include a combination of plenary sessions and break-out sessions, whereby the researchers work in smaller teams to plan and discuss ongoing research activities (see full details later in newsletter).

The official list of participating countries has grown to 18: Australia, Austria, Belgium, Brazil, Canada, China, Denmark, France, Germany, Italy, Netherlands, Norway, Singapore, Sweden, Switzerland, Turkey, UK, and USA. In total, there are about 110 researchers contributing to Annex 79, making it one of the largest of the projects of the Energy in Buildings and Communities (EBC) programme.

2021



IEA EBC Annex 79

Occupant-Centric Building Design and Operation

Operating Agents

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Newsletter No. 3 – January 2022 http://annex79.iea-ebc.org

Annex 79 Overview

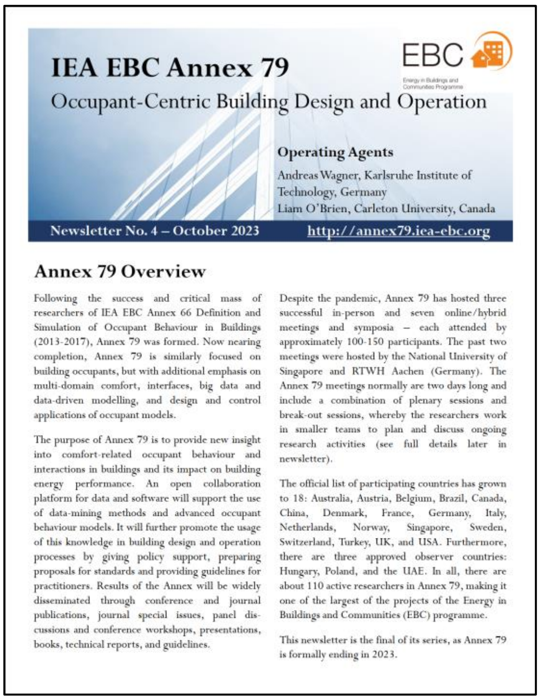
Following the success and critical mass of researchers of IEA EBC Annex 66 Definition and Simulation of Occupant Behaviour in Buildings (2013-2017), Annex 79 was formed. Now approximately, two-thirds through its five-year term, Annex 79 is similarly focused on building occupants, but with additional emphasis on multi domain comfort, interfaces, big data and data-driven modelling, and design and control applications of occupant models.

The purpose of Annex 79 is to provide new insights into comfort-related occupant behaviour and interactions in buildings and its impact on building energy performance. An open collaboration platform for data and software will support the use of data-mining methods and advanced occupant behaviour models. It will further promote the usage of this knowledge in building design and operation processes by giving policy support, preparing proposals for standards and providing guidelines for practitioners. Results of the Annex will be widely disseminated through conference and journal publications, journal special issues, panel discussions and conference workshops, presentations, books, technical reports, and guidelines.

Annex 79 has hosted four successful meetings and symposia –attended online by approximately 150 participants– during the pandemic. The 2021 meeting hosts were the Norwegian University of Science and Technology and the Washington State University. The symposia were focused on technical presentations, mainly by PhD students. The Annex 79 meetings are two days long and include a combination of plenary sessions and break-out sessions, whereby the researchers work in smaller teams to plan and discuss ongoing research activities (see full details later in this newsletter).

The official list of participating countries has grown to 18; Australia, Austria, Belgium, Brazil, Canada, China, Denmark, France, Germany, Italy, Netherlands, Norway, Singapore, Sweden, Switzerland, Turkey, UK, and USA. Furthermore, there are three approved observer countries: Hungary, Poland, and the UAE. In all, there are about 110 active researchers in Annex 79, making it one of the largest of the projects of the Energy in Buildings and Communities (EBC) programme.

2022



IEA EBC Annex 79

Occupant-Centric Building Design and Operation

Operating Agents

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Newsletter No. 4 – October 2023 http://annex79.iea-ebc.org

Annex 79 Overview

Following the success and critical mass of researchers of IEA EBC Annex 66 Definition and Simulation of Occupant Behaviour in Buildings (2013-2017), Annex 79 was formed. Now nearing completion, Annex 79 is similarly focused on building occupants, but with additional emphasis on multi-domain comfort, interfaces, big data and data-driven modelling, and design and control applications of occupant models.

The purpose of Annex 79 is to provide new insight into comfort-related occupant behaviour and interactions in buildings and its impact on building energy performance. An open collaboration platform for data and software will support the use of data-mining methods and advanced occupant behaviour models. It will further promote the usage of this knowledge in building design and operation processes by giving policy support, preparing proposals for standards and providing guidelines for practitioners. Results of the Annex will be widely disseminated through conference and journal publications, journal special issues, panel discussions and conference workshops, presentations, books, technical reports, and guidelines.

Despite the pandemic, Annex 79 has hosted three successful in-person and seven online/hybrid meetings and symposia – each attended by approximately 100-150 participants. The past two meetings were hosted by the National University of Singapore and RTWH Aachen (Germany). The Annex 79 meetings normally are two days long and include a combination of plenary sessions and break-out sessions, whereby the researchers work in smaller teams to plan and discuss ongoing research activities (see full details later in newsletter).

The official list of participating countries has grown to 18: Australia, Austria, Belgium, Brazil, Canada, China, Denmark, France, Germany, Italy, Netherlands, Norway, Singapore, Sweden, Switzerland, Turkey, UK, and USA. Furthermore, there are three approved observer countries: Hungary, Poland, and the UAE. In all, there are about 110 active researchers in Annex 79, making it one of the largest of the projects of the Energy in Buildings and Communities (EBC) programme.

This newsletter is the final of its series, as Annex 79 is formally ending in 2023.

2023

12.2.3.

Symposia organized by Annex 79

Annex 79 organized a series of symposia, connected to the Annex meetings, in order to stimulate young scientists and PhD students to present their Annex-related research on occupant behaviour. These were:

- A 1-day symposium in Ottawa (Canada) on October 10, 2018, organized and hosted by Carleton University (Liam O'Brien).
- A 1-day symposium in San Antonio (USA) on March 13, 2019, organized and hosted by University of Texas at San Antonio (Bing Dong).
- A 2-day symposium (online) on April 22 and 23, 2020, organized by University of Southampton (Abubakr Bahaj and Stephanie Gauthier).
- A 1-day symposium (hybrid) in Odense (Denmark) on September 23, 2020, organized and hosted by University of Southern Demark (Mikkel Kjaergaard).
- A 1-day symposium (online) on April 21, 2021, organized by the Norwegian University of Science and Technology (Vojislav Novakovic).
- A 1-day symposium (hybrid) in Singapore on Sept. 21, 2022, organized and hosted by National University of Singapore (Clayton Miller).

12.2.4. Panel discussions

Two panel discussions have been organized with international experts during the Annex meetings in 20021: one with architects and planners (sixth Annex 79 meeting, organized by Norwegian University of Science and Technology), and one with persons from the area of data-driven building management and control (seventh Annex 79 meeting, organized by Washington State University). These discussions provided valuable information whether research objectives (of the Annex) are in line with the needs of practitioners and how results from research should be transferred to practice for better and faster application.

12.2.5. Seminars, workshops at international conferences

Andreas Wagner represented Annex 79 at the IEA-led workshop titled "Behaviour change for energy efficiency: Opportunities for international cooperation in the G20 and beyond" on September 12, 2018 in Paris, France.

Liam O'Brien represented Annex 79 and EBC through an invited seminar at the National Energy Efficiency Conference in Sydney Australia on November 19, 2018.

Andreas Wagner was invited to contribute to an EBC Webinar on Reducing the Performance Gap between Design Intent and Real Operation in June and Liam O'Brien to an EBC Webinar on Energy Codes/Performance Standards in July 2021.

Further, participants of Annex 79 organized, led and contributed to a number of seminars and workshops at different international conferences:

- A seminar at the ASHRAE Winter Conference in Atlanta (USA) in January 2019 (Julia Day)

- A tutorial at the ACM e-Energy Conference in Phoenix (USA) in June 2019 (Mikkel Kjaergaard)
- A seminar at the ASHRAE Summer Conference in Kansas City (USA) in June 2019 (Zoltan Nagy)
- A workshop at the ISHVAC in Harbin (China) in July 2019 (Andreas Wagner, Da Yan together with Xiang Zhou)
- A session at the CISBAT in Lausanne (Switzerland) in September 2019 (Zoltan Nagy)
- A panel at the Building Simulation Conference in Rome (Italy) in September 2019 (Farhang Tahmasebi, Liam O’Brien, Da Yan, Tianzhen Hong)
- A panel at the Building Simulation Conference in Rome (Italy) in September 2019 (Bing Dong, Mikkel Kjaergaard, Salvatore Carlucci)
- A keynote at the Building Simulation Conference in Rome (Italy) in September 2019 (Ardeshir Mahdavi)
- A topical Session at the AIVC in Ghent (Belgium) in October 2019 (Andreas Wagner, Ardeshir Mahdavi)
- A seminar at the ASHRAE Winter Conference in Orlando (USA) in January 2020 (Bing Dong)
- A seminar at the ASHRAE Winter Conference in Orlando (USA) in January 2020 (Tianzhen Hong)
- A seminar at the ASHRAE Summer Conference (online) in June 2020 (Zoltan Nagy)
- A seminar at the Indoor Air 2020 Conference (online) in November 2020 (Andreas Wagner)
- A seminar at the ASHRAE Winter Conference (online) in January 2021 (Bing Dong with Chen-fei Chen, Tianzhen Hong, Clinton Andrews, Zheng O’Neill)
- A seminar at the ASHRAE Winter Conference (online) in January 2021 (Liam O'Brien with Julia Day, Mohamed Ouf, Jian Zheng, Burak Gunay)
- A seminar at the ASHRAE Summer Conference (online) in June 2021 (Han Li, Tianzhen Hong)
- A seminar at the European Healthy Buildings Conference (online) in June 2021 (Marcel Schweiker)
- A workshop at the ACM BuildSys in Coimbra (Spain), hybrid, in November 2021 (Bing Dong, Romana Markovic, Salvatore Carlucci)
- A workshop at the CLIMA Conference in Rotterdam (The Netherlands) in May 2022 (Ardeshir Mahdavi, Marcel Schweiker, Andreas Wagner)
- A workshop at the CLIMA Conference in Rotterdam (The Netherlands) in May 2022 (Runa Hellwig, Andreas Wagner)
- A seminar at the ASHRAE Summer Conference in Toronto (Canada) in June 2022 (Bing Dong)
- A seminar at the ASHRAE Summer Conference in Toronto (Canada) in June 2022 (Michael Kane)
- A seminar at the Indoor Air Conference in Kuopio (Finland) in June 2022 (Donna Vakalis, Sandra Dodesko, Ardeshir Mahdavi, Marcel Schweiker)
- A seminar at the COBEE Conference in Montreal (Canada) in July 2022 (Andreas Wagner)
- A workshop at the ACM BuildSys in Boston (USA) in November 2022 (Bing Dong, Salvatore Carlucci)
- A seminar at the ASHRAE Winter Conference in Atlanta (USA) in February 2023 (Tianzhen Hong)

- A seminar at the ASHRAE Winter Conference in Atlanta (USA) in February 2023 (Sonya Pouny)
- A workshop at the Healthy Building Europe Conference in Aachen (Germany) in June 2023 (Andreas Wagner, Isabel Mino Rodriguez)
- A seminar at the ASHRAE Summer Conference in Tampa (USA) in June 2023 (Burak Gunay)
- A seminar at the ASHRAE Summer Conference in Tampa (USA) in June 2023 (Bing Dong)
- A seminar at the ASHRAE BPACS Conference in Austin (USA) in September 2023 (Zoltan Nagy)
- A workshop at the ACM BuildSys in Istanbul (Turkey) in November 2023 (Bing Dong)
- A seminar at the ASHRAE 2024 Winter Conference in Chicago (USA) in January 2024 (Burak Gunay)

More seminars and workshops had been planned for 2020 and 2021 but were canceled due to the pandemic.

12.2.6. Topical journal issues and books

A special issue on literature review papers for the journal 'Building & Environment' was published with the title 'State-of-the-art in occupant-centric building design an operation: a collection of reviews'. It was guest-edited by Andreas Wagner and Liam O'Brien with 12 papers published by the 4 Subtasks besides a central paper and an editorial written by the Operating Agents and Subtask Leaders.

A second special issue, titled 'Simulation of Occupant-Centric Control for Building Operations', and guest-edited by members of Annex 79, has been published for the 'Journal of Building Performance Simulation'. It includes 14 papers with most of them by authors participating in Annex 79 and 4 papers are directly linked to Subtask 4 of the Annex.

A third special issue on 'Occupant-centric control strategies for building systems', guest-edited by members of Annex 79, is – at the time of reporting – being finalized journal of 'Energy and Buildings'.

A book titled 'Occupant-centric simulation-aided building design: theory, application, and case studies' was published in May 2023. The book is published as open access with Routledge/Taylor and Francis, which allows the book to be counted as an official deliverable of Annex 79.

12.2.7. Journal publications

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12.3. List of Annex 79 participants

Table 12-1: Participants who attended at least 50% (5) of experts' meetings

Participating Institution – name and country acronym	Participant name
Commonwealth Scientific and Industrial Research Organisation (CSIRO), AUS	Dong Chen
Deakin University, AUS	Astrid Roetzel
Technical University Vienna, AUT	Ardeshir Mahdavi
University of Ghent, BEL	Silke Verbruggen
Universidade Federal de Santa Catarina, BRA	Maira Andre
Universidade Federal de Santa Catarina, BRA	Mateus Bavaresco
CAN	Anja Jamrozik
Carleton University, CAN	Brodie Hobson
Carleton University, CAN	Burak Gunay
Carleton University, CAN	Connor Brackley
Carleton University, CAN	Liam O'Brien
Carleton University, CAN	Mohamed Ouf
Carleton University, CAN	Tareq Abuimara
Carleton University, CAN	Vinu Subashini Rajus
Université Laval, CAN	Jean Rouleau
Université Laval, CAN	Louis Gosselin
University of British Columbia, CAN	Adam Rysanek
University of British Columbia, CAN	Sarah Crosby
University of Toronto, CAN	Brent Huchuk
University of Toronto, CAN	Helen Stopps
University of Toronto, CAN	Marianne Touchie
University of Toronto, CAN	Maedot Andargie

University of Toronto, CAN	Shengbo Zhang
Tongji University, CHN	Han Zhu
Tsinghua University, CHN	Da Yan
Aalborg University, DNK	Christiane Berger
Aalborg University, DNK	Runa T. Hellwig
Aalborg University Copenhagen, DNK	Henrik N. Knudsen
Southern University of Denmark, DNK	Mikkel Kjaergaard
Technical University of Denmark, DNK	Lucile Sarran
Technical University of Denmark, DNK	Davide Cali
Technical University of Denmark, DNK	Ricardo Rupp
Technical University of Denmark, DNK	Rune Korsholm Andersen
Universite La Rochelle, FRA	Marika Vellei
Forschungszentrum Juelich GmbH, DEU	Ghadeer Derbas
Karlsruhe Institute of Technology, DEU	Andreas Wagner
Karlsruhe Institute of Technology, DEU	Romana Markovic
Karlsruhe Institute of Technology, DEU	Isabel Mino
Karlsruhe Institute of Technology, DEU	Romina Rissetto
Munich University of Applied Sciences, DEU	Jakob Hahn
RWTH Aachen University, DEU	Clara Lorenz
RWTH Aachen University, DEU	Felix Nienaber
RWTH Aachen University, DEU	Marc Syndicus
RWTH Aachen University, DEU	Marcel Schweiker
EURAC Research/Politecnico di Milano, ITA	Juan C. Mahecha Zambrano
Politecnico di Torino, ITA	Carola Lingua
Politecnico di Torino, ITA	Giorgia Spigliantini
Unipg, ITA	Ilaria Pigliautile
Università degli Studi di Perugia, ITA	Anna Laura Pisello
Università degli Studi di Perugia, ITA	Cristina Piselli
University of Calabria, ITA	Gianmarco Fajilla
University of Calabria, ITA	Marilena De Simone
Norwegian University of Science and Technology, NOR	Jakub Dziedzic
Norwegian University of Science and Technology, NOR	Vojislav Novakovic
Norwegian University of Science and Technology, NOR	Salvatore Carlucci
National University of Singapore, SGP	Clayton Miller
Chalmers University, SWE	Despoina Teli
Chalmers University, SWE	Quan Jin
EPFL, CHE	Dolaana Khovalyg
EPFL, CHE	Andrew Sonta
EPFL Fribourg, CHE	Verena Barthelmes
ETH Zurich, CHE	Yuzhen Peng
Khalifa University of Science and Technology, UAE	Elie Azar
arbnco, UK	Mahnameh Taheri

Cambridge University, UK	Alessandra Luna Navarro
Cardiff University, UK	Clarice De Souza
Cardiff University, UK	Eleni Ampatzi
Liverpool John Moores University, UK	Simon Tucker
Loughborough University, UK	Steven Firth
University College London, UK	Farhang Tahmasebi
University College London, UK	Gesche Huebner
University of Southampton, UK	Stephanie Gauthier
University of Southampton, UK	Leonidas Bourikas
Florida State University, USA	Laura Arpan
Lawrence Berkeley National Laboratory, USA	Tianzhen Hong
Louisiana State University, USA	Amirhosein Jafari
Louisiana State University, USA	Yimin Zhu
Northeastern University, USA	Kunind Sharma
Northeastern University, USA	Michael Kane
Northwestern University, USA	Giorgia Chinazzo
Rutgers University, USA	Clinton Andrews
Syracuse University, USA	Bing Dong
University of Alabama, USA	Zhihong Pang
University of Texas Austin, USA	June Park
University of Texas Austin, USA	Zoltan Nagy
University of Texas San Antonio, USA	Hannah Fontenot
University of Virginia, USA	Alan Wang
University of Virginia, USA	Arsalan Heydarian
Virginia Tech, USA	Philip Agee
Washington State University, USA	Julia Day
Syracuse University, USA	Meng Kong

Table 12-2: Interested parties – individuals attending at least two meetings, but fewer than five

Participating Institution – name and country acronym	Participant name
Deakin University, AUS	Hong Xian Li (Lily)
Deakin University, AUS	Abdul-Manan Sadick
Monash University, AUS	Jenny Zhou
RMIT University, AUS	Mohammad Saiedur Rahaman
Royal Melbourne Institute of Technology, AUS	Flora D. Salim
University of Melbourne, AUS	Masa Noguchi
Universidade Federal de Santa Catarina, BRA	Roberto Lamberts
Carleton University, CAN	Jayson Bursill
Carleton University, CAN	Weihao Li

Rowan Williams Davies and Irwin Inc., CAN	Sebastian Carrizo
University of Alberta, CAN	Omid Ardakanian
University of Waterloo, CAN	Joyce Kim
Hunan University, CHN	Yixing Chen
Tongji University, CHN	Cui Li
Tongji University, CHN	Zhengrong Li
Tsinghua University, CHN	Xuyuan Kang
Tsinghua University, CHN	Yuan Jin
Zhejiang University, CHN	Shuqin Chen
Danish Technological Institute, DNK	Babette Peulicke Slott
Danish Technological Institute, DNK	Kasper Furu Nielsen
Southern University of Denmark, DNK	Diane Bastien
University of Southern Denmark, DNK	Fisayo Sangogboye
Fraunhofer Institute, DEU	Sarah Weiner
ABUD, HUN	Andras Reith
DGNB Consultant, HUN	Zsófia Bélafi
Polytechnical University of Torino, ITA	Mariantonietta Tarantini
Eindhoven University of Technology, NLD	Isabella Gaetani
Huygen, NLD	Simona D'Oca
BRANZ, NZL	Manfred Plagmann
Norwegian University of Science and Technology, NOR	Masab Khalid Annaqeeb
National University of Singapore, SGP	Prageeth Jayathissa
National University of Singapore, SGP	Adrian Chong
Chalmers University, SWE	Theofanis Psomas
Dalarna University, SWE	Mengjie Han
Cardiff University, UK	Shuye Wang
Southampton University, UK	Philipp Turner
University College London, SWE	Athina Petsou
University College London, UK	Dejan Mumovic
University College London, UK	Shen Wei
Delos, USA	Carolina Campanella
Delos, USA	Jie Zhao
Drexel University, USA	Jin Wen
Iowa State University, USA	Debrudra Mitra
Lawrence Berkeley National Laboratory, USA	Marco Pritoni
Lawrence Berkeley National Laboratory, USA	Handi Chandra Putra
Michigan State University, USA	Dong Zhao

Northeastern University, USA	Qi Wang
Princeton University, USA	Hongshan Gua
Stanford University, USA	Rishee Jain
University of North Carolina at Charlotte, USA	William Tolone
University of Texas Austin, USA	Kingsley Nweye
University of Vermont, USA	Claire McIlvennie
Virginia Tech, USA	Farrohk Jazizadeh Karimi