SLUTRAPPORT

Projektnamn: En experimentell laborativ studie av interaktion mellan energieffektiva åtgärder i byggnader och boendes beteenden

Datum: 2026/2/23

Författare: Weizhuo Lu, Kailun Feng, Chanachok Chokwitthaya

Design för energieffektiv vardag
– ett program från Energimyndigheten med SVID som koordinator
c/o SVID, Stiftelsen Svensk Industridesign | Svensksundsvägen 13 | 111 49 Stockholm
08 – 406 84 40 | info@svid.se | www.designforenergi.se

Energimyndigheten
SVID

Datum
2026-03-22

Projektnr:
P2022-00141

Energimyndighetens titel på projektet – svenska
En experimentell laborativ studie av interaktion mellan energieffektiva åtgärder i byggnader och boendes beteenden

---

Energimyndighetens titel på projektet – engelska
An experimental lab study of interaction between building energy-efficient measures andoccupants' behaviors

---

Universitet/högskola/företag
Umeå universitet

Avdelning/institution
Institutionen för tillämpad fysik och elektronik

Adress
901 87 UMEÅ

Namn på projektledare
Weizhuo Lu

Namn på ev. övriga projektdeltagare
Santhan Reddy Penaka, Kailun Feng, Chanachok Chokwitthaya

Nyckelord: 5–7 st
energieffektiviserande åtgärder, interaktionen, energieffektivt beteende

---

Preface

This project was funded by the Swedish Energy Agency (Energimyndigheten) under the programme “Design för energieffektiv vardag”. We thank the project reference group and collaborating partners for feedback and support, and all study participants for their time and contributions.

Table of contents

Sammanfattning

Projektet undersöker hur energieffektiviserande åtgärder i byggnader (t.ex. förbättrade fönster, ventilationsuppgraderingar och isolering) påverkar människors beteenden, och hur dessa beteenden i sin tur påverkar energibesparing och inomhuskomfort. Vi utvecklade och testade ett hybrid-upplägg som kombinerar en immersiv virtuell miljö (VR) med ett fysiskt labb där temperatur, luftfuktighet och luftrörelse kan styras. I en första serie experiment i en temporär labbmiljö samlades 480 beteendeobservationer in under olika renoveringsscenarier. Resultaten visar att renoveringsåtgärder påverkar framför allt användning av personliga värmare och hur ofta dörrar öppnas, medan människors klädvanor var mer stabilt. Vi utvecklade också en datadriven modell (maskininlärning) baserad på stora simuleringsdataset och fältdata, som kunde förutsäga rumstemperatur med cirka 0,3 °C medelavvikelse i labbet. Projektet har etablerat en formell IHBI-labbmiljö och tagit fram en ram för att bedöma beteendeinterventioner med kausal inferens. Nästa steg är att skala upp experimenten med fler och mer varierade deltagare samt fler miljöparametrar och åtgärdsscenarier.

Summary

Energy-efficient renovations are essential for reducing energy use and emissions in buildings, but their real-world performance depends strongly on how occupants respond. This project studied (1) how renovation measures change occupants’ daily actions (e.g., use of electrical heaters, opening doors/windows, clothing habits) and (2) how these actions feed back into

indoor comfort and energy outcomes. We developed and validated a hybrid experimental method that links an Immersive Virtual Environment (IVE) with a climate-controlled Physical Laboratory Environment (PLE). Participants interact with realistic renovation scenarios in the IVE while the PLE reproduces the corresponding thermal conditions. A data-driven model (machine learning) was trained using large Building Performance Simulation datasets and calibrated with field/lab measurements to map renovation measures and occupant actions to indoor conditions. Key results include: (i) a calibrated model that predicted laboratory room temperature with an average deviation of about 0.3 °C; (ii) 480 behaviour observations showing that renovation scenarios strongly affect electrical heater use and door opening, while clothing behaviour is comparatively stable; (iii) a causal framework (CEOBI) to evaluate behavioural interventions and estimate their potential impact before deployment; and (iv) a guideline for the public to suggest the energy-efficient behaviors after building renovations. The project delivered a functional IHBI laboratory platform and scientific outputs. Next steps are to increase sample size and diversity, extend controlled variables (e.g., air movement), and translate the findings into more practices for renovation design and occupant-oriented energy saving.

Introduction/Background

Buildings account for a substantial share of final energy use. Renovation measures such as improved envelopes, windows, heat recovery and heating system adjustments can reduce energy demand, but the achieved savings often deviate from predictions because people adapt their behaviour. For example, occupants may reduce the use of electrical heaters in improved indoor conditions, or conversely open doors/windows more often when ventilation systems change. Understanding these interactions is necessary for occupant-centric, reliable energy efficiency.

Project objectives (as defined in the proposal):

1. Establish experimental planning and data collection to observe occupant behaviours under different energy-efficient measures.
2. Quantify how alternative occupant behaviours influence energy use and indoor environment, using big-data driven modelling and machine learning.
3. Develop and evaluate strategies to support energy-saving behaviour in an immersive, informative and engaging environment to foster durable behaviour change.

The project ran from August 2022 to December 2025 at Umeå University, building on the IHBI lab concept. The main target group for experimental participation was Umeå local residents, university teachers and students, reflecting the programme focus on everyday energy practices.

Implementation

The project activities were organised around three linked technical components: (a) data-driven modelling, (b) a hybrid IVE-PLE experimental pipeline, and (c) intervention evaluation.

1. Data-driven modelling of renovation–behaviour–indoor environment links

We developed a machine learning model trained on large datasets generated via Building Performance Simulation (BPS) combined with measured data from IHBI laboratory room (see Figure 1). The BPS dataset covered many combinations of energy-efficient measures and occupant actions. Field measurements collected during March–June 2023 were used to calibrate and validate the model via transfer learning.

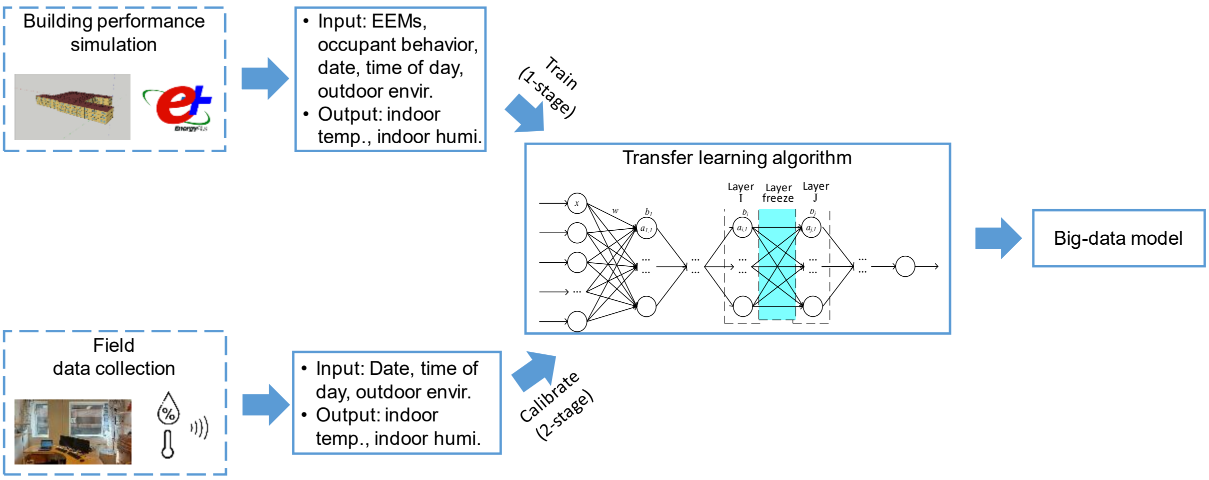

Figure 1. The training and calibration of data-driven model

2. Hybrid experimental approach: Immersive Virtual Environment + Physical Laboratory Environment

We implemented a hybrid approach integrating a detailed immersive virtual model of target rooms/buildings with a climate-controlled laboratory (see Figure 2). The workflow includes: (1) collecting building and renovation information; (2) building a virtual environment with interactive elements (doors, windows, electrical heaters, clothing, etc.); (3) observing occupants' interactions in the IVE; (4) feeding the observed behaviour to the data-driven model to predict indoor conditions under the renovation scenario; and (5) reproducing those conditions in the PLE through controlled HVAC/heating/humidification equipment and sensors.

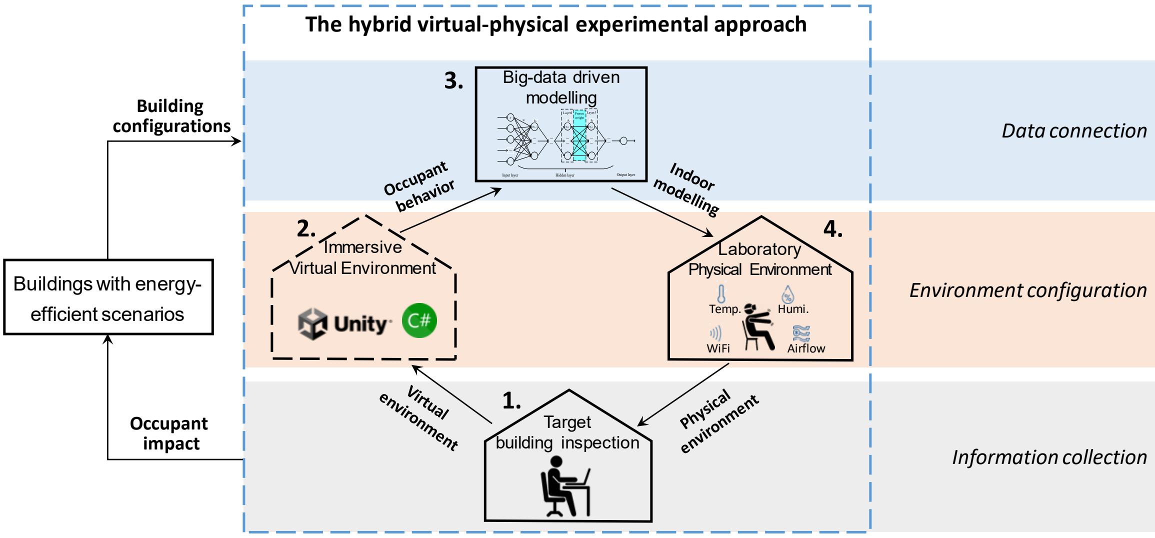

Figure 2. Overall process of the proposed hybrid experimental approach

3. Experimental campaigns

An experimental campaign was conducted in the Intelligent Human-Buildings Interaction (IHBI) laboratory in Teknikhuset at Umeå University. The IHBI Lab is developed at Umeå Campus as Figure 3. Participants attended experimental workdays (08:00–17:00) and performed cognitive tasks while interacting with virtual controls. Renovation scenarios included wall insulation, window improvement, district heating adjustment, and HVAC heat recovery. Behavioural events (heater use, door opening, clothing changes) and subjective votes (thermal sensation and acceptability) were recorded.

Figure 3. Intelligent Human-Building Interaction lab

4. Intervention evaluation with causal inference (CEOBI) and behavioral guide

To assess behaviour interventions before implementing them in real buildings, we developed the Causal-Elicited Occupant-Building Interaction framework (CEOBI). CEOBI structures experiments using a Spatial–Temporal Event–Driven (STED) approach and uses a Drivers–Needs–Actions–Systems (DNAS) model to define factors. Causal inference methods estimate the Average Treatment Effect of candidate interventions and include robustness checks via refutation tests. The Intervention Experiment in IVE will support the mapping of the STED and DNAS, providing evidence to causal inference analysis.

Results

1. Key results at a glance

- A combined modelling-and-experiment workflow was established to quantify how energy-efficient measures (EEMs) and occupant behaviour interact and jointly affect indoor conditions and energy use.
- A data-driven model was trained using a large Building Performance Simulation (BPS) dataset (175,200 samples) combined with laboratory measurements (March–June 2023) for calibration (see Figure 1); the model achieved an average temperature deviation of targets about 0.3°C compared with measured room temperature in the laboratory.
- A hybrid experimental method (Immersive Virtual Environment + Physical Laboratory Environment, as Figure 2) was piloted in a temporary lab at Umeå University, enabling safe and repeatable testing of renovation scenarios before full-scale implementation.

- Across the first-stage campaign, 480 behaviour observations were recorded for key thermal-related actions (electrical heater use, clothing adjustment, and door opening) under multiple renovation scenarios.
- Behavioural responses were scenario-dependent: some measures reduced electrical heater use while increasing door opening frequency, whereas clothing adjustment showed smaller changes across scenarios.
- The Intelligent Human–Buildings Interaction (IHBI) lab platform was developed and was advanced from concept to operational readiness, including core sensing/control infrastructure and experimental protocols for future studies (see Figure 3).

2. Performance of the data-driven model

This work package developed a data-driven surrogate model to rapidly estimate indoor thermal conditions and energy outcomes under different combinations of (i) renovation measures and (ii) occupant actions. The goal was not only predictive accuracy but also supports the experimental workflow. It intended to support evaluation and output to control the physical parameters of lab devices for laboratory testing.

2.1 Data sources and feature design

Two complementary data streams were used, see Table 1:

1) Building Performance Simulation (BPS) data: 175,200 simulated samples were generated to represent a wide range of EEM packages and occupant behaviour patterns. This synthetic dataset provides broad coverage of plausible conditions that are expensive or impossible to observe exhaustively in real buildings.
2) Laboratory field data: measurements collected in the lab room from March to June 2023 were used to calibrate and sanity-check the model predictions under real sensor noise, real control actions, and realistic boundary conditions.

The input features include descriptors of the renovation scenario (e.g., envelope upgrades and HVAC system changes) and occupant's thermal-related actions (e.g., the presence/absence or intensity of heater use, door opening events, and clothing adjustments). The model output focuses on indoor thermal states (in particular room air temperature and humidity) as a proxy for comfort and energy-service delivery.

2.2 Model training and validation approach

The BPS dataset was used for primary training, while the laboratory data provided an external reference for calibration. We applied standard train/validation splits and monitored generalisation performance to avoid overfitting to specific simulated patterns. Because the

BPS data cover many more combinations than the laboratory data, the model can be used as a fast 'scenario generator' to propose experimental conditions that are informative but still realistic.

2.3 Predictive performance (temperature)

When evaluated against measured room temperature in the laboratory, the model achieved an average deviation of approximately 0.3°C. This level of error is small relative to typical comfort-relevant temperature variations in offices and provides confidence that the surrogate model can support comparative scenario analysis. Importantly, the evaluation was performed on real measurements (March–June 2023), not only on held-out simulations.

Table 1. Summary of datasets used for the data-driven model.

Dataset	Purpose	Key details
BPS synthetic dataset	Primary model training and broad scenario coverage	175,200 samples spanning multiple EEM packages and behaviour patterns
Lab field measurements	Calibration and external validation	Measured indoor conditions collected March–June 2023 in a lab room

The calibrated model demonstrated strong predictive accuracy for laboratory indoor temperature. When tested against measured lab room temperatures, the model achieved an average deviation of approximately 0.3 °C.

3. Observed occupant behaviours under renovation scenarios

This section summarises the first-stage experimental evidence on how occupants adapt their thermal-related actions when exposed to different energy renovation scenarios. The experiments were designed to capture behavioural responses that are often simplified in building energy models but can strongly influence real-world performance.

3.1 Experimental setting and scenarios

The hybrid experimental approach was conducted and validated in a temporary laboratory located in Teknikhuset at Umeå University. Participants worked in the lab from 08:00 to 17:00 and experienced renovation scenarios through an Immersive Virtual Environment (IVE). Within the IVE, they could interact with key elements relevant to thermal adaptation, including a electrical heater, clothing options, and a door (representing ventilation through door opening).

The tested renovation scenarios included: wall insulation, window improvement, district heating adjustment, and an HVAC-related measure (heat recovery / ventilation system update). A baseline scenario without EEMs was used for comparison.

3.2 Observed behaviours and sample size

Up to this point, 480 behaviour observations have been recorded. Behaviours were coded as events or decisions during the experimental day and summarised as frequencies for three action categories: electrical heater use, office door opening, and clothing adjustment.

Table 2 reports descriptive statistics of the observed behaviours by scenario. The table is included to make the evidence transparent and reusable for future modelling and meta-analysis.

Table 2. Descriptive statistics of occupant behaviours under different renovation scenarios (first-stage dataset).

Scenario	N	Behavioral frequency (%)	Std. deviation (%)	Variance (%)
Heater use behavior				
no_EEM	96	53.13	50.16	25.2
ventilation system update	96	3.13	17.49	3.1
district heat adjustment	96	36.46	48.38	23.4
wall insulation	96	32.29	47.01	22.1
window type	96	37.50	48.67	23.7
all EEM	480	32.50	46.89	22.0
Door opening behavior				
no_EEM	96	3.13	17.49	3.1
ventilation system update	96	34.38	47.75	22.8
district heat adjustment.	96	6.25	24.33	5.9
wall insulation	96	4.17	20.09	4.0
window type	96	6.25	24.33	5.9
all EEM	480	10.83	31.11	9.7
People’s clothing habit				
no_EEM	96	48.96	50.25	25.3
ventilation system update	96	18.75	39.24	15.4
district heat adjustment	96	57.29	49.73	4.7
wall insulation	96	62.50	48.67	23.7
window type	96	51.04	50.25	25.3
all EEM	480	47.50	49.99	25.0

Key behavioural insights from the first-stage dataset are summarised below. These statements are descriptive (not causal) and are intended to guide future controlled studies and model parameterisation.

- Electrical heater use showed large variation across scenarios. The baseline (no EEM) had the highest heater-use frequency, while the ventilation/HVAC update scenario showed a much lower heater-use frequency. This suggests that perceived thermal improvement can reduce the need for personal heating, but the response magnitude depends on the specific measure and the perceived controllability of the environment.
- Door opening behaviour increased in some renovation scenarios (notably the ventilation/HVAC update case in this early dataset). This is an important finding for energy modelling because increased door opening can introduce additional heat losses and ventilation changes, potentially offsetting some savings if not accounted for.
- Clothing adjustment behaviour was comparatively more stable across scenarios. In this dataset, changes were smaller than for heater use, indicating that participants may prefer 'environmental' actions (heater/door) over changing clothing in an office-like context, or that clothing options were already near a comfort optimum.
- The results highlight the risk of evaluating renovation measures using energy simulations alone: behavioural adaptation may amplify or dampen expected energy savings depending on the measure and on how occupants perceive indoor comfort and control.

Across the first-stage experiments, 480 behaviour observations were collected. Descriptive statistics showed clear behavioural differences between scenarios. The baseline scenario (no renovation measure) had the highest frequency of electrical heater use, while the HVAC heat recovery scenario showed the lowest heater use but the highest door-opening frequency. Clothing adjustment behaviour was relatively similar across scenarios. In summary, this experiment found that:

- Energy-efficient renovations changed heater use and door opening behaviour, but had limited influence on clothing behaviour.
- For ventilation system update and window improvement, occupants used electrical heaters much less frequently, implying additional energy savings beyond the technology effect alone.
- Electrical heater use was strongly associated with renovation scenario, thermal sensation/acceptability, and time of day, but not strongly linked to other behaviours such as door opening or clothing.

4. Evaluation of experimental approaches for Human–Building Interaction study

Beyond the numerical results, a major output of the project is methodological: we tested how immersive virtual environments can be combined with physical laboratory infrastructure to study human–building interactions in a controlled, repeatable, and ethically acceptable way.

4.1 Why a hybrid approach was needed

Pure field studies capture realism but provide limited control over building systems, weather, and concurrent behavioural drivers. Pure laboratory studies provide control but typically cannot represent future or hypothetical renovation scenarios without costly physical retrofits. The hybrid approach addresses this gap by using VR/IVE to represent the renovated building state while maintaining a physical space where occupants can perform realistic tasks and interact with tangible controls.

4.2 Strengths observed in this project

- Scenario flexibility: multiple renovation options can be tested without physically rebuilding the lab for each case.
- Repeatability: participants can be exposed to the same scenario conditions, supporting comparison across groups and time.
- Behavioural traceability: interactions in the IVE can be logged with time stamps, enabling fine-grained behaviour analysis and linking to environmental measurements.
- Safety and ethics: potentially uncomfortable or extreme scenarios can be tested with safeguards and controlled exposure.

4.3 Limitations and mitigation strategies

- Ecological validity: VR may not reproduce all sensory cues (e.g., real radiant asymmetry or air movement). We mitigated this by pairing VR scenarios with physical environmental control and by prioritising behaviours that depend mainly on perceived comfort and control (heater/door/clothing).
- Learning and novelty effects: participants may behave differently due to the novelty of VR. We used familiar office-like tasks and allowed acclimatisation time before logging behaviours.
- Sample diversity: early observations were collected in a temporary lab and from a limited population (primarily students). A key next step is to broaden sampling in the full IHBI lab and include more diverse occupant profiles.

Overall, the project demonstrates that the hybrid approach is feasible and informative for studying renovation–behaviour interactions, while also clarifying where additional validation is needed for long-term deployment.

A methodological comparison experiment examined baseline (real setting), IVE-based observation, and survey-based approaches. Results indicated that the IVE approach produced thermal perception and interaction intention responses close to baseline conditions, while surveys were useful for preliminary insights but less faithful to in-situ experience. Some negative effects of IVE (e.g., discomfort or reduced realism) were observed and should be mitigated in future studies.

5. Laboratory platform development

The project also contributed to establishing the Intelligent Human–Buildings Interaction (IHBI) laboratory as a research platform. The aim is to provide a facility where building physics, sensing and control, immersive environments, and behavioural science can be integrated to evaluate energy efficiency from a human-centred perspective.

5.1 Platform components delivered

- A VR/IVE setup capable of presenting alternative renovation scenarios and logging user interactions.
- A physical lab space suitable for office-like occupancy experiments, including controllable thermal conditions and standard measurement points.
- An experimental protocol covering participant scheduling, task scripts, behaviour coding, and data management.
- An initial dataset that can be used as a baseline for replication and extension studies (480 coded behaviour observations).

5.2 Readiness assessment and planned use cases

To support long-term use, we assessed readiness from both a technical and a scientific perspective. Table 3 summarises the readiness dimensions and what is already operational versus what will be strengthened in follow-up work.

Table 3. IHBI platform readiness: what is operational and what remains to be improved.

Dimension	Status at project end	Notes / next steps
Immersive scenario delivery	Operational pilot	Expand scenario library and improve visual/thermal cue consistency
Physical lab environment control	Operational for office-like tests	Extend to wider temperature ranges and add airflow/radiant control options

Behaviour logging and coding	Operational for key actions	Standardise codebook and automate parts of logging where possible
Data integration (sensors + VR logs)	Operational in pilot form	Harmonise timestamps, metadata schema, and quality checks
Reproducible protocol and ethics	Operational pilot	Broaden participant recruitment and formalise long-term data governance

In summary, IHBI is ready for expanded experimental campaigns focused on renovation measures, occupant adaptation, and the 'performance gap' between predicted and realised energy savings. The platform also provides a foundation for student training and interdisciplinary collaboration.

The formal Intelligent Human–Building Interaction (IHBI) laboratory was completed and tested. In preliminary commissioning tests, the lowest achievable indoor air temperature was 19 °C and the highest was 28 °C (higher possible with additional heaters). A 5 °C decrease typically required about 10 minutes, while a 5 °C increase required about 5 minutes. These capabilities support controlled studies of comfort and behaviour under renovation scenarios.

6. Data products, transparency, and reuse

In addition to scientific findings, the project produced reusable assets that can accelerate future research and improve transparency. These assets are particularly valuable for human–building interaction research, where experimental data collection is expensive and often difficult to reproduce.

- Behaviour coding dataset: a structured dataset of the first-stage observations (N=480), including scenario labels and behaviour categories (heater use, door opening, clothing adjustment).
- Scenario definitions for EEMs: parameterised descriptions of the tested renovation measures that can be reused in simulations and in the IVE scenario library.
- Data-driven surrogate model: a trained model and the associated feature schema linking EEMs and behaviours to indoor temperature outcomes (validated against laboratory measurements with ~0.3°C average deviation).
- Experimental protocol package: participant schedule templates, task scripts, data logging procedures, and a behaviour codebook to support replication in the full IHBI lab.

These assets are intended to be shared within the project consortium and, where feasible, with the research community through publications and supplementary materials, subject to data protection and ethics requirements.

7. From findings to practice: implications for energy renovation

A practical motivation for this project is the well-known ‘performance gap’ between predicted and realised energy savings after renovation. The results highlight several concrete implications for practitioners and policymakers:

- Renovation measures can change behaviour: even when indoor temperatures improve, occupants may adjust other actions (e.g., door opening) that affect energy balance. Commissioning and user guidance should therefore accompany technical upgrades.
- Behaviour is measure-specific: different EEMs triggered different behavioural patterns in the pilot dataset. This means that a ‘one-size-fits-all’ behaviour assumption in renovation appraisal can be misleading.
- Focus on controllability and feedback: behaviours such as heater use are closely tied to perceived control. Providing clear feedback and convenient control interfaces may help align occupant actions with intended energy outcomes.
- Use experiments to de-risk investments: hybrid virtual–physical tests can be used early in renovation planning to identify potential unintended behavioural responses and to design mitigation strategies (e.g., communication, interface design, or complementary controls).

These implications are aligned with the funding programme’s emphasis on knowledge and competence for an energy-efficient everyday life, particularly among students and other building users.

8. Causal inference perspective (CEOBI) and next-step analysis

The project also scoped a causal inference approach (referred to as CEOBI) to move beyond descriptive statistics and to estimate how specific interventions (EEMs or behaviour-change measures) would causally affect energy and comfort outcomes. While full causal estimation requires larger samples and stronger experimental control, the project clarified an analysis roadmap:

- Define the intervention and outcome clearly (e.g., adding heat recovery as the intervention; heater-use probability and indoor temperature as outcomes).
- Specify the causal graph and confounders (e.g., baseline comfort preference, task intensity, and ambient conditions).
- Choose an identification strategy (randomised assignment when feasible; otherwise quasi-experimental approaches such as matching or difference-in-differences).

- Estimate treatment effects with uncertainty and perform robustness checks (sensitivity to unmeasured confounding).
- Translate effects into practical metrics (e.g., expected change in heater-use frequency and its energy implication).

This roadmap will be applied in follow-up campaigns in the full IHBI lab, where larger participant pools and repeated measures will allow stronger causal conclusions.

Discussion

The project demonstrates that renovation measures can trigger behavioural adaptations that meaningfully change energy outcomes. In particular, reduced electrical heater use under certain renovation scenarios suggests that traditional engineering evaluations may underestimate savings when behavioural feedback is ignored. Conversely, increased door opening in some scenarios may offset part of the expected benefit if it increases heat loss or disrupts ventilation control.

Methodologically, the hybrid IVE–PLE approach enables controlled, repeatable experiments while preserving contextual realism. The data-driven model serves as the “translation layer” linking what participants do in the virtual space to plausible physical indoor conditions. CEOBI provides a structured pathway to test behavioural interventions (information, nudges, feedback) and quantify likely effects using causal inference.

Recommended next steps:

- Scale up to larger and more diverse participant samples, including residents and users of public buildings.
- Extend controlled variables beyond temperature (humidity, air movement) and include additional renovation measures.
- Improve and expand virtual interactive components to reduce negative IVE effects and better reflect real control options.

Translate results into guidance for renovation design, commissioning, and occupant communication to maximise realised energy savings.

Publication List

1. Publications overview

Table 4 provides an overview of project-related publications included in the supporting materials. For transparency, DOI information is provided when available. In total 5 journal articles and 5 conference papers are produced supported by this project.

Table 4. Overview of project-related publications.

Title (short)	Type	Year	DOI
A Data-Driven Exploration of the Relations between Occupant Behaviors and Comfort Performances of Energy-Efficient Measures [1]	Conference paper (ICCREM 2023)	2023	--
Ontology for experimentation of human-building interactions using virtual reality [2]	Advanced Engineering Informatics	2023	10.1016/j.aei.2023.101903
Exploring mega-trend diffusion algorithms for synthetizing data associated with occupant-building interaction in IVEs [3]	Conference paper (ICCREM 2024)	2024	--
Exploring occupant behaviors and interactions in buildings with energy-efficient renovations a hybrid virtual-physical experimental approach [4]	Building and Environment	2024	10.1016/j.buildenv.2024.111991
Improved energy retrofit decision making through enhanced bottom-up building stock modelling [5]	Energy and Buildings	2024	10.1016/j.enbuild.2024.114492
Intelligent Human-Buildings Interaction Lab as a Platform to Investigate Inhabitants Adaptation Towards Temperature Extreme Weather [6]	Conference paper (SpliTech2024)	2024	--
Transfer of building retrofitting evaluations for data-scarce conditions: An empirical study for Sweden to China [7]	Energy and Buildings	2024	10.1016/j.enbuild.2024.114041
An Experimental Framework for Investigating Thermal-Related Occupant Behaviors and Interactions in Buildings under Future Climate Scenarios [8]	Conference paper (ICCREM 2025)	2025	--
Demand response optimization incorporating thermal comfort in single-family houses with on-site generation a systematic review [9]	Applied Energy	2025	10.1016/j.apenergy.2025.127305
Investigating occupant behavior and energy renovation through virtual-physical experiments Results from Intelligent Human-Buildings Interaction lab [10]	Conference paper (CISBAT 2025)	2025	--

2. Summary of appended publications

A data-driven exploration of the relations between occupant behaviors and comfort performances of energy-efficient measures

What the paper did: This study provides evidence and/or methods for understanding how people adapt their actions (such as using heaters, opening doors/windows, or changing clothing) when buildings are renovated for energy efficiency, and why these adaptations matter for comfort and energy outcomes.

Specific contribution to the project: This paper contributes the project's data-driven perspective on renovation–behaviour–comfort links, supporting the report's modelling component and highlighting why behaviour needs to be considered when assessing comfort performance after retrofits. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

An experimental framework for investigating thermal-related occupant behaviors and interactions in buildings under future climate scenarios

What the paper did: This study proposes an experimental framework to observe thermal-related behaviours under future climate conditions by combining VR scenarios with controlled physical thermal stimuli, enabling safer and more repeatable testing than field studies.

Specific contribution to the project: This publication relates to the project's overarching theme of occupant behaviour and energy renovation, and it supports dissemination of the developed lab platform and experimental evidence. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

Demand response optimization incorporating thermal comfort in single-family houses with on-site generation a systematic review

What the paper did: This review maps how demand-response control in homes can be optimised while still keeping people comfortable, summarising methods, performance indicators, and open research gaps.

Specific contribution to the project: This review paper complements the project by summarising state-of-the-art optimisation methods that incorporate thermal comfort, helping position the project results in the broader context of occupant-centric energy flexibility. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

Exploring mega-trend diffusion algorithms for synthetizing data associated with occupant-building interaction in IVEs

What the paper did: This study explores how to generate realistic synthetic datasets from small VR-based behaviour datasets, helping researchers train predictive models even when collecting large participant samples is difficult.

Specific contribution to the project: This publication relates to the project's overarching theme of occupant behaviour and energy renovation, and it supports dissemination of the developed lab platform and experimental evidence. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

Exploring occupant behaviors and interactions in buildings with energy-efficient renovations a hybrid virtual-physical experimental approach

What the paper did: This study provides evidence and/or methods for understanding how people adapt their actions (such as using heaters, opening doors/windows, or changing clothing) when buildings are renovated for energy efficiency, and why these adaptations matter for comfort and energy outcomes.

Specific contribution to the project: This paper documents the project's core experimental innovation: combining immersive virtual environments with a physical laboratory setup to study how renovation measures and occupant actions influence each other. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

Improved energy retrofit decision making through enhanced bottom-up building stock modelling

What the paper did: This study provides evidence and/or methods for understanding how people adapt their actions (such as using heaters, opening doors/windows, or changing clothing) when buildings are renovated for energy efficiency, and why these adaptations matter for comfort and energy outcomes.

Specific contribution to the project: This paper broadens the project's impact by linking retrofit decision making to enhanced bottom-up stock modelling, providing a complementary perspective on how evidence from experiments and models can inform retrofit planning. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

Intelligent Human-Buildings Interaction Lab as a platform to investigate inhabitants adaptation towards temperature extreme weather

What the paper did: This study provides evidence and/or methods for understanding how people adapt their actions (such as using heaters, opening doors/windows, or changing clothing) when buildings are renovated for energy efficiency, and why these adaptations matter for comfort and energy outcomes.

Specific contribution to the project: This publication relates to the project's overarching theme of occupant behaviour and energy renovation, and it supports dissemination of the developed lab platform and experimental evidence. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

Investigating occupant behavior and energy renovation through virtual-physical experiments Results from Intelligent Human-Buildings Interaction lab

What the paper did: This study provides evidence and/or methods for understanding how people adapt their actions (such as using heaters, opening doors/windows, or changing clothing) when buildings are renovated for energy efficiency, and why these adaptations matter for comfort and energy outcomes.

Specific contribution to the project: This publication relates to the project's overarching theme of occupant behaviour and energy renovation, and it supports dissemination of the developed lab platform and experimental evidence. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

Ontology for experimentation of human-building interactions using virtual reality

What the paper did: This study proposes a shared vocabulary (ontology) for describing VR-based human–building interaction experiments so that different research groups can document setups, variables, and protocols in a consistent way.

Specific contribution to the project: This paper provides an ontology-based foundation for describing and sharing VR-based human–building interaction experiments, supporting reproducibility and reuse of methods developed in the project. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

Transfer of building retrofitting evaluations for data-scarce conditions: An empirical study for Sweden to China

What the paper did: This study provides evidence and/or methods for understanding how people adapt their actions (such as using heaters, opening doors/windows, or changing clothing) when buildings are renovated for energy efficiency, and why these adaptations matter for comfort and energy outcomes.

Specific contribution to the project: This paper addresses methodological transferability: how retrofit evaluation approaches can be adapted when data are scarce, which is relevant for scaling occupant-centric evaluation beyond well-instrumented contexts. This publication supports Sections 2–3 of this report by providing either (i) methodological building blocks (hybrid experiments, ontologies, synthetic data methods) or (ii) evidence and contextualisation for occupant-centric evaluation of energy measures.

Appendix

Reference

[1] "A Data-Driven Exploration of the Relations between Occupant Behaviors and Comfort Performances of Energy-Efficient Measures," in *Proc. ICCREM 2023*, 2023.

[2] "Ontology for experimentation of human-building interactions using virtual reality," *Advanced Engineering Informatics*, 2023, doi: 10.1016/j.aei.2023.101903.

[3] "Exploring mega-trend diffusion algorithms for synthetizing data associated with occupant-building interaction in IVEs," in *Proc. ICCREM 2024*, 2024.

[4] "Exploring occupant behaviors and interactions in buildings with energy-efficient renovations: A hybrid virtual-physical experimental approach," *Building and Environment*, 2024, doi: 10.1016/j.buildenv.2024.111991.

[5] "Improved energy retrofit decision making through enhanced bottom-up building stock modelling," *Energy and Buildings*, 2024, doi: 10.1016/j.enbuild.2024.114492.

[6] "Intelligent Human-Buildings Interaction Lab as a Platform to Investigate Inhabitants Adaptation Towards Temperature Extreme Weather," in *Proc. SpliTech 2024*, 2024.

[7] "Transfer of building retrofitting evaluations for data-scarce conditions: An empirical study for Sweden to China," *Energy and Buildings*, 2024, doi: 10.1016/j.enbuild.2024.114041.

[8] “An Experimental Framework for Investigating Thermal-Related Occupant Behaviors and Interactions in Buildings under Future Climate Scenarios,” in *Proc. ICCREM 2025*, 2025.

[9] “Demand response optimization incorporating thermal comfort in single-family houses with on-site generation: A systematic review,” *Applied Energy*, 2025, doi: 10.1016/j.apenergy.2025.127305.

[10] “Investigating occupant behavior and energy renovation through virtual-physical experiments: Results from Intelligent Human-Buildings Interaction lab,” in *Proc. CISBAT 2025*, 2025.