ANNEX **71**

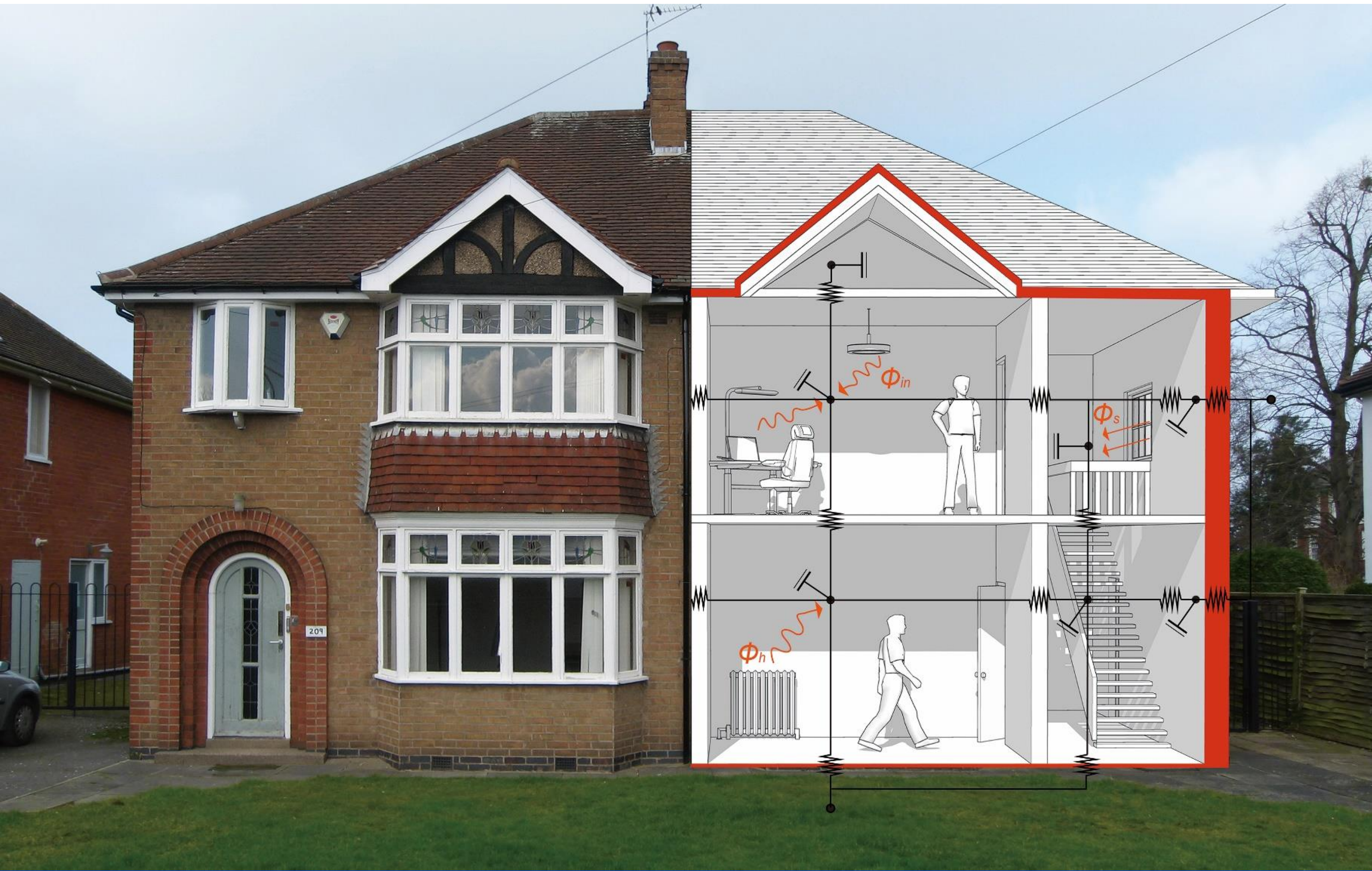
EBC

Energy in Building and Communities Programme

Building energy performance assessment based on in-situ measurements

Description and results of the validation of building energy simulation programs

August 2021



Technology Collaboration Programme

by iea

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Cover picture: drawing of Xiang Zhang (Jason) (KU Leuven, Belgium) on a picture of the Loughborough test houses (Loughborough University, UK)

ANNEX **71**

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Energy in Buildings and Communities Programme

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Description and results of the validation of building energy simulation programs

August 2021

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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 cooperation among the 30 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 high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives: The strategic objectives of the EBC TCP are as follows:

– reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
– improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
– the creation of 'low tech', robust and affordable technologies;
– the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;– the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means: The strategic objectives of the EBC TCP will be achieved by the means listed below:

– the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
– benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
– improving smart control of building services technical installations, including occupant and operator interfaces;
– addressing data issues in buildings, including non-intrusive and secure data collection;
– the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) 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 Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
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

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

IEA EBC Annex 71: Building energy performance assessment based on in-situ measurements

Annex 71 in general

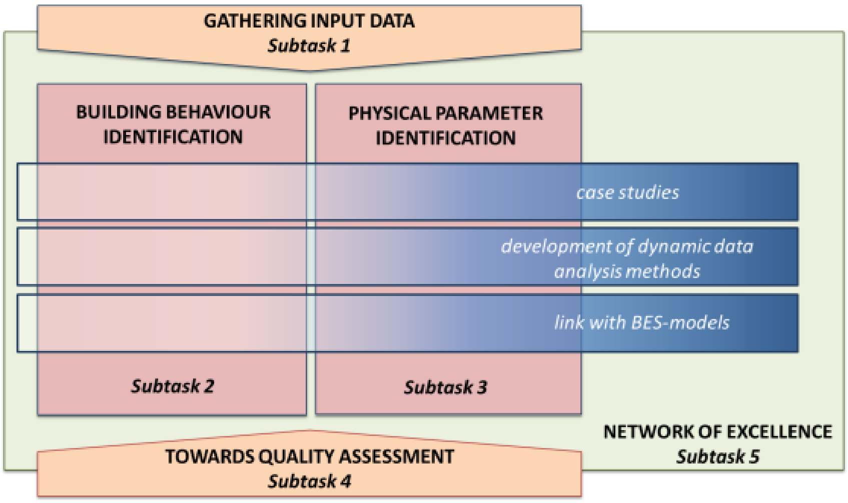
Decreasing the energy use in buildings can only be achieved by an accurate characterization of the as-built energy performance of buildings. This is mainly for two reasons. First of all, despite the ever more stringent energy legislation for new and renovated buildings, monitoring the actual energy performances reveals in many cases a significant performance gap compared to the theoretically designed targets. Secondly, the increasing need for integration of renewable energy stresses on the existing energy systems. This can be remedied by using intelligent systems and energy grids that are aware of the actual status of the buildings.

Within IEA EBC Annex 58, a first step was taken to characterize the actual energy performance of buildings based on full scale dynamic measurements. The onsite assessment methods applied within this project mainly focused on the thermal performance of the building fabric. By investigating the possibilities and limitations of black and grey box system identification models, guidelines were developed on how to assess the overall heat transfer coefficient of a building starting from dynamic measured data instead of static co-heating tests. Notwithstanding Annex 58 showed that onsite quality checks are feasible, the project highlighted at the same time the need of non-intrusive methods. Annex 71 progressed with the achievements of IEA EBC Annex 58, but aimed to make the step towards monitoring in-use buildings. The IEA EBC Annex 71 project focused on the **development of replicable methodologies embedded in a statistical and building physical framework to characterize and assess the actual energy performance of buildings starting from on board monitored data of in-use buildings**.

Structure of the project

The IEA EBC Annex 71-project was limited to residential buildings, for which the development of characterisation methods as well as of quality assurance methods have been explored. Characterisation methods aim to translate the (dynamic) behaviour of a building into a simplified model that can inform predictive control, fault detection, optimisation of district energy systems,… Within Annex 71 we refered to this as building behaviour identification. Quality assurance methods aim to pinpoint some of the most relevant actual building performance metrics. This part is referred to as physical parameter identification.

A reliable characterisation and quality assurance is strongly dependent on the availability and quality of the input data. At the same time, the expected quality and reliability of the outcome will be determined by the required accuracy to perform a quality assurance. As a result, the analysis of potential methods was steered by both the possibilities and limitations of the available input data as well as by the requested outcome to perform real quality checks. Therefore, the research project was organised as illustrated in the figure below and five subtasks were defined:



Subtask 1 investigated the possibilities and limitations of common data bases and monitoring systems. This subtask is strongly related to subtasks 2 and 3 by linking the available input data – as much as possible based on existing (non-intrusive) monitoring systems and data bases – to the accuracy of the predicted outcome. A state of the art survey of existing methods, their costs, timeframe and typical accuracy was made. In a second part the step from monitoring to current on board measuring methods was reviewed. Finally, the application of an on-site measured heat transfer coefficient within the global energy efficiency framework was proposed.

Subtask 2 focused on the development of dynamic data analysis methods suitable for describing the energy dynamics of buildings. Based on in-situ monitored data, prediction models were applied and optimised that can be used in model predictive control, fault detection, and design, control and optimisation of district energy systems,… Necessary data acquisition, development of methodologies and accuracy and reliability of the building behaviour identification models was investigated.

The focus of **Subtask 3** was on development of dynamic data analysis methods suitable for physical parameter identification of buildings. Contrary to Subtask 2, in which the identified parameters do not necessarily have a physical meaning (or do not correspond to the actual value), parameter identification aims to characterize the actual physical parameter. Subtask 3 hence investigated which methodologies are most suitable to determine the actual energy performance indicators of buildings, such as the overall heat loss coefficient, solar aperture,… As in subtask 2, the focus was on methodologies that can be used on occupied buildings, making use of (limited) monitored data.

Subtask 4 investigated to what extent the methodologies developed in ST2 and ST3 can be used in a quality assessment framework. A large survey was performed amongst possible stakeholders on interest and expectations of quality assessment methods based on in-situ measured data. The main focus was on the determination of the actual heat loss coefficient of a building in an easy, cheap and reliable way, so that it can replace the calculated design value in energy performance certifications. That way, subtask 4 made the link between the annex-participants and certification bodies, government, practitioners in the field. At the same time, subtask 4 gave the necessary boundary conditions (reliability, accuracy, cost,…) the methodologies have to fulfil to be applicable in real life quality checks.

Subtask 5 continued the collaboration with DYNASTEE (www.dynastee.info), started within Annex 58. This collaboration showed to be extremely fruitful in dissemination of the results, collecting and distributing research outcomes, and organizing conferences, workshops and training courses.

The **BES-validation exercise i**nvestigated the reliability of common building energy simulation programs. There has been significant work undertaken in past IEA EBC Annexes on validation, particularly inter-program comparisons (e.g BESTEST) and empirical validation on test cells. In Annex 58, empirical validation was extended to full-scale buildings, namely the Twin Houses at Fraunhofer IBP's test site in Holzkirchen, Germany. In this research, the focus was on fabric performance with simple internal heat gain schedules. The empirical validation undertaken in IEA Annex 71 extended the scope of the experiments in the Twin Houses by including underfloor heating systems and realistic occupancy schedules.

Overview of the working meetings

The preparation and working phase of the project encompassed nine working meetings:

Meeting	Place, date	Attended by
Kick off meeting	Leuven, Belgium, October 2016	49 participants
Second preparation meeting	Loughborough, UK, April 2017	61 participants
First working meeting	Chambéry, France, October 2017	62 participants
Second working meeting	Brussels, Belgium, April 2018	56 participants
Third working meeting	Innsbruck, Austria, October 2018	55 participants
Fourth working meeting	Bilbao, Spain, April 2019	59 participants
Fifth working meeting	Rosenheim, Germany, October 2019	56 participants
Sixth working meeting	On-line meeting, April 2020	50 participants
Seventh working meeting	On-line meeting, October 2020	50 participants
Eighth working meeting	On-line meeting, April 2021	56 participants
Closing event	Salford, UK, September 2021	

During these meetings, working papers on different subjects related to full scale testing and data analysis were presented and discussed. Over the course of the Annex, different experiments on characterisation and quality assessment were undertaken, and several common exercises on data analysis methods were introduced and solved.

Outcome of the project

The IEA EBC Annex 71-project worked closely together with the Dynastee-network (www.dynastee.info). One of the deliverables of the Annex project was the enhancement of this network and promoting of actual building performance characterization based on full scale measurements and the appropriate data analysis techniques. This network of excellence on full scale testing and dynamic data analysis organizes on a regular basis events such as international workshops, annual training, with outputs that support organisations interested in full scale testing campaigns.

In addition to the network of excellence, the outcome of the Annex 71-project has been described in a set of reports, including:

IEA EBC Annex 71 – Building energy performance assessment based on in-situ measurements: challenges and general framework (joint report of Subtasks 1 and 4)

IEA EBC Annex 71 – Building energy performance assessment based on in-situ measurements: building behaviour identification (report of Subtask 2)

IEA EBC Annex 71 – Building energy performance assessment based on in-situ measurements: physical parameter identification (report of Subtask 3)

IEA EBC Annex 71 – Building energy performance assessment based on in-situ measurements: design, description and results of the validation of building energy simulation programs (report of the BES-validation exercise)

IEA EBC Annex 71- Building energy performance assessment based on in-situ measurements: project summary report

List of participants and coregroup

In total 42 institutes from 11 countries participated in the IEA EBC Annex 71-project. The different participants are listed below:

Austria:	Max Blöchle, Austrian Institute of Technology
	A. Susanne Metzger, Vienna University of Technology
	Gabriel Rojas, University of Innsbruck
Belgium:	**Geert Bauwens, KU Leuven (subtask 3 co-leader)**
	Hans Bloem, INIVE – Dynastee (subtask 5 co-leader)
	Karel De Sloover, Belgian Building Research Institute
	Jade Deltour, Belgian Building Research Institute

Arash Erfani, KU Leuven

Nicolas Heijmans, Belgian Building Research Institute

Eline Himpe, Ghent University

Evi Lambie, KU Leuven / EnergyVille

Gabrielle Masy, UCLouvain

Glenn Reynders, VITO EnergyVille (subtask 2 co-leader)

Katia Ritosa, KU Leuven (secretary)

Staf Roels, KU Leuven (operating agent)

Dirk Saelens, KU Leuven / EnergyVille (subtask 2 co-leader)

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	Maria Jose Jimenez, CIEMAT (subtask 5 co-leader)
	Sandra Martínez Mariño, Vigo University
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	Zoe De Grussa, BBSA (ESSO)
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	Martin Fletcher, Leeds Beckett University
	Virginia Gori, UCL Energy Institute
	Chris Gorse, Leeds Beckett University
	Rajat Gupta, Oxford Brookes University
	Adam Hardy, Leeds Beckett University
	Ross Holleron, Knauf Insulation

Frances Hollick, UCL

Richard Jack, Build Test Solutions (subtask 4 co-leader)

Matthew Li, Loughborough University

Kevin Lomas, Loughborough University

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Paul Strachan, University of Strathclyde (BES validation co-leader)

Table of content

Abbreviations

List of frequently used abbreviations

Abbreviation	Meaning
AIM-2	Alberta Air Infiltration Model
ARX	Autoregressive with Exogenous Inputs
AVG	Average Method
BES	Building Energy Simulation
CI	Confidence interval
DHW	Domestic hot water
EN	European Norm
EPBD	Energy Performance of Buildings Directive
ES	Energy Signature Method
GB	Grey-box Modelling (in the context of this report same as State-space Modelling)
GBORO	Gainsborough Test House
HP	Heat pump
HR	Heat recovery
IEA EBC	Energy in Buildings and Communities Programme of the International Energy Agency
LBORO	Loughborough Matched Pair Test Houses
LR	Linear Regression
LR1	Linear Regression Approach 1, forced through zero
LR2	Linear Regression Approach 2, forced through zero
LR3	Linear Regression Approach 3
MLR	Multiple Linear Regression
SD	Standard deviation
SH	Space heating
SS	State-space Modelling (in the context of this subtask same as Grey-box Modelling)
Twin N2	Twin Test House N2
Twin O5	Twin Test House O5
Uccle	Uccle Test House
UFH	Underfloor heating
U-value	Thermal transmittance of a building element

Definitions

Explanation of frequently used definitions:

B-splines: B-spline is piecewise polynomial, where the m^{th} order B-splines signify series of polynomials of degree m-1. The key feature of B-splines is that the point-wise sum of infinitely B-spline series for the entire range of interest is always equal to one.

Building Energy Simulation (BES): computer modelling based on building physics, used in the evaluation of energy and environmental aspects of building performance.

Building thermal envelope: defined in ISO EN 52016 as "*total area of all elements of a building that enclose thermally conditioned spaces through which thermal energy is transferred, directly or indirectly, to or from the external environment".*

g-value (Total Solar Energy Transmittance): The total energy transmittance of a glazing, indicates the proportion of the incident radiation which is transmitted by the glazing, based on EN 410:2011.

HTC (Heat Transfer Coefficient): defined in ISO 13789 as the "*heat flow rate divided by temperature difference between two environments*". It represents the steady-state aggregate total fabric and ventilation heat transfer from the entire thermal envelope in Watts per kelvin of temperature difference (ΔT) between the internal and external environments, and is expressed in Watts/Kelvin (W/K) (BSI, 2017). In this document, HTC typically refers to the fabric heat transfer by conduction and air infiltration, unless explicitly stated otherwise.

Solar aperture (solar transmittance, gA value): The solar transmittance of an observed transparent building element as a function of window properties, window orientation, shading obstacles, and other variables which are infeasible to observe alone.

Test case: In the context of this Annex a test case is a dwelling subjected to (extensive) monitoring campaigns in order to get detailed measurement data which are used in HTC assessment.

Thermal zone: defined in ISO EN 52016 as **"***internal environment with assumed sufficiently uniform thermal conditions to enable a thermal balance calculation".* In the zoning procedure neighbouring spaces with similar services and comfort settings are merged in thermal zones. A dwelling is often treated as a two-zone building, consisting of a day and night zone.

U-value: U-value, also known as thermal transmittance, is defined in ISO 7345 as the "*heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on both sides of a flat uniform system*" in unit W/(m2·K).

List of symbols

Explanation of frequently used simbols:

Symbol	Description	Unit
C	Heat capacity	J/K
c_a	Specific heat capacity of air	J/kgK
C_i	Heat capacity of the indoor air in the observed dwelling	J/K
$C_{i,eff}$	Effective averaged heat capacity of the dwelling	J/K
C_m	Thermal mass of the dwelling	J/K
g	Total energy transmittance or g-value of the glazing	-
G_a	Ventilation air flow rate	kg/s
gA	Solar aperture	m^2
HTC	Heat transfer coefficient	W/K
HTC_{inf}	Heat transfer coefficient due to infiltration	W/K
HTC_{tr}	Heat transfer coefficient due to transmission	W/K
H_{vent}	Heat gains/losses due to ventilation	W/K
I_{sol}	Global solar irradiation	W/m^2
$I_{sol,dif}$	Diffuse solar irradiation	W/m^2
$I_{sol,dir}$	Direct solar irradiation	W/m^2
η_{HR}	Heat recovery efficiency	%
RH	Relative (air) humidity	%
θ	Temperature	K or °C
θ_e	Outdoor air temperature	K or °C
θ_i	Indoor air temperature	K or °C
θ_{sup}	Ventilation air supply temperature	K or °C
Φ	Heat flow rate	W
Φ_h	Heat input by the heating system	W
Φ_{inf}	Infiltration heat exchange	W
Φ_{int}	Internal heat gains from occupants and appliances	W
Φ_l	Latent heat exchange due to moisture loading and unloading of interior objects and building parts	W
Φ_m	Heat exchange when loading/unloading thermal mass of interior objects and building parts	W
Φ_{sol}	Solar heat gains through transparent fabric parts	W

Φ_{tr}	Transmission heat exchange towards adjacent, towards neighbouring buildings and towards the external environment taking into account solar radiation and long wave heat exchange at the exterior surfaces	W
Φ_v	Heat exchange due to mechanical ventilation	W

1. Introduction

1.1. Overview

This document sets out the specification for the empirical validation experiment conducted on the Twin Houses at the Fraunhofer IBP test site in Holzkirchen, Germany in the winter of 2018/19, as part of IEA EBC Annex 71. The details are also relevant for the common exercises of Subtasks 2 and 3 in the Annex 71, where the focus is on using the measured data to identify model parameters and for automatic fault detection research. This document, together with the additional information provided (images, thermal bridge calculations, layout drawings, experimental details and experimental data), constitutes a full specification of the experiment.

The focus of the experiments is the Twin Houses, as shown in Figure 1 and Figure 2. House O5 is on the right, in the top left photograph and on the left, in the top right photograph of Figure 1.

View of West

View of East

View of South

View of North

Figure 1. Views of Twin Houses in Holzkirchen, Germany.

Figure 2. Location of Twin Houses in Holzkirchen, Germany.

All experimental data and specification details are publicly available in Fraunhofer's research data repository: http://dx.doi.org/10.24406/fordatis/76 (Kersken & Strachan, 2020)

1.2. IEA EBC Annex 58

In the previous Annex 58 (KU Leuven, 2015), two Building Energy Simulation program empirical validation experiments were undertaken (Strachan, et al., 2016). The detailed specifications can be found here:

- Experiment 1:
  http://dx.doi.org/10.15129/8a86bbbb-7be8-4a87-be76-0372985ea228 (Strachan & Kersken, 2015)
- Experiment 2:
  http://dx.doi.org/10.15129/94559779-e781-4318-8842-80a2b1201668 (Strachan & Kersken, 2015)
- A journal publication of the first experiment can be found here:
  https://doi.org/10.1080/19401493.2015.1064480 (Strachan, et al., 2015)

The first validation experiment was undertaken in August/September 2013 using both Twin Houses. A second validation experiment was undertaken on one of the twin houses (House O5) in cooler conditions (April/May 2014). The dataset collected in the second experiment was also designed to be useful as an Annex 58 common exercise for identification analysis.

1.3. Changes to Experimental Configuration for Annex 71 Experiment

The Building Energy Simulation (BES) model validation study, conducted during Annex 58 (Strachan, et al., 2016), (Strachan, et al., 2015)) was designed to focus on the fabric-related functionality of BES programs including transmission heat losses, thermal bridges, solar gains, internal heat gains, window / blind models and internal and external air exchange. It did not consider occupancy user behaviour or typical heating and cooling systems. The following were deliberately not included in order to reduce complexity:

- No internal gains representative of occupants (heat, moisture and CO_2)
- Constant set temperatures in constant temperature periods, no temperature profile or night setback
- Constant operation of a simple mechanical ventilation system
- No opening of windows
- No operation of internal doors
- No building service equipment, just electrical heating.

The empirical model validation study of Annex 71 described in this specification increases the realism and complexity. Key aspects of the changes are as follows.

- Including building services equipment:
  - One of the Twin Houses (House O5: the test house) has an underfloor heating system supplied by an air source heat pump (Main Experiment only).
  - The other Twin House (House N2, the reference house), for comparison, has electrical heating as for the Annex 58 experiments.
- Inclusion of attic space in the experimental configuration in addition to the ground floor rooms that were the focus in Annex 58. The construction properties of the walls of the buildings have also changed, although these changes are small.
- Including synthetic occupancy profiles: it was considered too complex to monitor real occupants, so a realistic synthetic occupancy profile was developed for the various rooms in the house, including window and door opening in part of the experiment.
- Including moisture injections for assessing moisture buffering effects (Extended Experiment only).
- A “Main Experiment” consisting of a multi-stage operational schedule: a constant temperature period (for Co-heating test assessment), a simple User-1 period with a temperature profile consistent across all rooms, and a User-2 period with a more complex user profile which varies from room to room and includes window and door opening. A second experiment, the “Extended Experiment”, included moisture injection of the synthetic users in the O5 test house. This Extended Experiment consists of a User-3 period, a period with randomised heat injection (PRBS) and a Free-Floating period (including synthetic users).

The experimental design took into account that a too complex validation scenario would make it difficult for the modelling teams to identify the reason for deviations from the measurement data.

The experiment was also designed to be used as common exercises by the Annex 71 participants working with simplified models and methods of system identification. The datasets were designed to be suitable for identification of building performance characteristics (Subtask 3) and development of reduced order models useful for fault detection and model predictive control (Subtask 2). These analyses may also provide useful information to explain differences between measurements and predictions from detailed modelling tools.

1.4. Validation procedure

The datasets from the Main and Extended Experiments can be used for many different purposes such as education and training, the development of simplified reduced order models and other scientific research requiring measurement data from well-specified real buildings. For these purposes usually the full dataset, containing all the data collected during the experiment, should be used. However when the focus is a BES program validation (and/or model development) it is recommended to follow the 2-phase blind/open validation approach (used in Annex 71), as described below, to separate user from program errors.

In this approach, the model validation team predicts the temperatures and heating inputs using the program(s) under investigation. The validation methodology is a two phase blind validation, as used in Annex 58 (Strachan, et al., 2016) and similar to other previous IEA empirical validation studies. Ideally this procedure has different persons (or even organisations) working collaboratively to improve model quality assurance and analysis techniques.

The required steps are as follows:

1) Blind validation (“Blind phase”).

a) Modellers predict heating energy and indoor climate using the experimental specification, measured climate data and operational schedules but without knowledge of the measured heating energy consumption (in the case of known indoor climate) or indoor climate (in the case of known heating energy consumption).

b) Modellers submit their simulation results and a modelling report with details of the programs used and assumptions made.

2) Blind stage analysis. This compares predictions against experimental data for indoor climate and heat fluxes. Inevitably at this stage, differences are due to a mix of user / modelling errors and program deviations (and potentially measurement uncertainties).

3) Re-modelling ("Open phase"). The measured data is disseminated. Modellers are encouraged to investigate differences between measurements and predictions and resubmit predictions and up-dated the report. Only changes which correct user modelling errors or alter a modelling assumption (with documented rationale) are allowed. It is important to ensure that model input parameters are not simply calibrated to improve agreement with measurement. In principle, this step identifies program errors by eliminating modeller errors.

4) The improved predictions are compared against the measurements to identify remaining flaws and identify areas where program improvements are required. When complete, validation data sets and models are archived.

2. Experimental Design

Experimental design was undertaken to plan the test sequence that ensures the experiments are fit for purpose, i.e. in this case, they should provide a statistically robust dataset suitable for empirical validation of Building Energy Simulation (BES) programs. The aim is to test the ability of BES programs to predict the behaviour of the overall system based on the building and systems specification and measured boundary conditions.

Experimental design theory usually is based on being able to randomise and replicate. At the simplest level this involves altering each influencing factor one at a time, or changing a few factors in a defined scheme to determine interactions. However, for complex systems where there are multiple interactions between many different elements of the system, it is difficult (or perhaps impossible) to construct rigorous design of experiment strategies. A report by the American Physical Society (Energy Future: Think Efficiency (Schlachter, et al., 2008)), characterizes the design of energy efficient buildings as a complex system. For example, internal temperatures are affected by solar gains, internal gains, radiant/convective split, wind-induced airflow, insulation levels, glazing properties, shading, window opening etc.

A pragmatic approach was therefore taken with the following elements:

- Determine the main influencing factors on performance; vary them through realistic range using the BES program EnergyPlus.
- Include random elements in the experiment which cover the range of conditions expected in real conditions. Regarding the weather, this means covering an extended period. For occupancy, it means making sure the magnitude and frequencies are realistic. A stochastic occupancy profile is used ((Flett & Kelly, 2016), (Flett & Kelly, 2017)).
- Include the most important user influences on a building: internal heat and moisture gains, operation of internal doors and external windows.
- Ensure the variable factors have a significant effect on the independent metric used. This could be temperature (e.g. in a Free-Float period) or heat input to maintain a setpoint (e.g. in a discrete interval of constant temperature periods). This is checked by running BES on models of the Twin Houses using Test Reference Year climate data.
- Ensure all important influencing factors are measured to a sufficient level of accuracy. This was investigated through sensitivity analysis (Mantesi, et al., 2019).
- Reduce measurement error through calibration of all instrumentation used and data checking.
- Fully document experimental specification and measurement.
- Use side-by-side experiments to focus on one or more important influencing factors (the degree of similarity between both Twin Houses and the experiment reflects the precision that can be derived from this side-by-side design; see baseline measurements in section 3.2).
- Use statistical measures of merit (power and confidence) to quantify discrepancy between model predictions and experiment.
- Use statistical analysis (e.g. regression analysis and calibration procedures) to determine possible reasons for deviations between simulation and experiment.

3. Experiment

3.1. Climate and location

The houses are situated in a flat location at Holzkirchen, Germany (near Munich). The latitude of the buildings is 47.874 °N, the longitude is 11.728 °E. The elevation above mean sea level (MSL) is 680 m. Time of all data provided is in Central European (Winter) Time i.e. (UTC/GMT +1).

Information on the external shading can be found in the additional document under
02_Additional Documents.zip\Geometry\External Shading\
(https://fordatis.fraunhofer.de/bitstream/fordatis/161/3/02_Additional%20Documents.zip)

Snow levels can provide additional shading especially on the living rooms' glass door. Data from the weather station's snow height sensor are included but note that increased wind speeds usually reduce the snow heights, particularly on the south and west facades.

3.2. Baseline measurement

3.2.1. Air tightness

To ensure comparable air tightness of both buildings a pressure difference test (blower door test) was conducted prior to the experiment. The test results are shown in Table 1. As expected, the under-pressure tests show a lower tightness than the test conducted using overpressure. In particular, the operable window in the child1 room is expected to be slightly pulled open by the under-pressure since it can't be locked fully (to allow the electric actuator to operate it). The overall buildings' mean air tightness values are 0.87 h^{-1} and 1.10 h^{-1} at 50 Pa pressure difference and both fulfil the requirements of the German building energy code of 1.50 h^{-1}. From the measured n_{50}-values, infiltration air change rates of 0.077 h^{-1} and 0.061 h^{-1} respectively can be estimated in accordance with DIN V 18599-2 (E) (DIN, 2014), assuming 7 % of n_{50} as average infiltration. Together with the buildings' internal air volume of 337 m³ this means a difference of 5.4 m³/h. Combining the mechanical ventilation of 200 m³/h and the estimated mean infiltration of 23.2 m³/h the absolute difference 5.24 m³/h results in a relative difference in both buildings' air exchange of 2.4 %.

Table 1 Results of the pressurization test carried out on November 29th, 2018.

	Mean of over- and under-pressure test n_{50} [h^{-1}]	
	Test house (O5)	Reference house (N2)
entire building	1.10	0.87
ground floor	1.44	1.19
	Result of overpressure test n_{50} [h^{-1}]	
	Test house (O5)	Reference house (N2)
entire building	1.06	0.80
ground floor	1.43	1.13
	Result of under-pressure test n_{50} [h^{-1}]	
	Test house (O5)	Reference house (N2)
entire building	1.15	0.93
ground floor	1.45	1.26

3.2.2. Tracer Gas

After the end of the Extended Experiment in the O5 building the mechanical ventilation was deactivated and the outside air inlets and outlets were sealed. All doors and the trap door were opened and four air mixing fans were installed into the ground floor and the attic to ensure homogenous mixing of injected SF_6 within the Twin House's entire air volume.

On June 18th 7:00 and 19th 9:20 a SF_6 injection was done and the resulting decay was recorded until June 19th 2019 17:00. The measured concentrations, resampled to 10 minutes mean values, can be seen left in Figure 3. On the right side the resulting Air Change Rates (ACR) for all five sampling points inside the Twin House can be seen. This calculation was carried out according to DIN EN ISO 12569 (DIN, 2012). Only 10 minute data with a decay in concentration between two data points were used.

The two seemingly high peaks of ACRs directly after the SF_6 injection, occurring mostly in the living and other ground floor rooms, are the result of the tracer gas dissipating to the other rooms of the Twin House. Filtering these two peaks, an average ACR of 0.04 h^{-1} can be calculated for the entire O5 house. The ACR data can be found in "04_Data_Extended_Experiment.zip\TracerEnd" (https://fordatis.fraunhofer.de/bitstream/fordatis/161.2/5/04_Data_Extended_Experiment.zip); the associated weather data is included in data provided for the Extended Experiment.

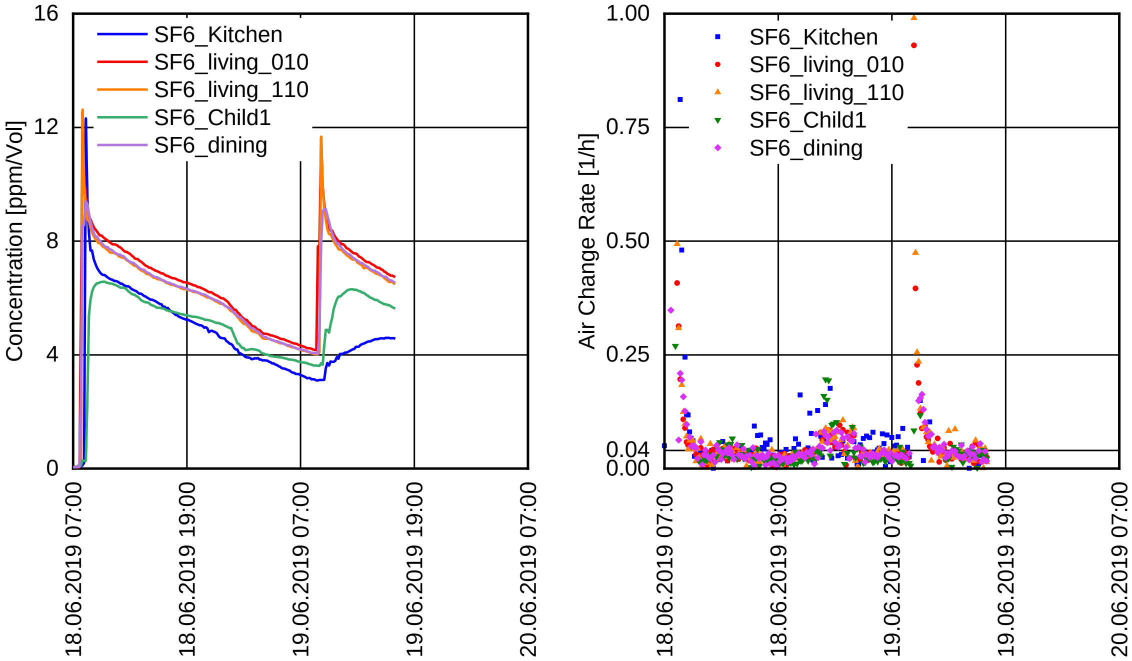


Figure 3. Measured SF_6 concentration (left) and resulting Air Change Rate (right) during the infiltration tracer gas experiment after the end of the Extended Experiment without mechanical ventilation.

3.2.3. Analysis of the Co-heating data

An analysis of the Co-heating dataset was done by Alex Marshall and Richard Fitton from Salford University, UK. The detailed report is included with the additional documents provided with this specification. This analysis found a Heat Transfer Coefficient of 103 W/K for the O5 house and 107 W/K for the N2 house (Figure 4).

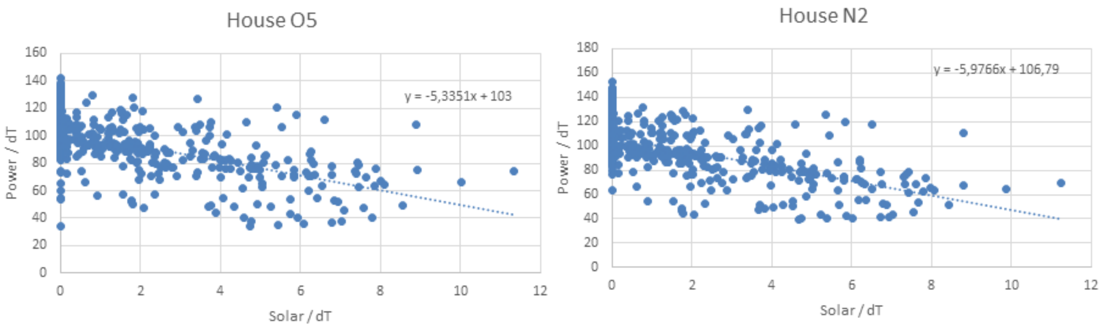


Figure 4. Regression analysis of the Co-heating data. Left for O5, right for N2.

To further investigate the difference between both houses their electric energy consumption during the Co-heating test were compared over a period of 12 days as a baseline measurement. Figure 5 shows the cumulative heating energy of both Twin Houses (red and blue line) and the cumulative deviation (black line). As can be seen in this figure after the 12 days the cumulative deviation between both Twin Houses has stabilized at a value of -4.25 %, in good agreement with the Co-heating analysis.

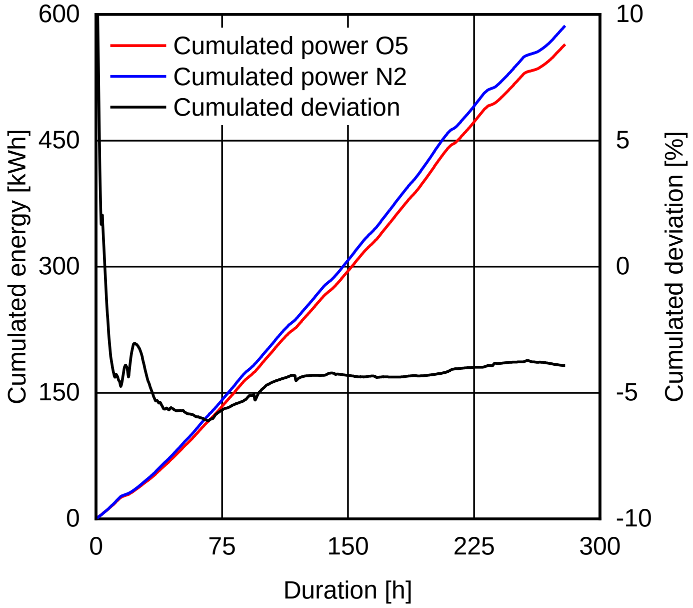


Figure 5. Baseline measurement conducted during the Co-heating test, conducted between 7th December 2018 18:00 and 19th December 2018 09:00.

3.3. Geometry

Detailed drawings with dimensions can be found among the additional documents:

- Plan attic.pdf
- Plan groundfloor.pdf
- section_TwinHouses.pdf

Figure 6 and Figure 7 show an overview of the Twin Houses' geometry including the ventilation and door elements. The connection between both floors is a stair that is open in the living room on the ground floor and ends in a staircase in the attic from where doors lead to the children's rooms. This door can be sealed by a double trap door to create two separate air spaces for the ground floor and the attic.

Glazing configurations are shown in Figure 8.

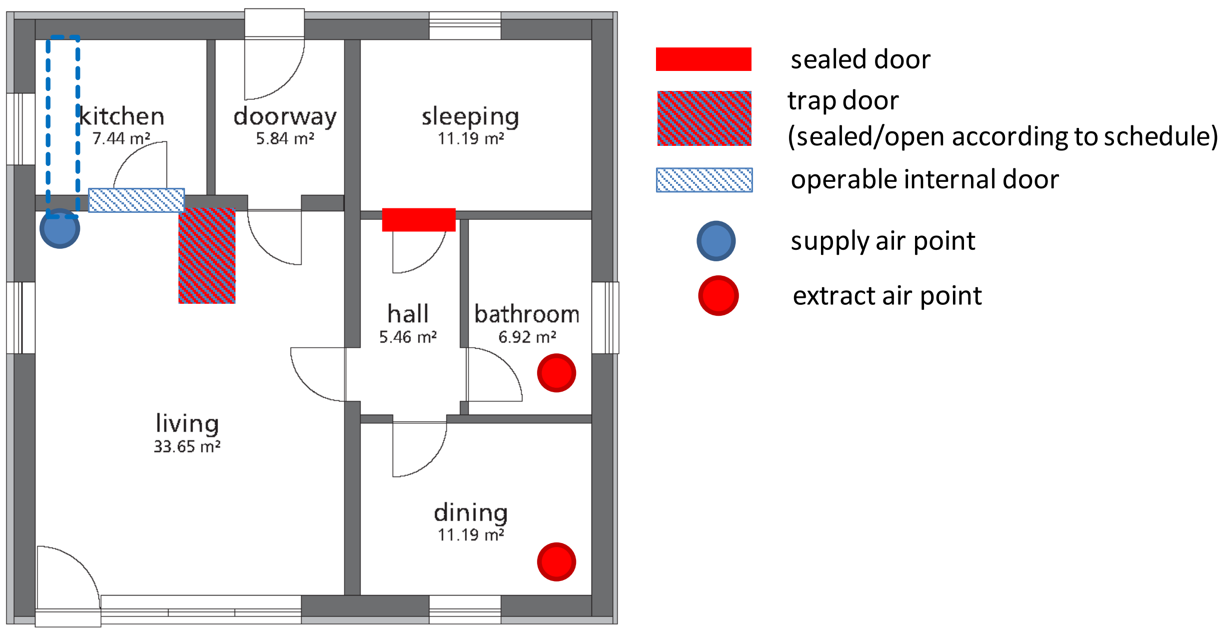


Figure 6. Floor plan ground floor.

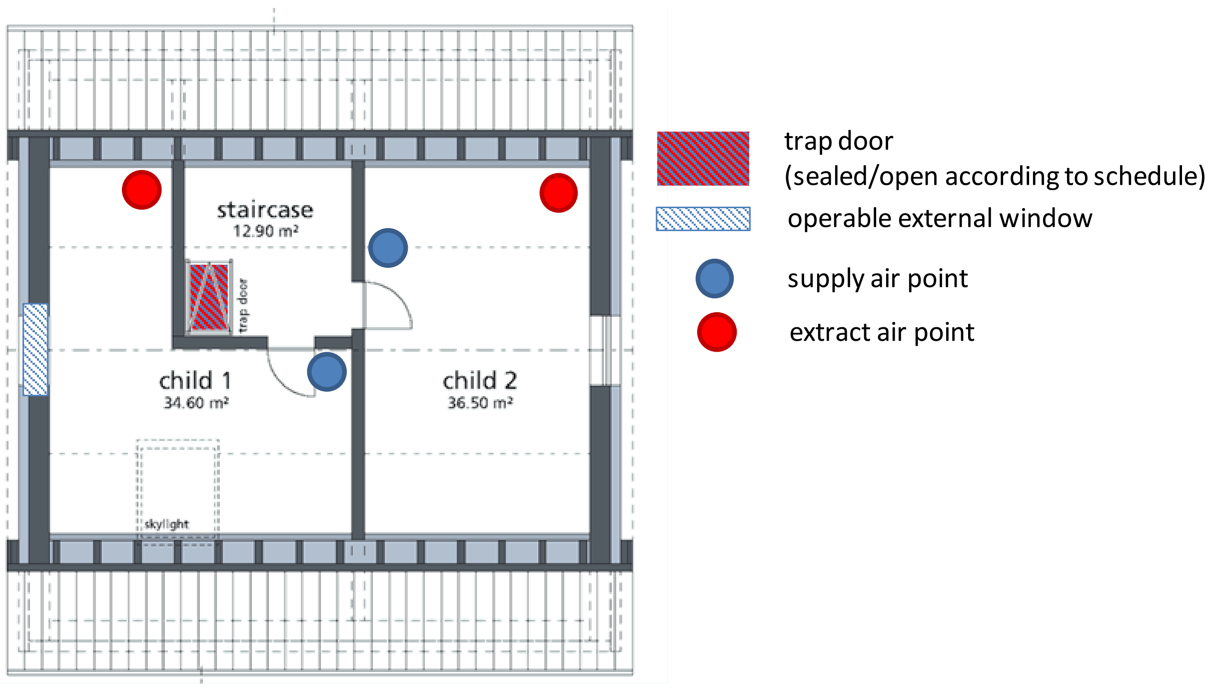


Figure 7. Floor plan attic.

Figure 8. Twin House views: clockwise from top left: south, north, west, and east.

Details of the windows and glazing areas are given in Figure 9 and Table 2.

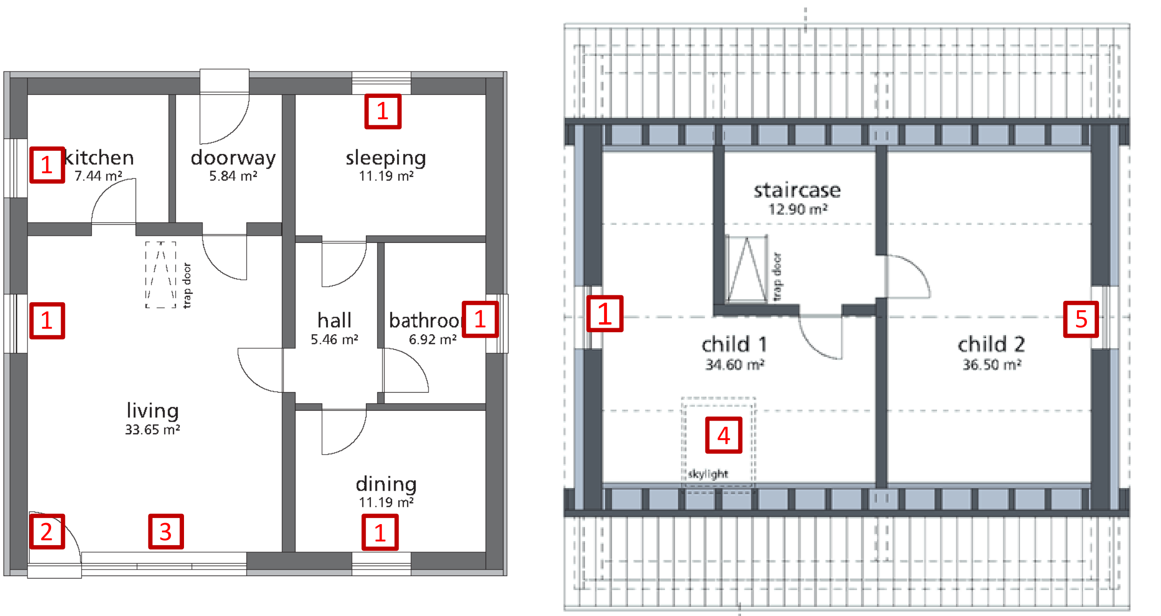


Figure 9. Overview of the window types. The window types are shown as red numbers.

Table 2. Specification of the window types' properties

Window type	Overall dimensions (including roller blind housing) [m²]	Overall dimensions (excluding roller blind) [m²]	Glass area without sealing strip [m²]	Glass edge length [m]	Frame area [m²]
1	1.74*1.23 = 2.14	1.54*1.23 = 1.89	1.30*0.99 = 1.29	4.62	0.60
2	2.57*1.11 = 2.85	2.37*1.11 = 2.63	2.13*0.865 = 1.84	6.04	0.79
3	1.74*3.34 = 5.81	1.54*3.34 = 5.14	3 panes, each 1.385*0.99 = 4.11 (total)	14.4	1.03
4	-	1.20*1.24 = 1.49	0.93*0.97 = 0.90	3.8	0.59
5	2.67*1.23 = 3.28	2.44*1.23 = 3.00	2.20*0.99 = 2.18	6.38	0.82

The ground floors' ceilings are supported by four concrete columns located in the living room, the dining room, the bedroom and the kitchen. Their geometry can be taken from Figure 10.

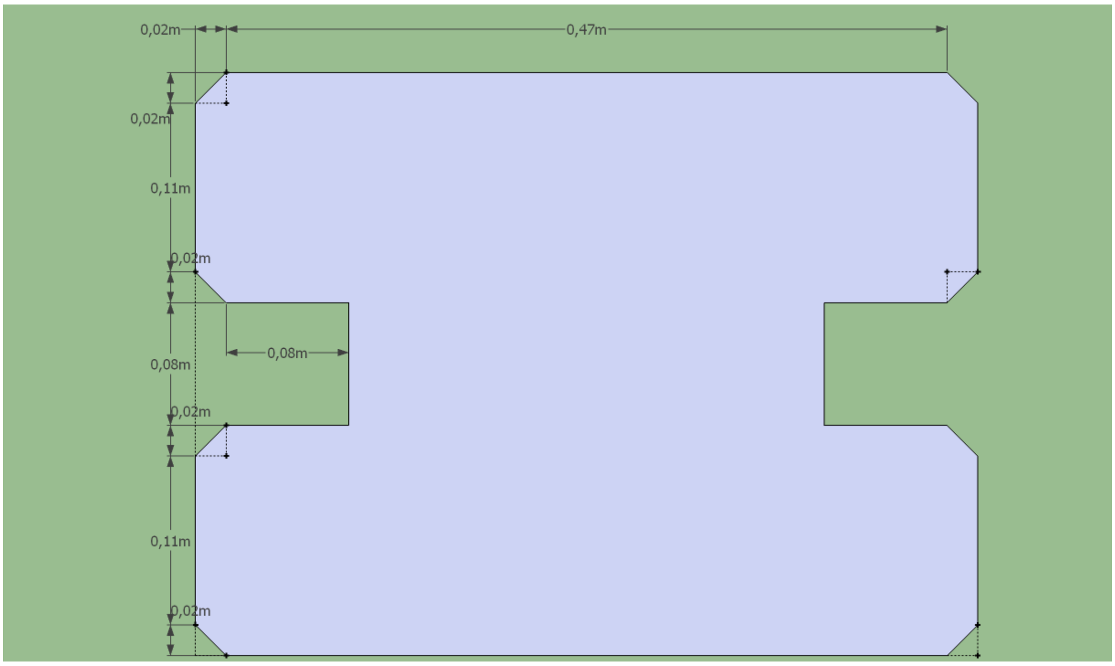


Figure 10. Geometry of the ground floors' four columns.

3.4. Constructions

The U-values of the constructions can be found in Table 3. The detailed constructions can be found in the additional documents in “01_Constructions_TwinHouses.xlsx”;

“Humidity properties.pdf” contains an estimate for the moisture properties of the materials.

Table 3. U-values of the Twin Houses constructions.

Component		U-value [W/(m^{2}K)]
Exterior Wall	West	0.24
	East	0.24
	South:	
	ground floor	0.21
	railing main window	0.25
	knee wall 2nd floor	0.28
	North	
	ground floor	0.21
	knee wall 2nd floor	0.29
Ceiling	Currently not insulated	0.51
Floor		0.29
Roof		0.22
Window		1.20
Front door		0.94

Absorptivity of the internal wall and ceiling surfaces was not measured before the experiment. As in Annex 58 these surfaces were painted directly before the experiment with the same colour and type of paint. The value measured in Annex 58 could be a good assumption. “Absorptivity of the white painted internal plaster was measured as 0.17.” (Strachan, et al., 2016). During the same experiment the absorptivity of the external walls was measured as 0.23.

3.5. Internal doors

The internal doors (Figure 11) have a height of 2.00 m and a width of 0.95 m. The material is wooden honeycomb board with a thickness of 4 cm with a single pane glazed area of 38.0 x 64.5 cm. The ventilation slots near the base of the doors are tape sealed. The bottom gap is about 2 mm on average. During the Co-heating period all doors are open. As shown in section 4 during the following periods all internal doors are open except for the sleeping rooms’ doors (permanently closed; not sealed), the kitchen door (as documented in section 4, operated in some periods) and the trap door between ground floor and attic space (open/closed during some periods as described in section 4)).

Figure 11. Internal door.

3.6. Trap door

The trap door between the ground floor and attic is 1.39 x 0.57 m. The door leaves are massive wood with 4 cm for the upper and 2 cm for the lower leaf. Both have a 4-sided rubber seal. The horizontal air layer between the two leaves is 34.5 cm. For the Extended Experiment the attic doors' positions are added to the measurement data as "n2_attic_door_pos" and "o5_attic_door_pos".

3.7. Glazing optical and thermal properties

The glazing is double glazing with low emissivity coating and argon fill. Layers are (outside to inside):

- Interpane Clear float 4 mm
- Gas fill 16 mm (90% argon, 10% air)
- Interpane Iplus E 4 mm inner pane

The window U-value (following EN ISO 10077-1) is 1.2 W/m^{2}K for all windows in the façade (Calculated for the windows' individual sizes and rounded to two significant digits. The ψ -value of the glass edge is 0.05 W/mK. The glass U-value is 1.1 W/m^{2}K and the frame U-value is 1.0 W/m^{2}K.

Window 6.3 was used to obtain the optical properties of the glazing by selecting the glazing panes from the International Glazing Database (LBNL, 2017) and using EN 673 boundary conditions. Table 4 and Table 5 give the angular dependent properties for both NFRC and EN 410 spectra.

Table 4. Glazing optical properties: NFRC

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Visible transmittance	0.803	0.807	0.796	0.782	0.762	0.722	0.632	0.459	0.214	0	0.671
Solar transmittance	0.512	0.515	0.508	0.498	0.484	0.458	0.401	0.293	0.136	0	0.427
Reflectance (front)	0.292	0.287	0.285	0.286	0.293	0.31	0.351	0.448	0.644	1	0.338
Reflectance (back)	0.281	0.275	0.273	0.275	0.285	0.303	0.34	0.423	0.611	0.999	0.325
Absorptance outer layer	0.112	0.112	0.114	0.117	0.122	0.127	0.133	0.137	0.132	0	0.123
Absorptance inner layer	0.084	0.086	0.093	0.098	0.1	0.104	0.115	0.123	0.087	0	0.102
SHGC	0.571	0.575	0.572	0.566	0.554	0.531	0.481	0.378	0.197	0	0.497

Table 5. Glazing optical properties: EN410

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Visible transmittance	0.803	0.808	0.797	0.782	0.762	0.722	0.632	0.459	0.214	0	0.671
Solar transmittance	0.543	0.546	0.538	0.528	0.514	0.486	0.426	0.310	0.145	0	0.452
Reflectance (front)	0.264	0.260	0.258	0.259	0.267	0.286	0.329	0.433	0.640	1	0.315
Reflectance (back)	0.255	0.249	0.247	0.249	0.260	0.279	0.317	0.404	0.599	0.999	0.302
Absorptance outer layer	0.107	0.108	0.109	0.112	0.116	0.121	0.126	0.130	0.124	0	0.118
Absorptance inner layer	0.085	0.087	0.094	0.100	0.102	0.106	0.119	0.127	0.091	0	0.104
SHGC	0.602	0.606	0.604	0.598	0.585	0.560	0.508	0.398	0.208	0	0.525

The glazing supplier (Interpane) has quoted figures for the glazing normal incidence properties that conform to those in Table 5 with the exception that they quote the solar heat gain coefficient as 0.62.

To prevent driving rain from being blown into the building during this automated experiment the external windows (see Figure 12) can only tilt but not swing fully open. The upper part of the window is tilted inward for 14.3 cm while the bottom is not moved, so the two side openings form a triangle, with a rectangular shape on the top.

Figure 12. Operated external window in tilted position.

3.8. Roller blinds

Details are shown in Figure 13. The roller blind absorptivity was measured by Fraunhofer IBP as 0.32. The geometry of the roller blind slats can be found in the supplementary file “Rollerblinds.zip". The air gap between the glazing and the blind is 59 mm (±2 mm) and 23 mm (±1 mm) for the three (not openable) glazings beside the living room glass doors. The living rooms’ roller blinds on the west façades were closed during the entire experiment; the kitchens’ roller blinds were closed at the start of the User-2 period.

exterior view

exterior bottom detail

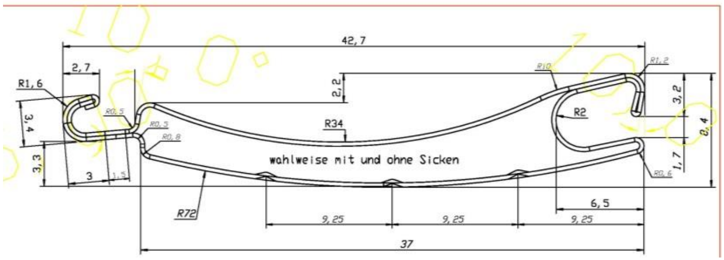
Gap between blind and frame/window

opened window with closed roller blind

lamella segment – internal view

lamella segment – external view

lamella segment – section view



lamella segment – section drawing

Figure 13. Details of roller blinds.

3.9. Thermal bridges

The following thermal bridge ψ –values were obtained with HEAT2.

Wall – Ceiling joint

The wall – ceiling joint is shown in Figure 14 (solution with 70 mm insulation).

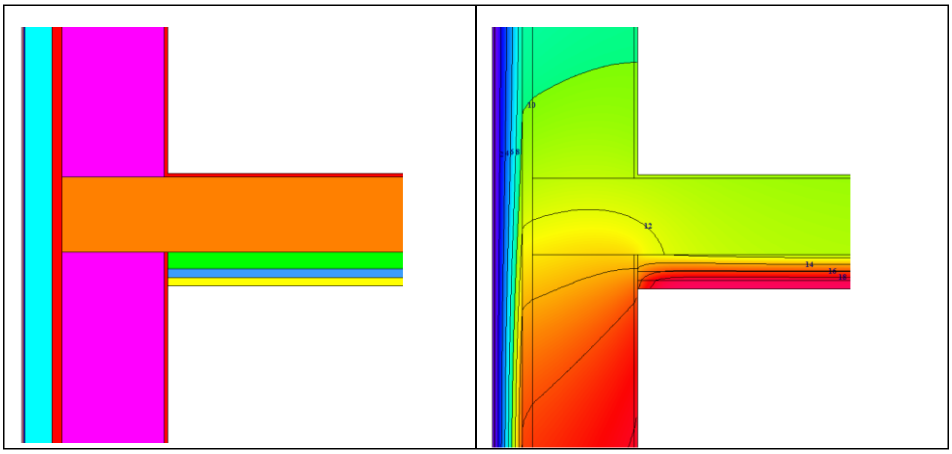


Figure 14. Wall – ceiling joint with 80 mm insulation. Model and temperatures.

Since there are three different temperatures in the calculation the linear thermal transmittance will be dependent on temperature. In the following it is assumed that the indoor temperature is 20 °C, the outdoor temperature is 0 °C and the attic temperature is 10 °C. Table 6 presents the results.

Please note: This thermal bridge contains losses to the outside AND the attic. The combined losses from ground floor and attic to the outside can be found in Table 11.

This detail models the gable wall joint to the ceiling on the east and west sides of the Twin Houses. The knee walls' joint to the ceiling on the north and south can be found in Table 11 as "TM-06".

Table 6. Linear thermal transmittance for wall – ceiling joint in W/mK.

	External measurements	Internal measurements
70 mm insulation (east wall)	0.383	0.542
120 mm insulation (north, south, west)	0.370	0.536

Alternatively, the linear thermal transmittance is split in two, i.e. linear thermal transmittance from room to outside and linear thermal transmittance from room to attic as can be seen in Table 7.

Table 7. Linear thermal transmittances for wall – ceiling joint in W/mK. Subscript io is room to outside; subscript ia is room to attic.

	External measurements		Internal measurements	
	Ψ_{io}	Ψ_{ia}	Ψ_{io}	Ψ_{ia}
70 mm insulation (east wall)	0.121	0.509	0.194	0.696
120 mm insulation (north, south, west)	0.115	0.511	0.187	0.699

Wall – Wall joint

The wall – wall joint is shown in Figure 15 (solution with 70 mm insulation).

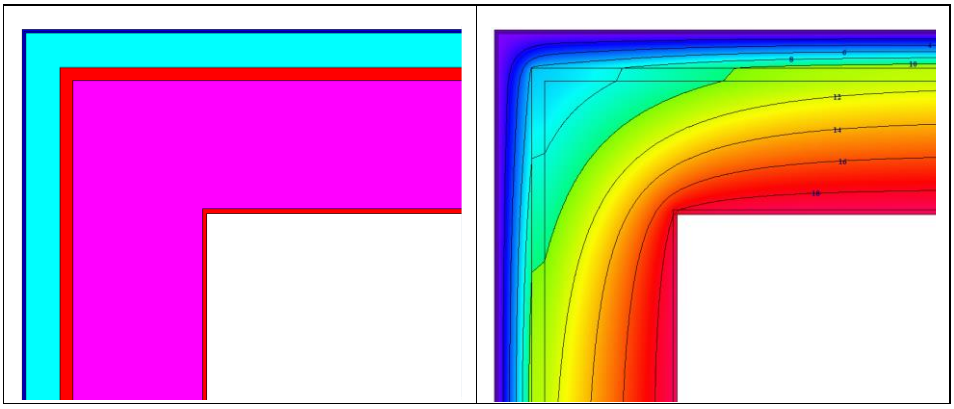


Figure 15. Wall – wall joint with 70 mm insulation. Model and temperatures.

Table 8 presents the results.

Table 8. Linear thermal transmittance for wall – wall joint in W/mK.

	External measurements	Internal measurements
70 mm insulation South-east North-east	-0.095	0.095
120 mm insulation South-west North-west	-0.110	0.095

Wall – Floor joint

The wall – floor joint is shown in Figure 16 (solution with 70 mm insulation).

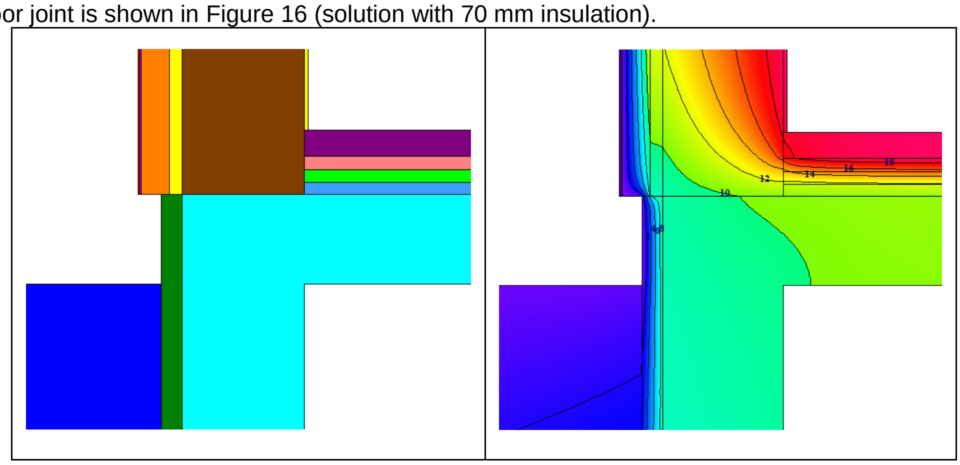


Figure 16. Wall – floor joint with 70 mm insulation. Model and temperatures.

As with the wall – ceiling joint there are three different temperatures in the calculation. In the following it is assumed that the indoor temperature is 20 °C, the outdoor temperature is 0 °C and the basement temperature is 10 °C. Table 9 presents the results.

Table 9. Linear thermal transmittance for wall – floor joint in W/mK.

	External measurements	Internal measurements
70 mm insulation (east wall)	-0.036	0.108
120 mm insulation (north, south, west)	-0.038	0.111

Again, the linear thermal transmittance is split in two, i.e. linear thermal transmittance from room to outside and linear thermal transmittance from room to basement (see Table 10).

Table 10. Linear thermal transmittances for wall – floor joint in W/mK. Subscript io is room to outside; subscript ib is room to basement.

	External measurements		Internal measurements	
	Ψ_{io}	Ψ_{ib}	Ψ_{io}	Ψ_{ib}
70 mm insulation (east wall)	-0.064	0.045	0.020	0.177
120 mm insulation (north, south, west)	-0.059	0.044	0.023	0.176

Table 11. Thermal bridges of the Twin Houses.

Model:		position	Ue:	Ψext:	Ψint:	χ:
TM-01	Ridge junction			-0.009	0.006	
TM-02	Rake Junction- Mineral wool	Junction between roof and external wall west		0.043	0.188	
TM-03	Rake Junction- Polyurethane	Junction between roof and external wall east		0.051	0.186	
TM-04	Eaves Junction- Combined	between roof / south and north knee walls		-0.015	0.165	
TM-05	Eaves Junction, isolated			0.070	0.181	
TM-06	Ceiling-wall junction (knee walls)			0.022		
TM-07	Column - Floor					0.656
TM-08	Column - Ceiling					0.643
TM-10	Internal wall, thin - Ceiling			0.047		
TM-11	Internal wall, thin - Floor			0.239		
TM-12	Internal wall, thick - Ceiling			0.045		
TM-13	Internal wall, thick - Floor			0.331		
TM-14	Window Jamb - brick wall, Wood fibre insulation	applies to windows in south and north walls		0.037		
TM-15	Window Lintel - brick wall, Wood fibre insulation	applies to windows in south and north walls		0.039		
TM-16	Window Sill - brick wall, Wood fibre insulation	applies to windows in south and north walls		0.034		
TM-17	Window Jamb - brick wall, Mineral wool insulation	applies to windows in west wall		0.038		
TM-18	Window Lintel - brick wall, Mineral wool insulation	applies to windows in west wall		0.040		
TM-19	Window Sill - brick wall, Mineral wool insulation	applies to windows in west wall		0.035		
TM-20	Window Jamb - brick wall, Polyurethane insulation	applies to windows in east wall		0.029		
TM-21	Window Lintel - brick wall, Polyurethane insulation	applies to windows in east wall		0.032		
TM-22	Window Sill - brick wall, Polyurethane insulation	applies to windows in east wall		0.027		
TM-23	Trapdoor - Ceiling			0.054		

The external thermal bridge ψ –values shown in Table 11 have been obtained with TRISCO. For a better understanding Figure 17 gives an overview of the names for roof components.

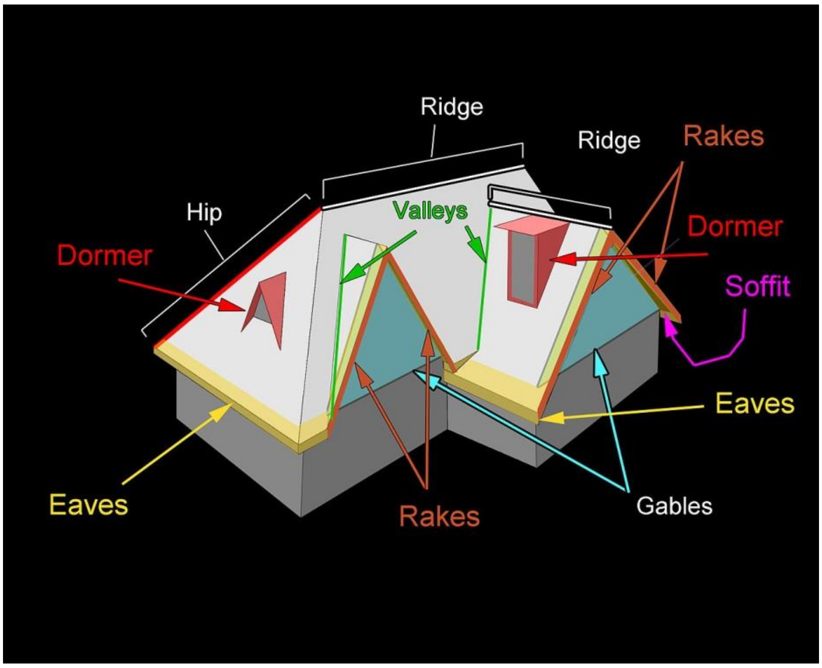


Figure 17. Naming of a roof's components (KDS444, 2012).

3.10. Ventilation

As in Annex 58 this experiment mainly uses mechanical ventilation because the resulting mass and energy flows can be measured much better than the air exchange caused by an open external window. Despite this experimental difficulty, opening windows are an essential part of user behaviour and will be included in part of the experiment (see section 3.17.6). As typical for a residential situation the ventilation system operates based on a target constant air change rate of 0.6 h^{-1}. The total supply and exhaust air volume for the entire building is measured and precisely PLC controlled, separately for ground floor and attic. The instrumentation gives the volume flow rate corrected to standard temperature and pressure (1013.25 hPa and 20 °C). To convert that signal into a mass flow rate, the air properties at sea level must be used. The air density at sea level and at 20 °C is 1.204 kg/m³. To calculate the ventilation mass flow rate (kg/s) the measured volume flow rate (m^3/s) must be multiplied by 1.204 kg/m³.

The rooms' individual air volume share is adjusted using disc valves once during the experiment's setup. So the room air volumes can vary caused by changes to the pressure regime and are not controlled to be constant. The rooms' individual ventilation air flow rates and temperatures are measured. Since a multi-room tracer gas measurement is part of this experiment the number of air bodies, separated by (sealed) doors, was limited. As Figure 18 and Figure 19 show, the experiment has four separate air bodies (Table 12). Table 13 specifies the set volume flows of the mechanical ventilation system. In some extreme winter conditions (e.g. morning of 1st of January) the external ventilation inlets were cloaked by ice and cause reductions from the set values until they were de-iced. However, the measured flow rates are given as input data so this information can be included in the model. The supply air duct to the living room runs through the kitchen, the bath exhaust air duct runs through the dining room and all ducts concerning the children's rooms run through the stairs. These ducts are insulated with 20 mm aluminium laminated mineral wool.

Table 12. Air bodies of the experiment (not considering the air space in the door frames).

Air body	Rooms	Floor Area [m²]	Volume [m³]
Ground	living, corridor, bath, dining, doorway	63.06	164.00
Kitchen	kitchen	7.44	19.34
Sleeping	sleeping (north)	11.19	29.09
Attic	child 1, child 2, staircase	84.06	151.72
Total	all rooms	165.75	364.15

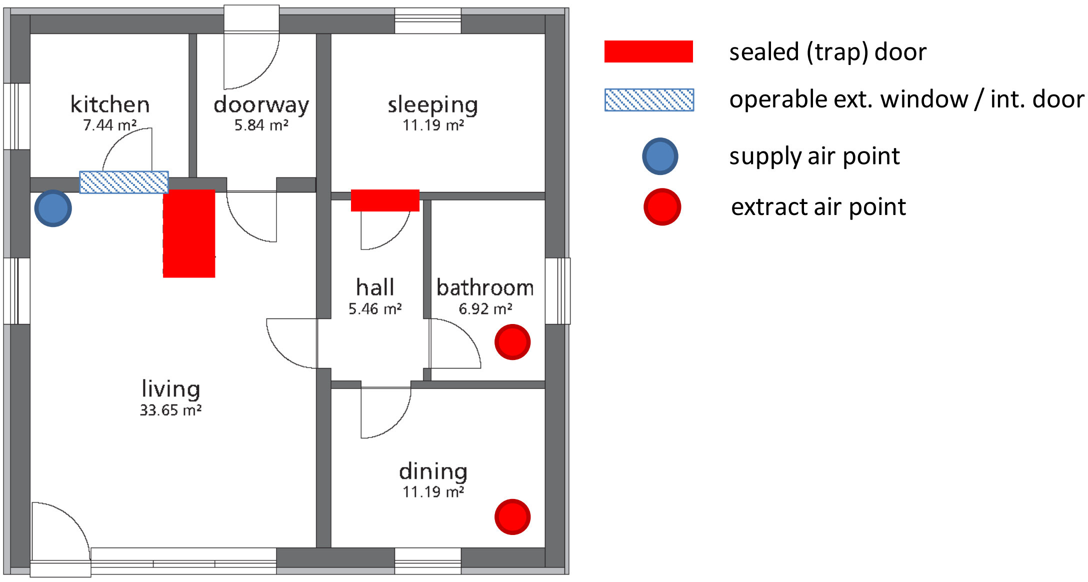


Figure 18. Floor plan ground floor.

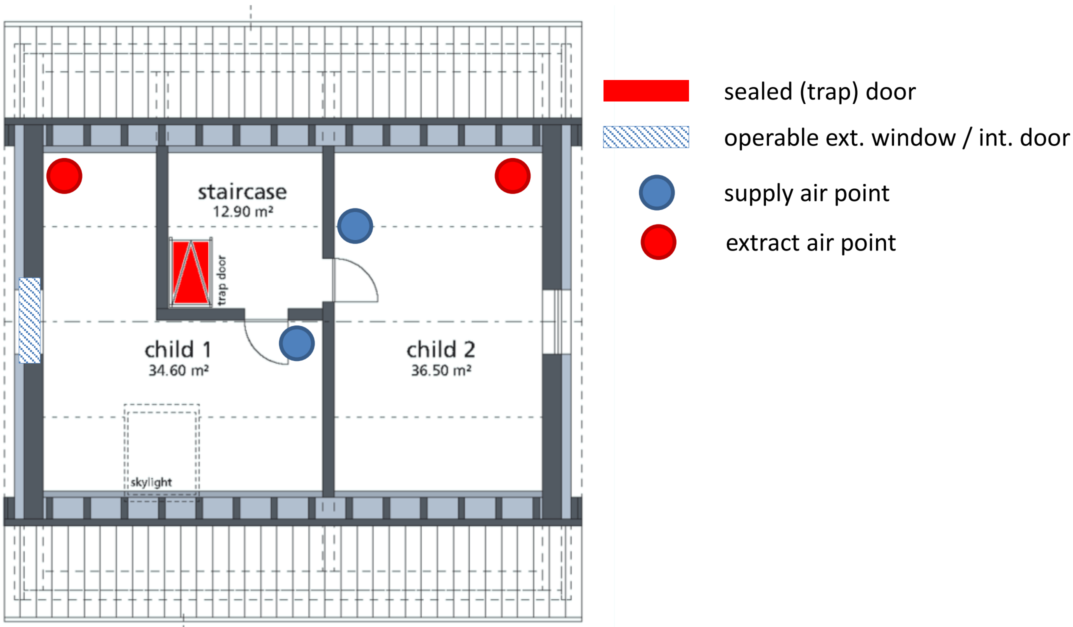


Figure 19. Floor plan attic.

Table 13. Resulting air flows.

Location	Type	Flow [m³/h]
Living room	Supply	100
Bathroom	Exhaust	50
Dining	Exhaust	50
Child1 and Child2	Supply and Exhaust	50

3.11. Heating / cooling

Cooling is not part of this experiment. The Twin Houses were configured to have a side-by-side measurement of two different heating systems during the Main Experiment and to investigate the effects of moisture loads during the Extended Experiment.

- Reference Building (N2): Electrical
- Test Building (O5):
  - Underfloor heating with air source heat pump (Main experiment)
  - Moisture loads (Extended experiment)

The corridor, doorway and stairs were unheated (after the Co-heating period).

3.12. Electrical heating (N2 house)

The electric heaters were power controlled to keep the set temperatures in the rooms. This was realized through a PI controller, integrated into the Twin House PLC. The power consumption in every room was measured. The heaters used were Dimplex AKO K 810/K 811 (Figure 20). The manufacturer gives the radiative / convective spilt as 30 % / 70 %. The heaters were lightweight with a fast response – estimated as 1 or 2 minutes by Fraunhofer IBP. Details of the heaters used are given in Figure 21. In each room one heater is located as can be seen in Figure 22. The kitchen and bathroom of the N2-house have a separate second electrical heater to separate the relatively high internal heat sources (IHS) from the heating power.

These heaters' power output is controlled by a PI controller (implemented into the Twin Houses' PLC) with a proportional gain of 4 and an integration time of 5 Minutes. The individual rooms' shielded air temperature sensors at 110 cm are used for control.

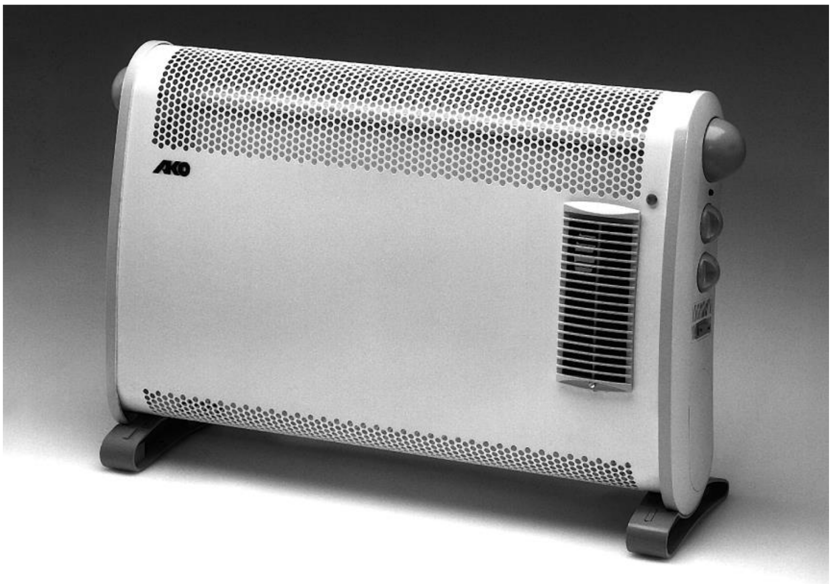


Figure 20. Electric heater.

Technical specifications

Convector	K 810	K 820
Nominal voltage	230V~ / 50 Hz	
Power	750 / 1250 / 2000 W	
Switched levels	- 1 (OUT) - 2 (750 W) - 3 (1250 W) - MAX (2000 W) Thermostat with frost protection function	- 1 (OUT) - 2 (750 W) - 3 (1250 W) - MAX (2000 W) Thermostat with frost protection function - Fans
Protection classe	I	
Approx dimensions (W x H x D)	70 cm x 45 cm x 15 cm	
Approx. weight	4,0 kg	

2. Technical data

Heat output:	2000 W
Connection voltage:	1/N/PE~, 230 - 240 V, 50 Hz
Protection type:	IP20
Protection class:	I (with protective conductor)
Dimensions:	
free-standing	(W x H x D) 575 x 418 x 200 mm
wall-mounted	(W x H x D) 575 x 345 x 120 mm
Weight:	3.5 kg (K 811), 4.1 kg (K 821)

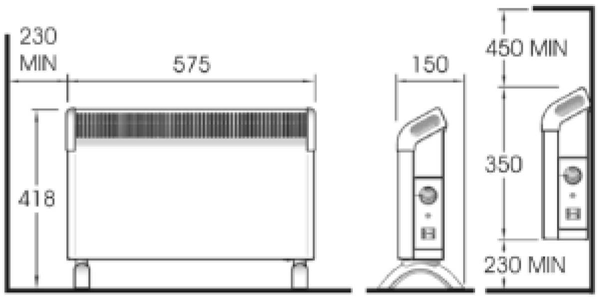


Figure 21. Heater specifications.

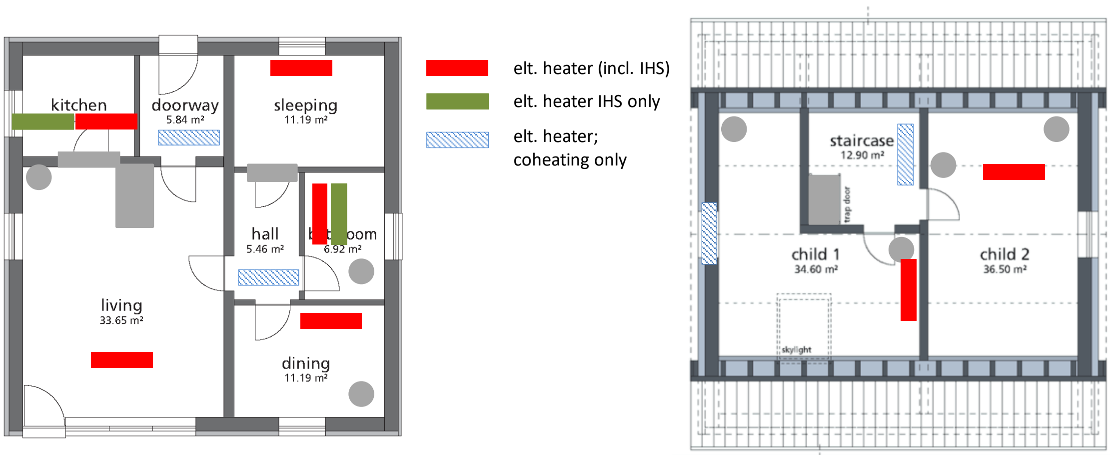


Figure 22. Heater layout.

3.13. Heat pump (O5 house)

The air source heat pump is an “aroTHERM VWL 55/2 A” (see Figure 23 and Table 14) from the manufacturer Vaillant. The heat pump’s internal controls were used. The electrical consumption and fluid temperatures and flow rate were measured on the secondary side. This system comprises a 4.9 kW heat pump with a COP of 2.40 and an additional 6 kW direct heating. The COP for domestic hot water is 1.80. The system switches its compressor's set point between heating- and DHW-mode. The underfloor heating is designed for 35 °C supply temperature. In heating mode, the heat pump feeds directly into the underfloor heating system; the 300 litre tank is for DHW buffering only.

See "arotherm-vwl-55-85-115-155-2-datenblaetter-1115125.pdf" in the additional documents.

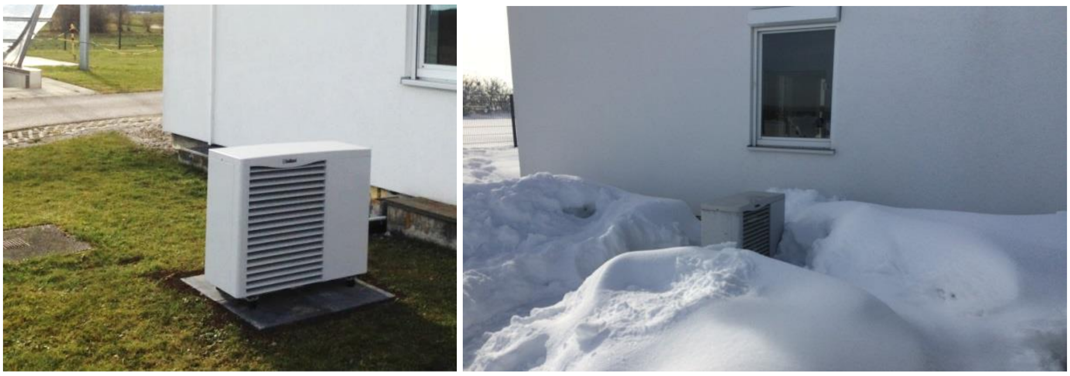


Figure 23. External installation of the Twin Houses Vaillant "aroTHERM VWL 55/2 A" air source heat pump, left in summer, right in winter.

Table 14. Technical specifications (COP) of the heat pump Vaillant aroTHERM VWL 55/2 A

Outside air temperature [°C]	Supply water temperature [°C]		
	35	45	55
-15	2.3	1.9	*
-7	2.4	2.3	1.8
2	3.1 (Δt = 5 K)	2.9 (Δt = 5 K)	3.0 (Δt = 8 K)
7	4.7 (Δt = 8 K)	3.4 (Δt = 8 K)	2.7 (Δt = 8 K)
10	5.0	3.8	3.0
12	3.0	4.0	3.2

* outside envelope of performance chart.

https://www.vaillant.de/heizung/produkte/luft-wasser-warmepumpe-arotherm-704.html

3.14. Domestic Hot Water (O5 house)

During the User-1 period DHW is only of importance for the O5 Twin House which is heated by the heat pump. A 300 litre DHW buffer vessel is connected to the heat pump. Attached to this buffer is a PLC controlled system that allows drawing defined DHW amounts in terms of energy. The DHW valve is opened until the amount heat defined by the current energy per draw is reached.

The drawn DHW was drained directly out of the building. The entire DHW installation is located in the cellar and there is no DHW circulation. Therefore all internal heat and moisture gains resulting from DHW are in the cellar and do not influence the ground floor and attic spaces which are the focus for the validation experiment. The heat pump alternates between heating and DHW production while DHW has the priority option. The air temperatures in the cellars are recorded as boundary conditions. Therefore the hot water draw will only be of interest to modelling teams who are modelling the heat pump. The measured data includes the flow rates and supply temperature to the underfloor heating system - this can be used by modellers who are not including a model of the heat pump.

3.15. Underfloor heating (O5)

The floors of the Twin Houses (both ground floor and attic floor) are equipped with a hydronic underfloor heating system. These systems are supplied by the heat pump. The room temperatures are controlled by the Twin Houses' PLC via a 2-point (on/off) controller with a 1 K hysteresis (±0.5 K) as is typical for a floor heating system. The individual rooms' air temperature sensors at 110 cm are used for control. The underfloor heating is designed for 35 °C supply temperature but the real supply temperature was set by the weather-compensated heating curve.

The underfloor heating was used in the O5 house only.

In the ground floor the piping is installed in a counterflow system (spiral shape) with spacing of 10 cm in a wet screed system. Logafix PE-RT 17 x 2.0 mm is used (nominal internal diameter 17 mm and pipe thickness 2 mm). The attics' piping of the dry screed system has a spacing of 15 cm in a serpentine installation with heat transfer aluminium profiles. The pipe material is a ROTO Alu-Laserflex 14 x 2.2 mm (nominal internal diameter 14mm and pipe thickness 2.2 mm). These installations can be seen in Figure 24. The system's supply water temperature is controlled by the heat pump's weather compensating heating curve.

Table 15. Overview of the ground floor underfloor heating.

No.	room	ground floor				
		[m²]	piping [m]	through living [m]	through corridor [m]	[m/m²]
1	doorway	5.9	56	6	4	9.5
2	kitchen	7.5	59	11	3	7.9
3	living (3 circuits)	33.6	309	-	24	9.7
4	dining	11.1	97	-	10	8.8
5	bath	6.2	59	-	8	9.5
6	bed	12.2	110	-	4	9.1
7	corridor (not circuit, just pipes from other rooms to the distribution)	4.8	53	-	(53)	11.1
	sum	81.2	743.0	17	53	
No.	room	attic				
		[m²]	piping [m]		through staircase [m]	[m/m²]
2	child1 (3 circuits)	34.7	77+72+71	-	3	6.3
3	child2 (3 circuits)	36.8	81+81+84	-	3	6.7
	sum	71.5	466.0		6	

Figure 24. Spiral pipes of the dining room in the ground floors (left) and the child 2 rooms' serpentine pipes in the attics' (right) underfloor heating during installation.

3.16. Hydronic Scheme

The hydronic scheme for the heat and DHW installation (including instrumentation) of the Test House O5 is shown in Figure 25. A higher resolution diagram is included in the additional documents.

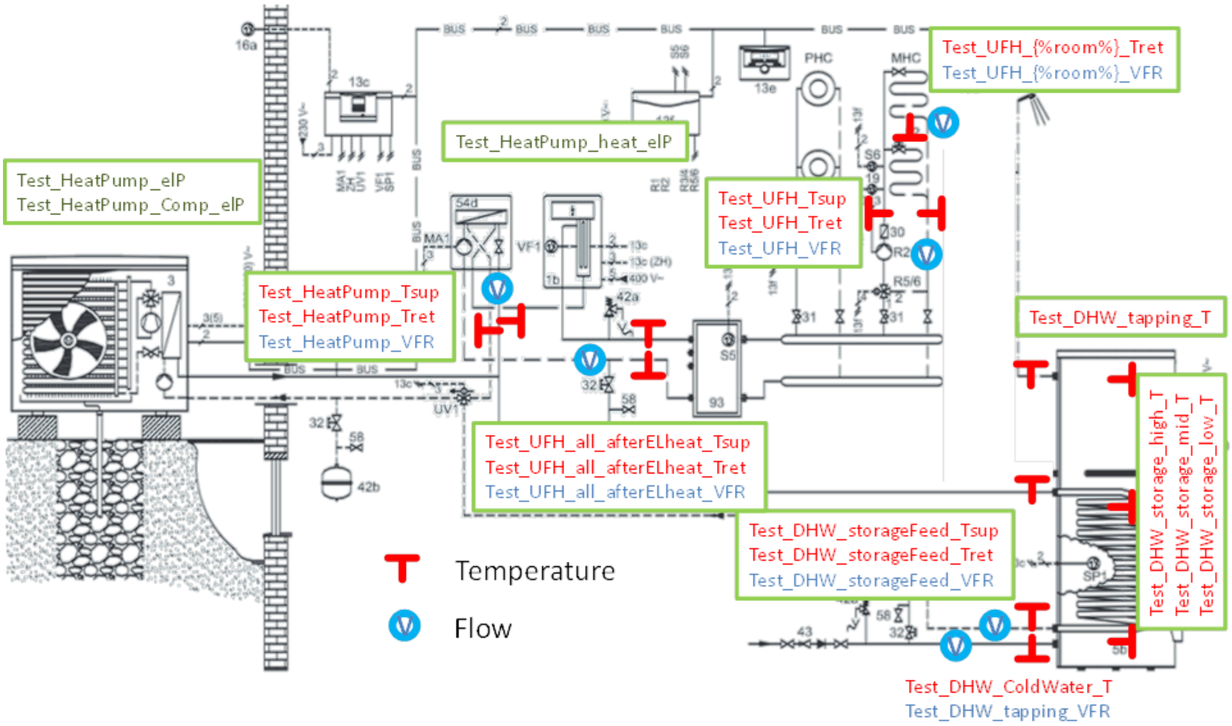


Figure 25. Hydronic scheme of the Test House O5's heat and DHW installation including the instrumentation.

3.17. Synthetic user

The validation specification of Annex 71 also includes realistic occupancy profiles. Occupying the Twin Houses with real humans would bring some disadvantages for the experiment because there would large uncertainties regarding their room-wise occupancy and the magnitude of the occurring internal loads (heat, moisture and CO_2) caused by them. Also real users always bring internal humidity sources to the building that should not be present during the first parts of the experimental schedule to keep these parts of the validation simpler. To avoid this, "synthetic users" were used in this validation experiment. This means that a typical room-wise usage profile was developed. From this, occupancy profiles synchronized to the internal load profiles were derived.

These profiles are required for the following experimental periods (see section 4):
- User period
- Free-Floating period
- Controlled moisture period
- Free-Float moisture period

3.17.1. Occupancy

The occupancy profiles used in this experiment are simulated profiles for a family with two children. The simulation model used is based on time use survey data (Flett & Kelly, 2016) (Flett & Kelly, 2017). This means that the data have a stochastic element and are different for every day. Figure 26 shows two example days of this dataset. These occupancy data are provided as a time series dataset.

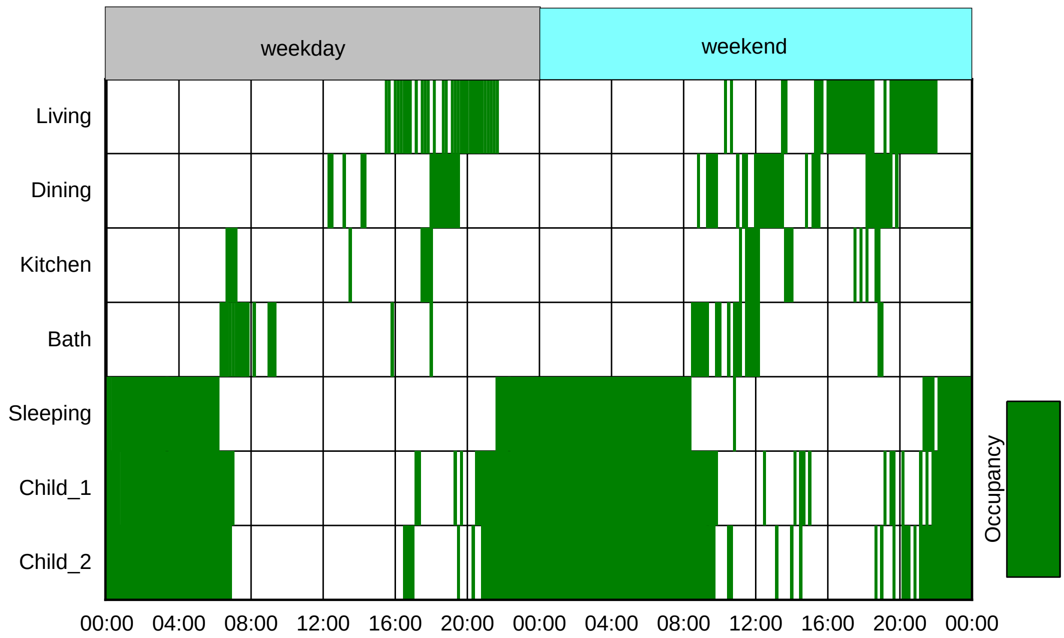


Figure 26. Typical occupancy profiles for two days.

3.17.2. Internal heat sources

A profile for the internal heat loads, caused by the occupants, their usage of appliances and artificial lighting has been derived from the occupancy profiles. The heat loads were injected into the rooms by the same electrical convectors as described in Section 3.12. Figure 27 shows two example days of this dataset. These occupancy data are provided as a time series dataset. Figure 28 gives an overview of the buildings' total heat gains during the entire test period.

In the case of electric heating, internal heat gains and additional heating inputs are provided as separate inputs. For the kitchen and the bathroom, the internal heat gains and additional heating inputs are measured separately and are provided by separate convectors. For the living room, bedroom and the children's rooms this is a calculated split based on the internal heat gain scheduled values. The dining room has heating only (no internal heat gains); the corridor has only internal heat gains; doorway and stairs have no heat input after the Co-heating period. The O5 corridor has an additional constant heat input of 12x 2.4 W through the underfloor heating's flow meters. The O5s' children rooms hold one flow meter each.

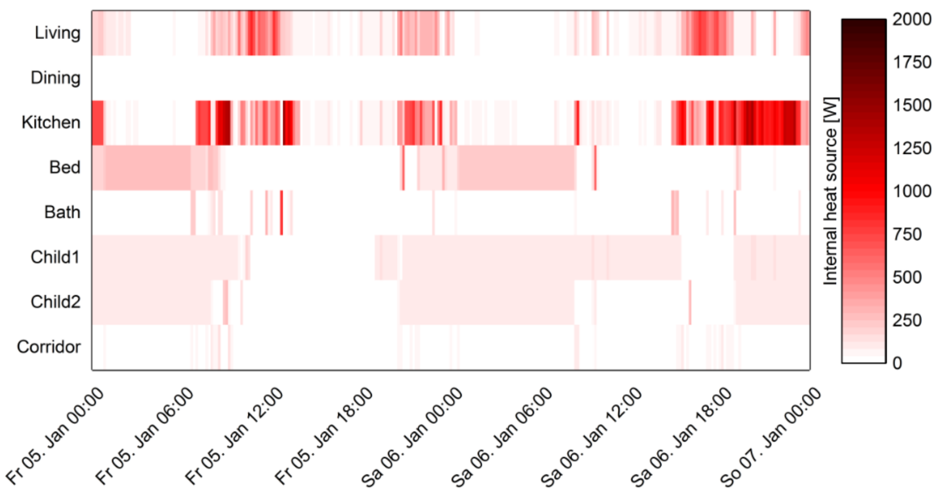


Figure 27. Resulting internal heat gains for two example days.

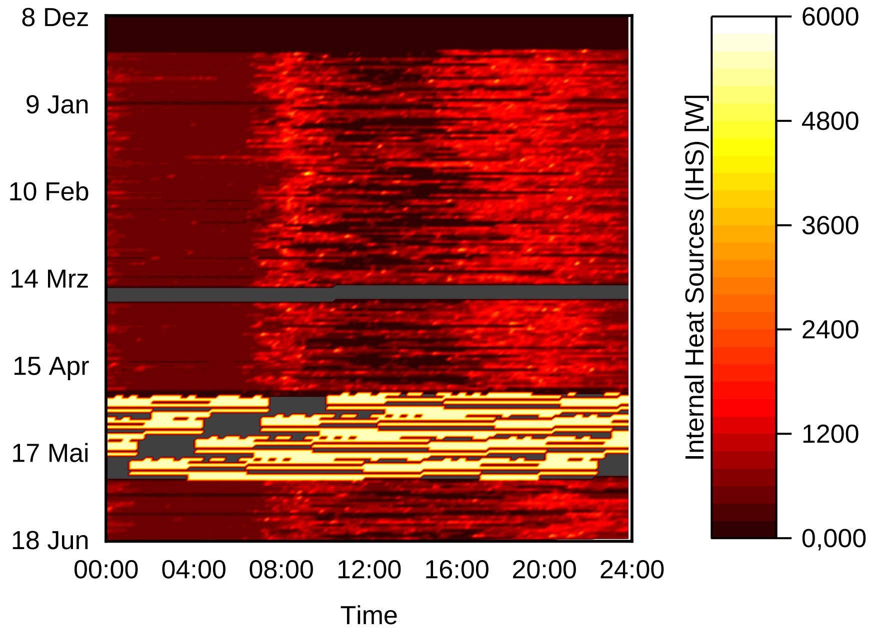


Figure 28. Overview of the internal heat gains for the entire building for the complete test period. The bright, yellow section in April/May is the PRBS.

3.17.3. Internal humidity sources

In the Extended Experiment, the humidity source was injected through the living room's supply air to avoid the necessity to enter the houses during the experiment to refill the evaporators as shown in Figure 29. Figure 30 gives an overview of the estimated building's total moisture gains during the entire test period. A comparison between the heat and moisture profile can be found in Figure 31. The fresh air temperature "o5_ZVent_out_Tamb" was not part of the data provided for the Main Experiment and was added for the Extended Experiment at the end of the O5 data files to preserve the original file structure.

This internal humidity source profile is calculated according to Equation (0.1), following the course of the internal heat source profile. The average daily internal humidity source is chosen to be about 8 kg/day, representing a 4 person family household (Hartmann, et al., 2009). The minimum value is set to 0.2 kg/h and the maximum to 1.3 kg/h.

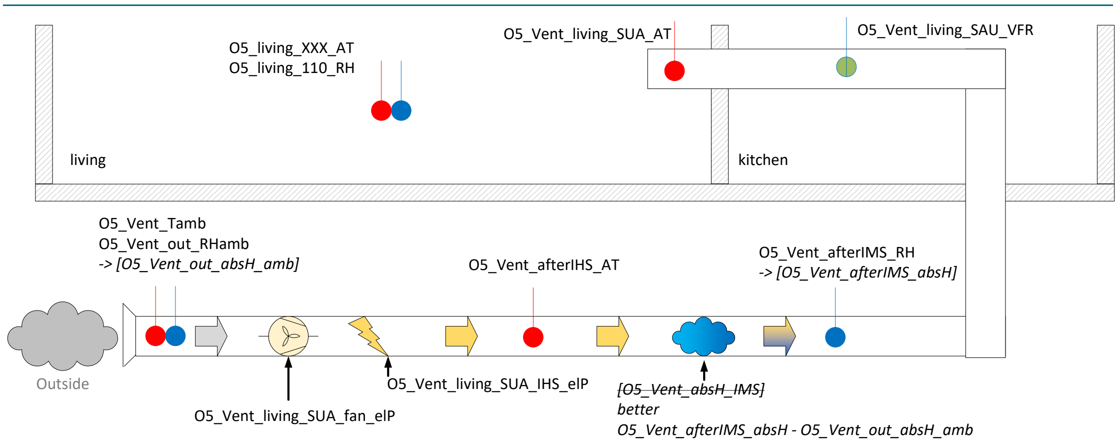


Figure 29. Realisation of the internal moisture source through the living room's supply air system.

$$\dot{w}_{IMS} = \dot{w}_{IMS,min} + \frac{\dot{Q}_{IHS}}{\dot{Q}_{IHS,max}}(\dot{w}_{IMS,max} - \dot{w}_{IMS,min}) \tag{0.1}$$

$\dot{w}_{IMS}$	water vapour mass injection rate of the internal moisture source	[kg/h]
$\dot{w}_{IMS,min}$	minimum water vapour mass injection rate of the internal moisture source	[kg/h]
$\dot{w}_{IMS,max}$	maximum water vapour mass injection rate of the internal moisture source	[kg/h]
$\dot{Q}_{IHS}$	power of the internal heat source (see section 3.17.2)	[W]
$\dot{Q}_{IHS,max}$	maximum power of the internal heat source	[W]

The provided absolute humidity are calculated from the corresponding relative humidity and air temperature according to Equation (0.2). To calculate the water vapour saturation pressure the Magnus formula (Deutscher Wetterdienst (DWD), 1997) was used.

$$H_{abs} = \frac{610.78 * e^{\frac{17.08085 * \theta_{air}}{234.175 + \theta_{air}}} * \frac{H_r}{100\%}}{\frac{R_W * (273.1 + \theta_{air})}{\rho_{air}}} * 1000\, g/kg \tag{0.2}$$

H_{abs}	absolute air humidity	[g/kg]
Θ_{air}	air temperature	[°C]
H_r	air relative humidity	[%]
R_W	gas constant of air: 462 J/(kg*K)	[J/(kg*K)]
ρ_{air}	density of air (set to 1.2041 kg/m³)	[kg/m³]

Due to the injected humidity source by the supply air, design set points for temperature and relative humidity of the ventilation device are necessary. They are calculated considering the estimated climate data for the location. Outdoor air must be heated to transport the humidity. This supply air set point temperature is kept between 5 and 17 °C. According to the internal humidity source profile, the absolute humidity of the estimated outdoor air condition and the supply air volume flow rate, the relative humidity supply air set point is calculated. However, the relative humidity is constrained between 30 and 90 %. As a result of these considerations and the fact that the humidity injector (condair Defensor MK5) injects hot steam generated by boiling water, the supply air temperature of the O5 house is systematically higher than in N2.

Due to the usage of estimated climate data in the figure, the provided internal humidity source during the test may differ compared to the shown profiles.

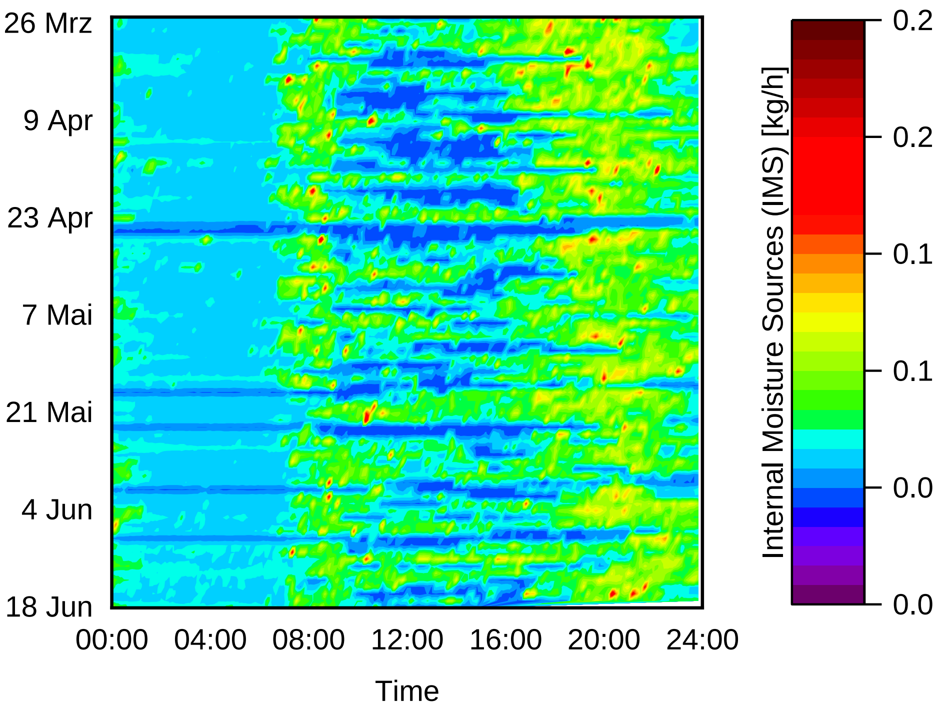


Figure 30. Internal moisture gains for the entire building for the complete period.

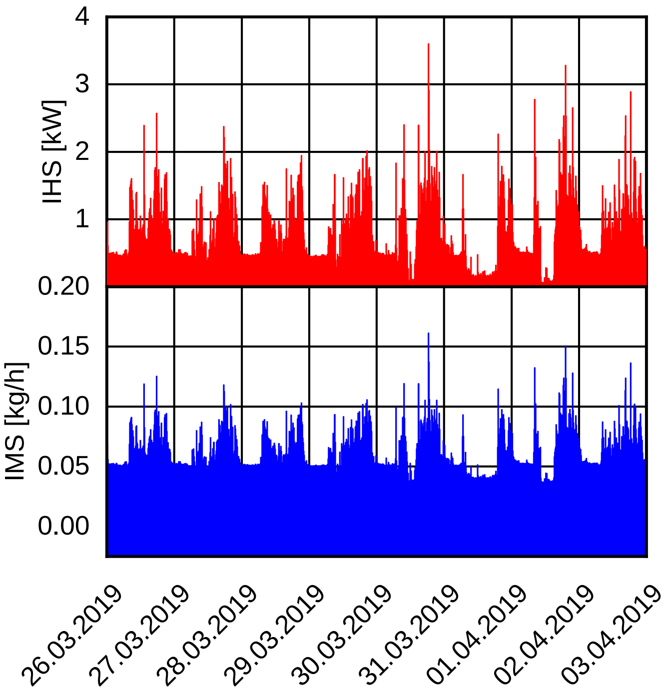


Figure 31. Comparison between the internal heat and moisture load profiles over a period of eight days.

3.17.4. Internal CO_2 sources

This is not possible since CO_2 is one of the tracer gases used to monitor intra-room air exchange.

3.17.5. Set temperatures

A set temperature of 21 °C was chosen for occupied rooms, with 17 °C as the (night-time) setback temperature. All set temperatures / profiles are realized through room thermostats and not by the heat source / heat pump (e.g. setback of the supply temperature) to avoid complicated interactions in the hydronic system. Figure 32 shows two example days of this dataset for the User-2 and User-3 periods. These occupancy data are provided as a time series dataset. It is assumed that the heating system will not be put on setback for an absence period of 2 hours or shorter.

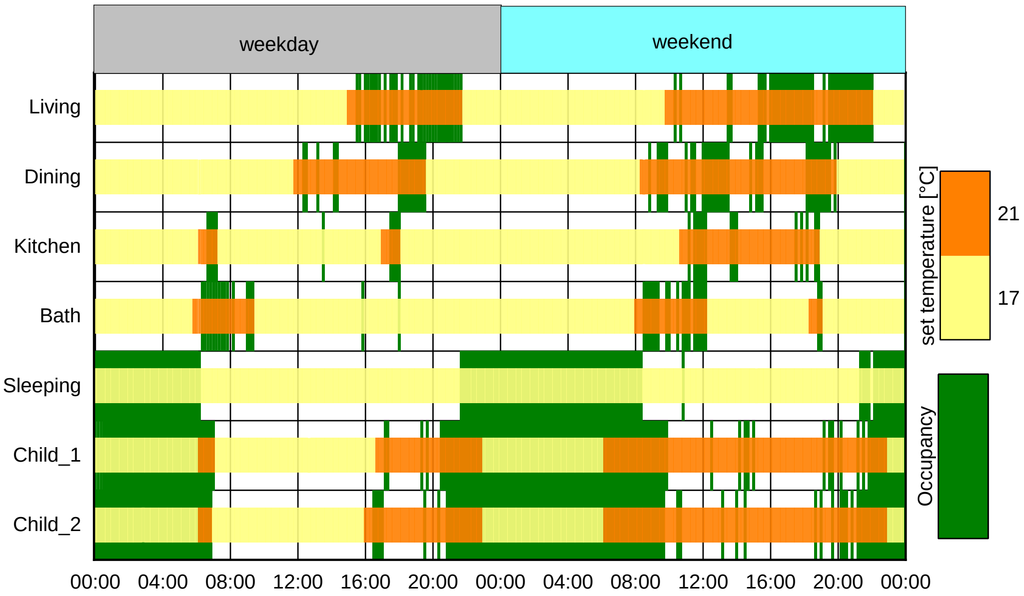


Figure 32. Resulting occupancy and set temperatures for two example days.

3.17.6. External window and internal doors

The operable external window is located in the child1 room. The operable internal door is located between the living room and the kitchen. The four possible configurations of both operable components defined in Table 16 were cycled through the injections. Since the injection cycle is 12 hours, the total cycle of the four possible configurations was 48 hours.

Table 16. Operation cycle of the operable external window and internal door.

No.	external window	internal door
1	closed	closed
2	closed	open
3	open	closed
4	open	open

The intra-room airflow was monitored with a two-gas tracer gas system during the Extended Experiment. The tracer gas setup is described in section 4.9. The gas monitor (Innova PD 1412 PW; see filter number below)) is specified with a detection dynamic of the factor 100000 for the gases used in the experiment. The following ranges are applicable:

- SF_6: 0.006 – 600 ppm (filter: 988)
- CO_2:0.06 – 6000 ppm (filter: 973)

The living room has a volume of 87 m³ and a mechanical ventilation rate of 100 m³/h (1.14 h^{-1}). To decay to 110 % of the atmospheric CO_2 concentration (700 ppm) takes 5 hours. 700 ppm were chosen as lowest limit because this is the highest atmospheric concentration measured on site as can be seen in Figure 33.

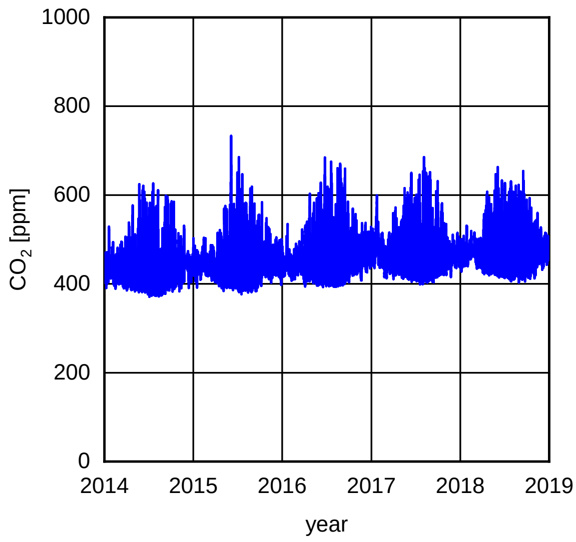


Figure 33. CO_2 cycle over the years 2014 – 2019 in Holzkirchen; 1 hour sampling.

3.17.7. Roller blinds

The roller blinds and their influence on solar gains and transmission losses were investigated in Annex 58. Therefore it was decided not to operate them in this experiment. The blinds on the north, east and south facade are open permanently while the blinds of the west facing windows of the ground floor are always closed. The reason for this is a slightly different external shading of solar radiation on the two houses in winter because of a new test facility on the site. The attics' west façade roller blind of the child 1 room remains open so the airflow through the operable window is not obstructed.

3.17.8. Domestic Hot Water

The domestic hot water demand during the User-1 period is calculated by the occupancy model (see Figure 34) and provided as a time series along with the other measurement data.

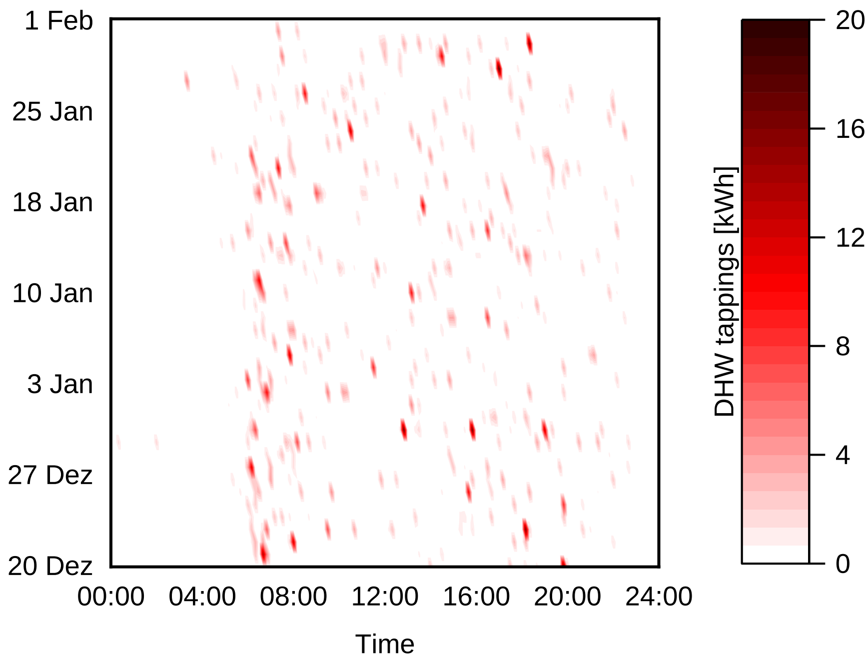


Figure 34. Domestic hot water tappings during the User-1 period.

3.18. Weather

The weather data during the experiment is collected on site and provided to the modelling teams. Site wind speed is measured at the standard 10 m above the ground. The weather data is collected at 1 minute intervals and is provided as 10 minute and hourly averages. Details of the weather monitoring sensors are given in the additional documentation (https://fordatis.fraunhofer.de/bitstream/fordatis/161/3/02_Additional%20Documents.zip).

3.19. Ground properties

Shortwave ground reflectivity was measured previously over grass as 0.23 (measurement data of about 2 days). Additional measurements of ground reflectivity have been made above asphalt (0.17) and gravel (0.45). During the experiment the albedo in front of the south windows of both houses was measured continuously. Note the increased albedo during periods of ground snow cover.

Measured ground temperatures are included at a number of depths (0 m, 0.05 m, 0.1 m and 0.2 m). The sensor at 0 m is not exposed and is now covered by soil and grass.

4. Experimental schedule

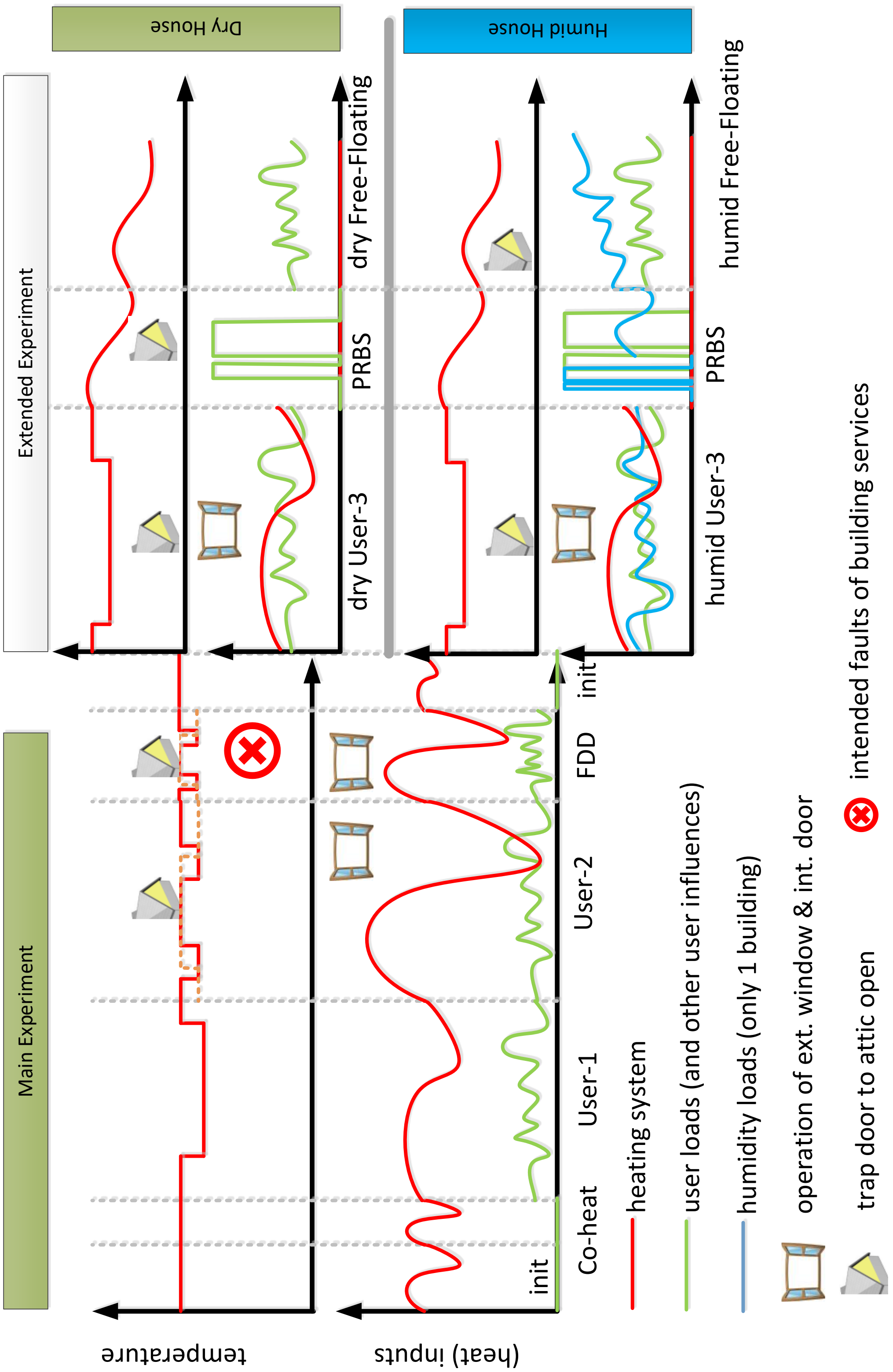


Figure 35. Experimental schedule with main experiment followed by extended experiment.

Table 17. Experimental configuration of all periods.

	Co-heating	User-1	User-2	FDD	reinitialisation	User-3 (moisture)	PRBS	Free-Float	tracer gas
Duration [days]	7 start: 7.12.2018 18:00	35	30	14	7	25	~8+8+8+8	20	1.5
End	19th Dec. 9:00	1st Feb. 10:30	1st March 00:00	16th March 13:30	22nd March 10:30	25th April 10:30	26th May 22:20	18th June 7:00	19th June 17:00
set temperature	constant	Night setback; identical for all rooms	room wise profile, incl. stochastic deviations	room wise profile, incl. stochastic deviations	constant	room wise profile, incl. stochastic deviations	5°C	5°C	5°C
heating power	variable	variable	variable	variable	variable	variable	0	0	0
heating system N2	electrical	electrical	electrical	electrical	electrical	electrical	-	-	-
heating system O5	electrical	UFH	UFH	floor	electrical	electrical	-	-	-
thermal user profile		incl. stochastic deviations	incl. stochastic deviations	incl. stochastic deviations	-	incl. stochastic deviations	PRBS	incl. stochastic deviations	-
	Co-heating	**User-1**	**User-2**	**FDD**	**reinitialisation**	**User-3 (moisture)**	**PRBS**	**Free-Float**	**tracer gas**

moisture user profile	-	-	-	-	-	O5 only; incl. stochastic deviations	O5 only; 2 large pulses then stochastic deviations	O5 only; incl. stochastic deviations	-
internal doors kitchen - living	open	open	operated (Closed: 00:00 - 6:00 Open: 6:00 - 24:00)	operated (Closed: 00:00 - 6:<00 Open: 6:00 - 24:00)	open	operated (Closed: 00:00 - 6:00 Open: 6:00 - 24:00)	open	operated (O5) (Closed: 00:00 - 6:00 Open: 6:00 - 24:00)	open
doors sleeping	open	closed	closed	closed	closed	closed	closed	closed	closed
roller blinds	living west closed	living west closed	living west and kitchen closed	no change	no change	no change	no change	no change	no change
operable window (Child1)	closed	closed	operated (24 h cycle)	operated (24 h cycle)	closed	operated (24 h cycle)	closed	closed	closed
mechanical ventilation	off - sealed	on	on	on	on	on	on	on	off - sealed
trap door to attic	open	closed	open	open	open	open	open	open	open

O5 is the house with underfloor heating during the main experiment and the “wet” house during the extended experiment.

4.1. Initialisation period(s)

These periods were used to bring both buildings to identical initial conditions for the experiment. All rooms of both buildings were set to the same constant set temperature. The ventilation system was on and no occupancy profile was implemented.

In the first initialisation period all doors were open since this was required for the Co-heating test. Also both buildings were heated electrically as this is also required for the Co-heating test.

In the 2nd re-initialisation period, all doors were open or closed according to the chosen setup (see section 3.3, Figure 6 and Figure 7).

4.2. Co-heating period

The Co-heating period has two purposes. On the one hand the Heat Loss Coefficients of both buildings are determined to be available as a baseline for all further analysis. On the other hand it serves as a simple constant temperature period to give the modelling teams a possibility to have and check a model with basic functionalities only. To be comparable both buildings are heated using electrical heaters. The ventilation system is off and no occupancy profile is included. This Co-heating experiment is carried out in compliance with the draft of “CEN/TC89/WG13 TG5 (Working Draft 12/01/17)”. In this period every room is equipped with a fan to break the air temperature stratification. The electrical input of the mixing fans is included in the measured data in the sockets’ power. These fans are switched off in other experimental periods (e.g. User-1 and User-2 periods). The constant set temperature for the Co-heating period is 21 °C.

4.3. User-1 period

In this period the occupants’ influence was created through synthetic user profiles while the building was heated using electrical (N2 house) or hydronic underfloor heating (O5 house). The User-1 period is a simple realistic period with mechanical ventilation and identical temperatures in all rooms including a night setback between 23:00 until 6:00. The purpose of this period is to check if simulation programs are able to reproduce more complex cases than the Co-heating period or the Annex 58 experiment and can handle user interactions such as small room-wise occupancy differences and some building service equipment (underfloor heating). The electrical input of the supply fans is included in the measured data as separate channels, as is the exhaust fans’ consumption. The supply air temperatures are measured after the fans, the exhaust air temperature before them.

4.4. User-2 period

In this period the occupants’ influence is created through synthetic users while the building is heated using electrical/hydronic underfloor heating. The User-2 period is a more complex realistic situation including operating internal doors and external windows and different set temperature profiles in the individual rooms.

The purpose of this period is to check if simulation programs are able to reproduce more complex cases than the Co-heating period or the annex 58 experiment and can handle user interactions like changing air flows caused by operated windows and doors, more significant room-wise occupancy differences and basic building service equipment (underfloor heating and ventilation).

4.5. FDD period

This part of the experiment was specified by Annex 71 Subtask 2 and is not part of the validation experiment. This period is identical to the period User-2 but two errors in the building service systems were introduced deliberately to provide data to test fault detection abilities of various algorithms.

4.6. User-3 period: including moisture release

The purpose of this period was to check if simulation programs are handling the thermal and energetic influences of moisture effects and how significant the influence of the moisture is in general. It is similar to the User-2 period but with additional moisture source in house O5. To ensure that both Twin Houses are identical except for the presence of the moisture source in this period both houses were heated electrically. The heat pump provided DHW only. The trap door to the attic space was opened for this experiment.

4.7. PRBS-period

In this period there was no heating and instead of the synthetic users a Pseudo Random Binary Sequence (PRBS) with heat pulses of 700 W was realized through the electric convectors. In this sequence the ground floor and the attic were partially excited synchronously, partially separately and with two different frequencies in both setups, synchronously and partially. This period was located at the end of the experimental schedule because as a Free-Float experiment it is not negatively impacted by higher external temperatures that could occur during the start of the spring season. The purpose of this PRBS period was to create a dataset that is optimized for statistical identification tasks and could be realized in this design in a real building.

4.8. Free-Float period

There was no heating in this period, but synthetic users were included. This period is located at the end of the experimental schedule because as a Free-Float experiment it is not negatively impacted by higher external temperatures that could occur during the start of the spring season. The purpose of this Free-Float period was to test if simulation programs are able to correctly predict performance with heat inputs dominated by solar gains under summer conditions. The purpose of the Free-Float in the wet building (O5) was to check if simulation programs can include the thermal and energetic influences of moisture effects and how significant the influence of the moisture is in general.

4.9. Tracer gas air change rate measurement (O5 house only)

For the last 1.5 days of the experiment the O5 house infiltration was measured by tracer gas. The mechanical ventilation was inactive and the inlets and outlets were sealed on the outside.

5. Instrumentation

5.1. Overview

A detailed overview of all existing measurement channels, used instrumentation and data loggers, calibration certificates and associated accuracies can be found in the “Measurement Channel List.xlsx” among the additional documents provided. All instrumentation values are recorded with a frequency of 1 second and are stored as 1 minute means. The calculation of all hydronic and ventilation thermal powers is also performed at 1 second intervals and stored as 1 minute mean values.

- external climate (full weather station):
  - air temperature
  - ground temperatures
  - sky temperature
  - solar radiation (global, diffuse, (direct is calculated), total vertical in all 4 main orientations)
  - wind speed and direction
  - 2x South Albedo (downward-facing sensor)
  - CO_2
- electric power consumption
  - heaters, room wise
  - internal heat sources, room-wise
  - heat pump (compressor, controls, direct heating)
  - supply and extract fans
  - heat pump auxiliary heater (UFH)
  - DHW storage auxiliary heater
- heat pump
  - supply and return temperatures
  - flow rates
  - (thermal power is calculated; 1 second basis)
- domestic hot water
  - hot water flowrate and temperature
  - cold water supply temperature
  - buffer vessel temperatures (1 or 3 positions)
- under floor heating (room wise)
  - supply temperature
  - return temperature
  - flow rate

    - thermal power is calculated
    - 2x Heat flux sensors under child-1 and living room
- ventilation (central and point-wise)
    - supply / exhaust air temperature
    - supply air humidity (O5, wet house)
    - air flow
- rooms (all)
    - air temperature @4 heights
      10 cm, 110 cm, 170 cm and 10 cm below ceiling
    - globe temperatures @ 110 cm
    - relative humidity
- air flows through tracer gas measurement; for all air bodies
  (only in 1 house); started at: March 11th 2019
- cellar air temperature (2x); 30 cm below ceiling;
  located at the columns closest and furthest from cellar door
- constructions:
    - 2x heat flow through west wall: location internal surface centre of wall
    - 2x internal west wall temperature between plastered brick and thermal insulation composite system
    - 2x internal and external surface temperature west wall
- internal solar irradiance behind the living room's south window (O5 house)
- draught through open doors
    - investigated at the door between living and corridor
    - air speed sensors inside the doorframe @~ 3 heights;
      10 cm, 110 cm, 170 cm.
      1 measurement per minute; not 1 minute means.

5.2. Co-heating concept

The Co-heating test was conducted with electrical heating only and fans were used to break the air stratification and to reach homogenous air temperatures. The required devices' locations are shown in Figure 36. Only in this period every room was equipped with a fan to break the air temperatures' stratification. On December 10th there was a minor repositioning (shifting by ~ 1 m / turning by ~20°) of the fans to improve the air mixing. The aim of this change was to intersect the hot air plumes of the electrical heater with a fan's air stream.

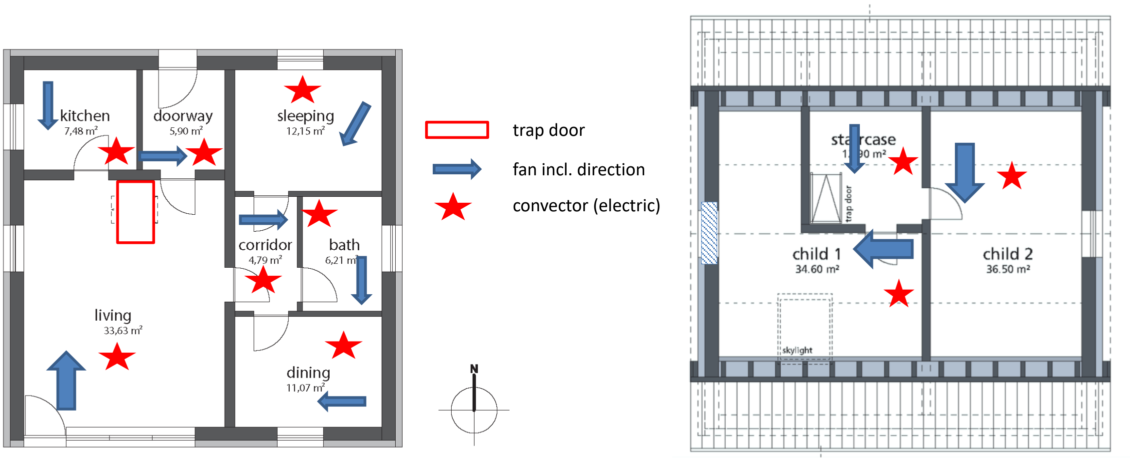


Figure 36. Setup of electrical heaters and fans during the Co-heating test in the ground floor and the attic before December 10th.

5.3. Tracer gas concept

The tracer gas measurement accompanying the Extended Experiment started on March 11th 2019. Tracer gases SF_6 and CO_2 were used. SF_6 is not part of the natural atmosphere and therefore doesn't require compensation concerning the outside and supply air. CO_2 however is part of the exterior air. The current CO_2 concentration is available from the weather data of the IBP's weather station. The tracer gas measurement is only available in the O5 house (underfloor heating). For all used gases 6 (identical) sampling points are available. One sampling point was installed into the supply air to give an accurate measurement of the outside gas concentration. For the CO_2-injections a boolean signal ("O5_CO2_dosing_flow") is available; for the SF_6 this is not the case. This described setup can be found in Figure 37. SF_6 is injected into the living room and CO_2 into the child 1 room. These data can be found in "04_Data_Extended_Experiment.zip\TracerGas".

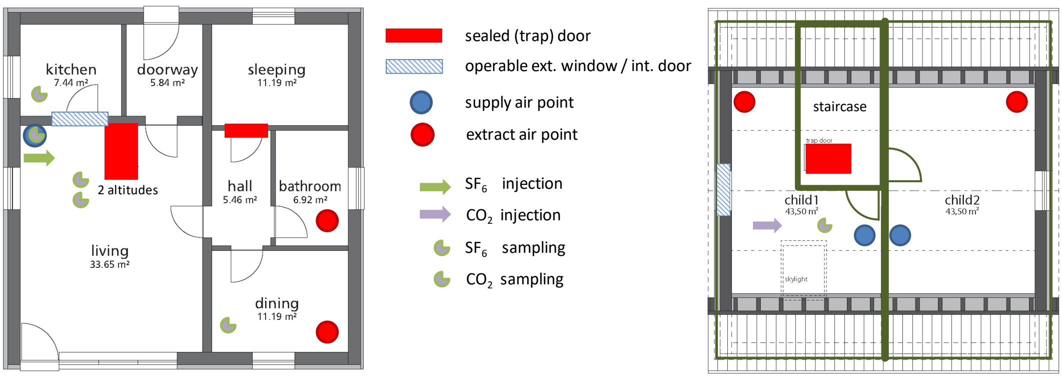


Figure 37. Illustration of the tracer gas concept on the ground floor (left) and the attic space (right)

6. Practical aspects of modelling the measured data

6.1. Overview

A key element of this validation study is that the focus is on testing the capability of simulation programs to predict performance, given knowledge of boundary conditions and internal heat gains. It is not aimed at testing the ability of users to construct a model (although the dataset can also be used for this training purpose). Therefore, modelling teams are encouraged to undertake quality assurance of their models, perhaps by another experienced modeller, in order to reduce the likelihood of input errors.

The remainder of this section sets out the modelling instructions for participating modelling teams in the Annex 71 validation experiment. Modellers using the experimental datasets subsequently can follow the same procedure, or adapt it to their own requirements.

Co-heating / Constant temperature period

- Both houses have electric heating controlled to a nominal constant setpoint (21 °C). There are no internal gains apart from the fans and no mechanical ventilation.
- Measured air temperatures are provided (there are occasions of overheating due to solar radiation, so measured temperatures as well as the setpoint temperature are provided). The temperatures provided are the air temperatures at mid-height in the room (110 cm). The measured fan power is also provided as an integral for the entire buildings' electrical sockets.
- Modellers are asked to predict heat input to electric heaters. Modellers only need to model one house, as the constructions and operations are identical (both have underfloor heating installed, but not operational in this period). However, due to sensor uncertainty, the measured temperatures differ slightly, so modellers should provide results for both houses. The O5 house's corridor has constant heat gains of 12x 2.4 W due to the installed flow meters (not included in the measured internal gains).
- Initialisation period. The first three days of the Co-heating experiment can be included in the results but will be excluded in the analysis to compensate for initialisation effects. Internal preconditioning of the building to a constant 21 °C can be assumed.

User-1 and User-2 periods

House O5: Underfloor heating (UFH)

- The house is much more dynamic in these periods - internal heat gains, plus window/door openings in the User-2 period.
- User-1 period: setpoint 21 °C with 17 °C night setback for all rooms between 23:00 and 6:00.
- User-2 period: setpoints (21/17 °C) vary between rooms.
- Measured internal heat gains are provided.
- Inputs provided are supply flow rates and temperatures to each UFH circuit. After the Blind validation phase, the total thermal input to the UFH will be provided. This is based on 1 second data to avoid averaging errors.
- Setpoint temperatures (for the air temperature in centre of rooms at 110 cm height) are provided but they may not be achieved at all times.
- Modellers should predict the room air temperature for comparison with the measured/calculated volume-averaged air temperature in the rooms and for comparison with the measured air temperature at the centre of the room. (In practice, most modellers are likely to be assuming fully mixed spaces.) Additional information on stratification should be provided by modellers, if possible. The open phase measurement data provide information on the stratification at four heights.
- Modellers should use the provided room-wise supply temperatures and UFH flowrate instead of the setpoint signal.
- Modellers should also predict the UFH's return temperatures.
- For teams wishing to model the heat pump, data is provided on the compressor's power consumption and switching information on the direction of heat flow for the defrosting cycle and on/off switching of the direct electric auxiliary heater. Note that during the User-1 period the heat pump is also producing domestic hot water on a priority option, meaning the heating's supply will stop during DHW production.

House N2: (reference) electric

- The schedule in the User-1 and User-2 periods (temperature setpoints, internal heat gains, door and window operation) are the same as for house O5.
- Measured heat inputs into each room are provided, separated into the scheduled (measured) internal heat gains and additional heat inputs that are trying to maintain the setpoint.
- Heating setpoints are provided, but they may not be achieved at all times, and may also be exceeded in periods of high solar radiation. Air temperature in centre of rooms (@110 cm).

- The measured heater capacity (nominally 2 kW) ranges from 1.80 to 1.93 kW. However, this will not affect the modelling predictions because measured heat inputs are provided.
- As mentioned above, internal heat gains and additional heater inputs are provided as separate inputs. For the kitchen and the bathroom, the internal heat gains and additional heater inputs are measured separately. For the living room, bedroom, child 1 room and child 2 room, which only have 1 heater, this is a calculated split based on the internal heat gain scheduled values. The dining room has heating only (no internal heat gains); the corridor has only internal heat gains; doorway and stairs have no heat input after the Co-heating period.
- Modellers should predict the room air temperature for comparison with the measured/calculated volume-averaged air temperature in the rooms and for comparison with the measured air temperature at the centre of the room. (In practice, most modellers are likely to be assuming fully mixed spaces.) Additional information on stratification should be provided by modellers, if possible. The open phase measurement data provide information on the stratification at four heights.
- Modellers should use the provided room-wise heat inputs instead of the setpoint signal.

Both houses

- The measured exhaust temperatures from the mechanical ventilation system were not available in the Blind validation phase, but were released in in the Open phase.
- The supply air fan power is provided in case modellers wish to model the ductwork. The ductwork is insulated, but there will still be residual losses. The supply air temperatures are measured after the supply fans' heat input. The exhaust fans are located after the exhaust air temperature sensors.

Modellers are also encouraged to provide more detailed data – e.g. temperature distribution in rooms where this has been predicted, and air change rates through internal doors and the operable external window.

Modellers are encouraged to undertake sensitivity studies and include results of these in the modelling report. For those teams undertaking sensitivity analyses, it is suggested that the following parameters could be investigated:

- radiative-convective split of the heating system
- uncertainty in the temperatures in the cellars of the two houses
- infiltration assumptions
- assumptions concerning the operable external window
- uncertainty in the measurement of the internal heat gains
- interaction between stratification and exhaust air temperature

6.2. Main Experiment: operational details

Figure 38 provides a summary of central measurement data of both Twin Houses. Some gaps of short measurement failures were filled by linear interpolation for temperatures and set to zero for powers and flowrates. The full experimental dataset is available for more detailed graphing and analysis at https://fordatis.fraunhofer.de/bitstream/fordatis/161.2/4/03_Data_Main_Experiment.zip.

In the top left, the measured air temperatures in all rooms at a height of 110 cm are shown.

In the middle left the buildings' set temperatures of all heated rooms are shown. In first quarter of the dataset (24.12.2018 07:00 until 25.12.2018 11:00) the set temperatures of the O5 building drop to "0" in the provided data. Here the O5 building's PLC did not properly reboot after a power failure of a few seconds. This also affects the IHS (top right) the ventilation (middle right) and the underfloor heating. The O5 building is in Free-Float during this period.

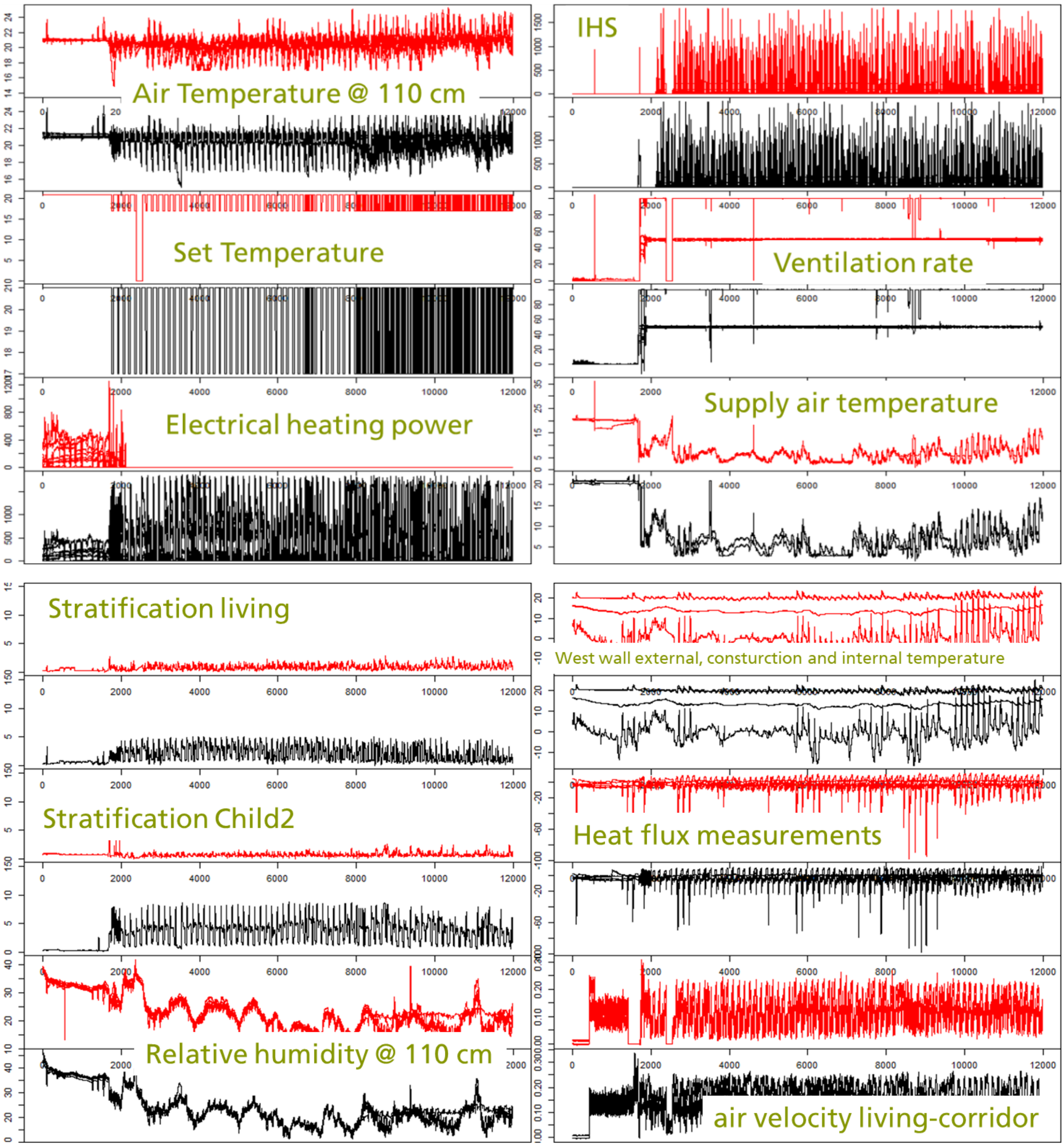
Thorough investigations showed that the O5 building went from heat pump to electrical heating with a constant setpoint of 21 °C. The heating power was simulated, and the missing data filled for all ten "heat_elP" columns in this period.

The set temperatures (middle left also) also show a quite regular behaviour in the first half of the non-Co-heating measurements during the User-1 period and a more complicated behaviour later in the main experiment during the User-2 period. Also, during the User-1 period about 1.5 days (23.01.2019 ~9:00) a more complicated behaviour can be seen. Here the User-2 profile was started too early and was reset to User-1 as soon as the deviation was discovered. This affects the set temperatures, the resulting heating inputs and the IHS.

The O5 house shows some electrical heating power at the beginning of the User-1 period (bottom left). These heat inputs occurred in reality due to an improper configuration of the PLC.

The IHS (top right) and the ventilation flow rate (middle right) show some very short peaks during the Co-heating period. These occurred because of short (unsuccessful) changes to the O5's PLC. The same is true for the single peak in the N2's supply air temperature (bottom right).

In some extreme winter conditions (e.g. morning of 1st of January) the external ventilation inlets can be cloaked by ice and cause reductions from the set values until they have been de-iced. However, the measured flow rates are given as input data so this information can be included in the model. Since thermoanemometers are used to derive the volume from the air speed the volume flow measurement's accuracy is not influenced.



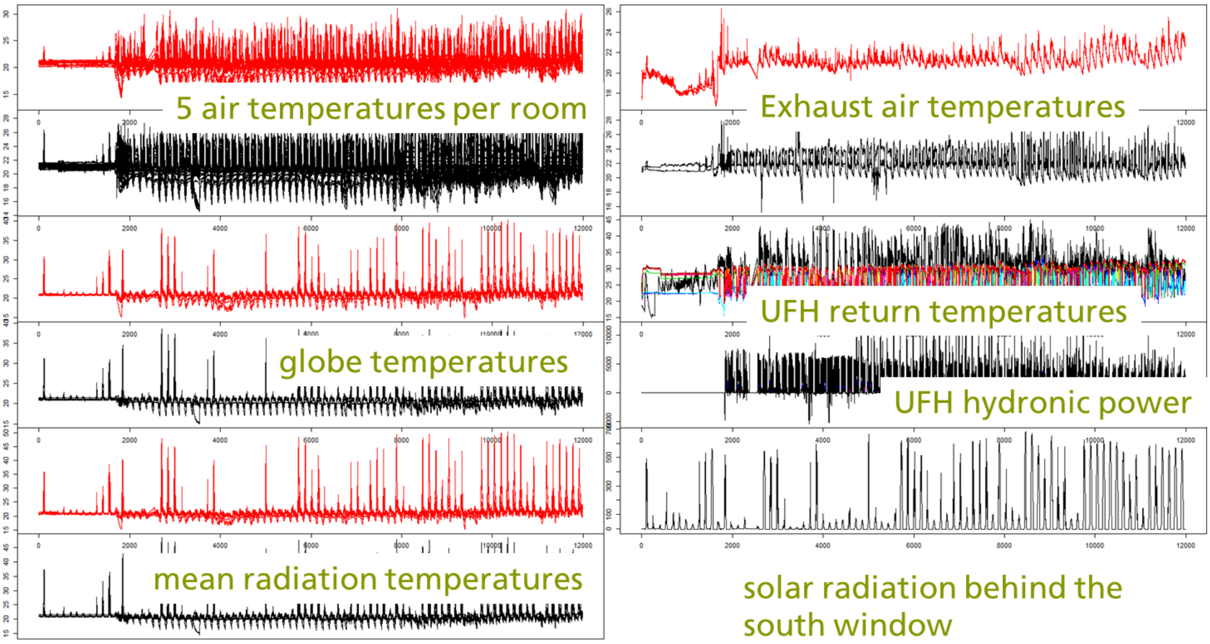


Figure 38. Selection of the Main Experiment's measurement data of the O5 house (red) and the N2 house (black).

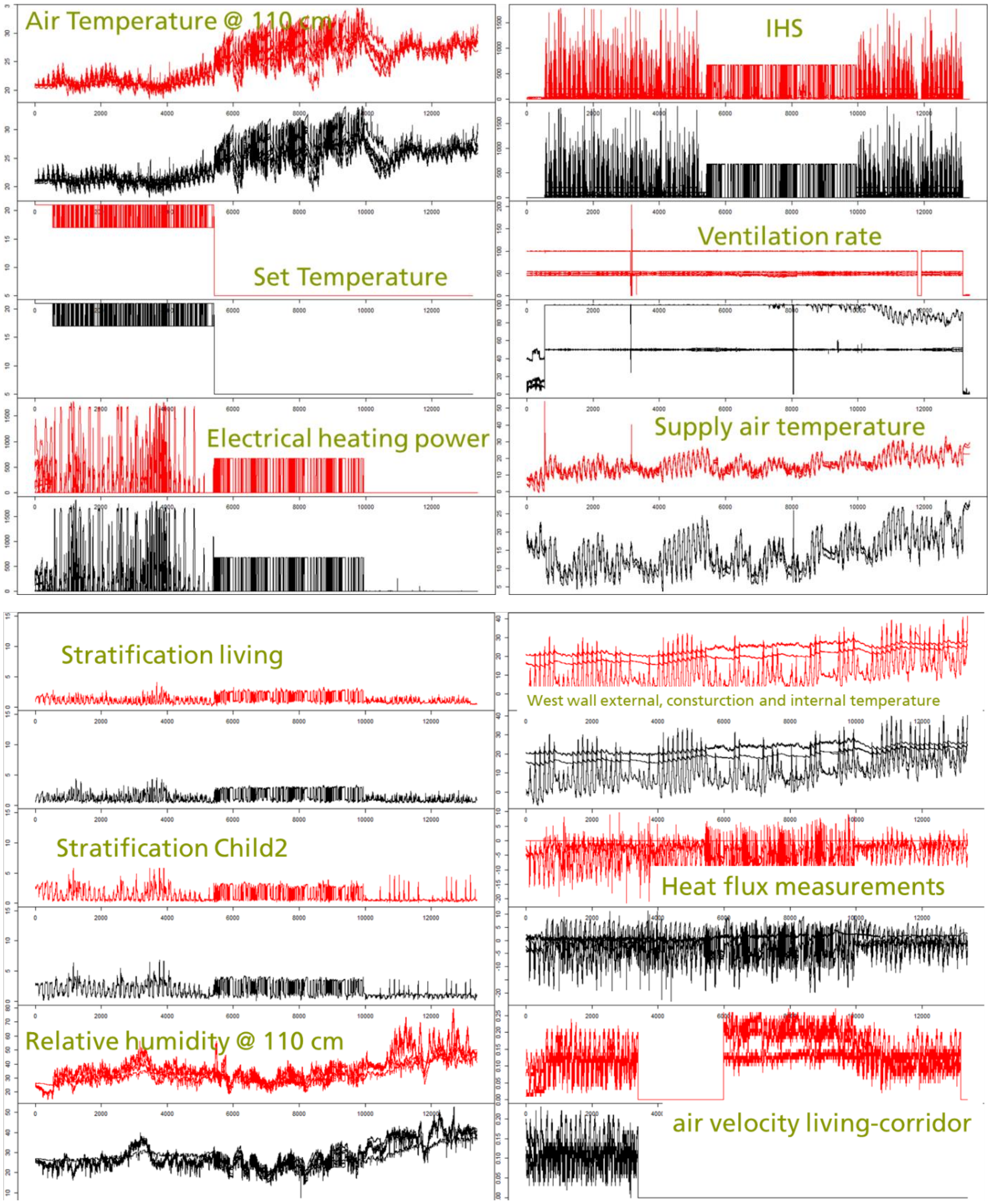
6.3. Extended Experiment: operational details

Figure 39 gives an overview of the data provided for the Extended Experiment. The dining room's PRBS power signal was measured on the heating power channel since the dining room has no separate IHS channel. This is the reason the PRBS can be seen at the heating and the IHS.

In the N2 house, a decrease in the living room's supply air ventilation rate (nominally 100 m³/h) can be seen towards the experiment's end. To provide an uninterrupted dataset the experiment was not stopped to fix the fan. This drop is contained in the measurement data and should be considered in the simulation model.

For the Extended Experiment the measured concentrations of the two tracer gases are provided in the "CONCENTRATION_10/60Min.xlsx" files.

After the User-3 period the air velocity sensors between living and corridor of the N2 house were needed in another experiment.



Air Temperature @ 110 cm
IHS
Set Temperature
Ventilation rate
Electrical heating power
Supply air temperature
Stratification living
West wall external, consturction and internal temperature
Stratification Child2
Heat flux measurements
Relative humidity @ 110 cm
air velocity living-corridor

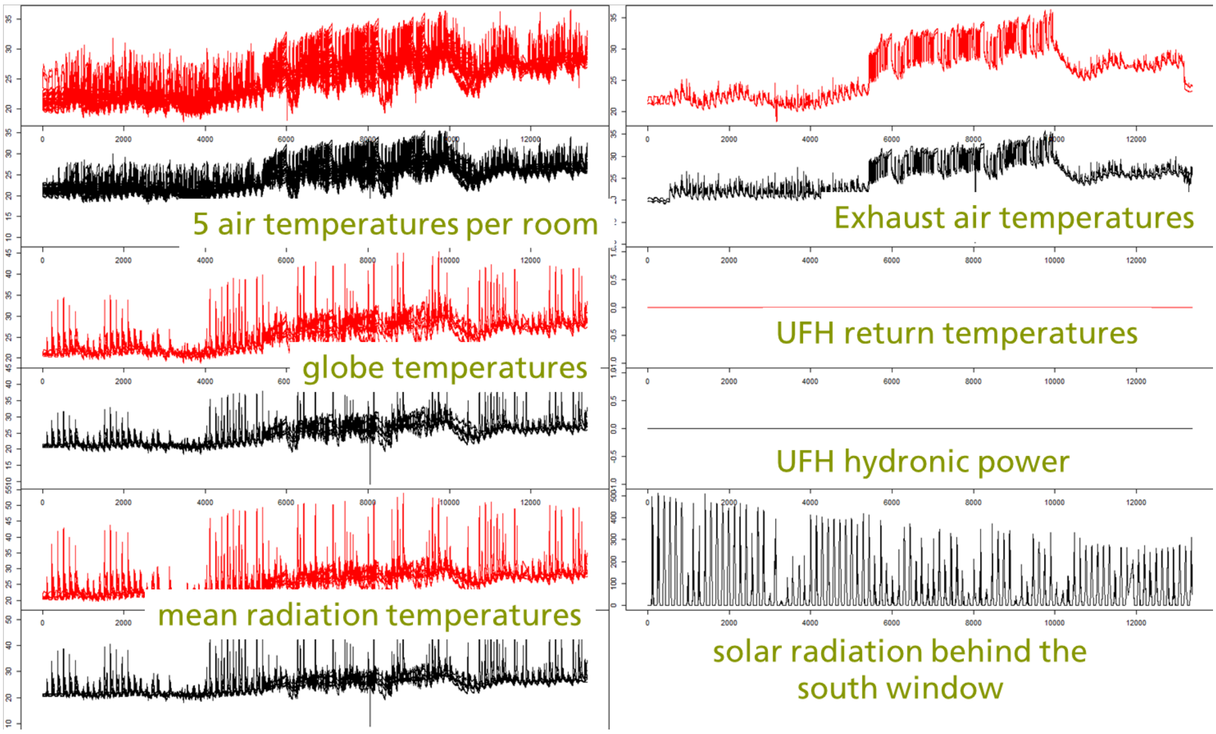


Figure 39. Selection of the Extended Experiment's measurement data of the O5 house (red) and the N2 house (black).

7. Results

The results are organized in two sections. The first section analyses the simulated raw data and gives an overview over the performance of all participating teams regarding different aspects. In the second section the authors try to identify dependencies between good or poor results and specific modelling approaches. An overview of the 13 participating modelling teams (from 7 countries) and the programs used is compiled in Table 18. The datasets created were also used by the subtasks 2 and 3 of this Annex as development cases ("Common Exercises") for their work on model predictive control (MPC), fault detection and diagnosis (FDD) and regarding the identification of building standard metrics, like the heat loss coefficient (HLC), from field data obtained during realistic typical operating conditions.

Table 18. Modelling participants and programs for the Main Experiment (ME) and the Extended Experiment (EE).

Organisation	Country	Annex71 participant	Program	ME blind	ME open	EE blind	EE open
Ghent University	BE	yes	Modelica 3.2.3 & IDEAS 2.1.0	x	x	x	X
Universität Innsbruck coop. with Passivhaus Institut	AT DE	yes yes	Dynbil 0.8.1 & DynPP 190822	x	-	-	-
University of Wollongong University of Strathclyde (developer)	AU UK	no yes	ESP-r 13.3.7	x	x	-	-
KU Leuven	BE	yes	Modelica 3.2.2 & IDEAS 2.1.0	x	-	-	-
TalTech	EE	yes	IDA ICE 4.8 SP1	x	x	x	x
bbri	BE	yes	TRNSYS 17	x	x	-	-
SAXION	NL	yes	IDA ICE	x	-	-	-
Fraunhofer IBP coop. with Transsolar (developer)	DE DE	yes no	TRNSYS 18 18.01.0000 & TRNFlow	x	x	x	x
Fraunhofer IBP (developer)	DE	yes	WUFI Plus™ 3.2.0.1	x	x	x	x
TH Rosenheim	DE	yes	IDA ICE	x	-	-	-
IES (developer)	UK	no	IES 2018.2.0.0	x	x	x	x
University of Vigo	ES	yes	TRNSYS 17	x	x	x	x
UCL Louvain (developer)	BE	yes	individual Python code	x	x	-	-

7.1. Results' overview

Two approaches are typically used when comparing calculated results to measurements. First there is a visual inspection of the data, comparing simulation trend lines to the measurements. This visual inspection helps to identify outliers and general problems such as the misinterpretation of specifications and requirements. The visual behaviour often gives an indication of the cause of the observed deviation. The second approach is the calculation of numeric metrics that allow an objective comparison between simulation and measurement and also between different simulation results. For some metrics documented standard limits exist, allowing for a classification such as pass or fail.

During the analysis several different metrics were considered and calculated. In general two different types of metrics need to be distinguished. Firstly, there are metrics describing the bias between measurement and simulation. The metrics calculated in this analysis are the mean deviation (MD) and the Normalized Mean Bias Error (NMBE). These metrics indicate whether the average prediction is above or below the measurement. There is no indication of the agreement in the shape of the time series data. Secondly, the Coefficient of Determination (R^2) and the Spearman's Rank Correlation (SRC) quantify the agreement of the shapes of the simulated and measured trend lines but are not influenced by the bias. The Root Mean Square Error (RMSE) and its normalized coefficient CV(RMSE) respond to both bias and shape but don't differentiate between them. In order to analyse both bias and shape separately, two metrics were selected. In order to keep this analysis comparable to the work done and described in Annex 58, Mean Deviation (MD) and the Spearman's Rank Correlation (SRC) were selected as the preferred metrics for presenting results.

The results presented have been anonymised so that it is not possible to identify any particular result set with the modelling team or program. The reasons for this are: firstly, that some of the programs are commercial and anonymity was promised to encourage participation; secondly, that some of the discrepancies, even in the Open phase, are likely to be as a result of modeller error and thus do not necessarily offer a definitive assessment of a program; and thirdly, that if results were published, it is more likely that teams would undertake tuning of the Open phase submissions.

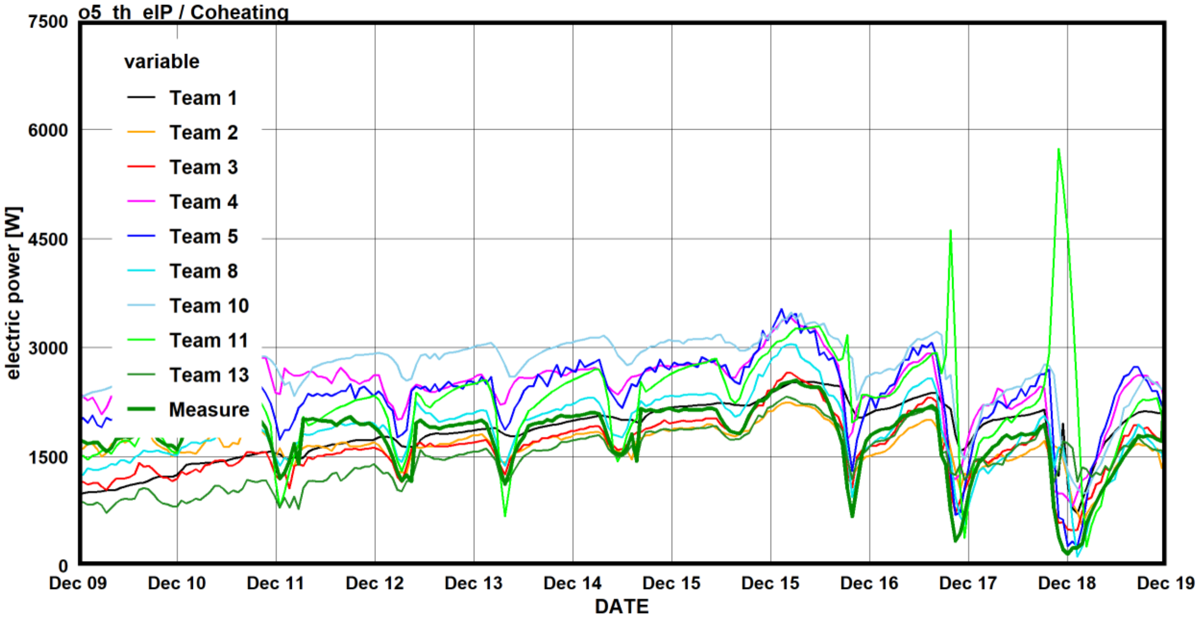
7.2. 2-steps validation approach

As described in section 1.4 a two steps approach was chosen for the validation procedure to separate user from program errors. In the first Blind phase the participating modelling teams were provided with the detailed specifications (sections 3 and 4 of this report) and measured climate and other boundary conditions. Following modelling, the teams submitted simulated predictions of the validation goals (time-varying power consumption or indoor temperatures, depending on the experimental period) and a short modelling report to document their approaches and assumptions. After all teams have completed the Blind phase the second Open phase starts with the release of all the measurement data. The modelling teams compare this data to their simulations to identify any modelling errors. Only identified modelling corrections are allowed while generic optimizations and calibrations are prohibited. To ensure this all changes made have to be documented in an Open phase modelling report or extension of the first report. As a result of this procedure an improvement of the results' quality can be expected from the Blind to the Open phase. Figure 40 shows the electrical heating power for the entire O5-house for both phases during the Co-heating period. Here, as in all other analysis, only teams are shown that participated in both phases. As expected a significant improvement can be seen. However, the fact that not all results have improved agreement and that some results even show a decreased agreement need to be considered. The abbreviations used to display and discuss the results are compiled in Table 19.

Table 19. List of results' abbreviations

N2 / O5	House N2 / O5
th	entire twin house
gf / att	ground floor / attic space
elP / AT	electric power / air temperature
RH	relative (air) humidity
heat	heating system

Table 20 shows an overview of the mean deviation between measurements and predictions of both phases' Co-heating period results. The first two rows ("..._AT") show that, especially in the O5-house, some teams have temperature deviation even though during the Co-heating period the measured temperatures were provided for the Blind phase (because the heating power is the validation goal in this period). The following rows show the mean deviation of the electrical heating power of the entire houses, the ground floor, the attic and individual rooms. Several cases can be seen where individual rooms or floors have sometimes negative and sometimes positive sign leading to a quite good agreement of the entire house. There are two effects that shift heat within the houses' envelopes. On the one hand only a minimal deviation in a PLC's temperature sensor controlling the heating leads to an increased heat input into one room and a corresponding reduction in heat input in neighbouring rooms. On the other hand the interzonal air flows through the open doors, transporting significant amounts of heat between the rooms, are difficult to model exactly. For this two reasons the correct prediction of the roomwise heat demand is difficult for state of the art building energy simulation programs when doors are open. Considering this the further analysis of this validation will focus on the entire building and ground floor /attic metrics for the Co-heating period. Table 21 shows the related shape fit quality, represented by the Spearman's Rank Correlation. Although visually the dynamics look reasonably good, small differences in lag were found to have a large impact on the SRC, resulting in the apparent poor fit.



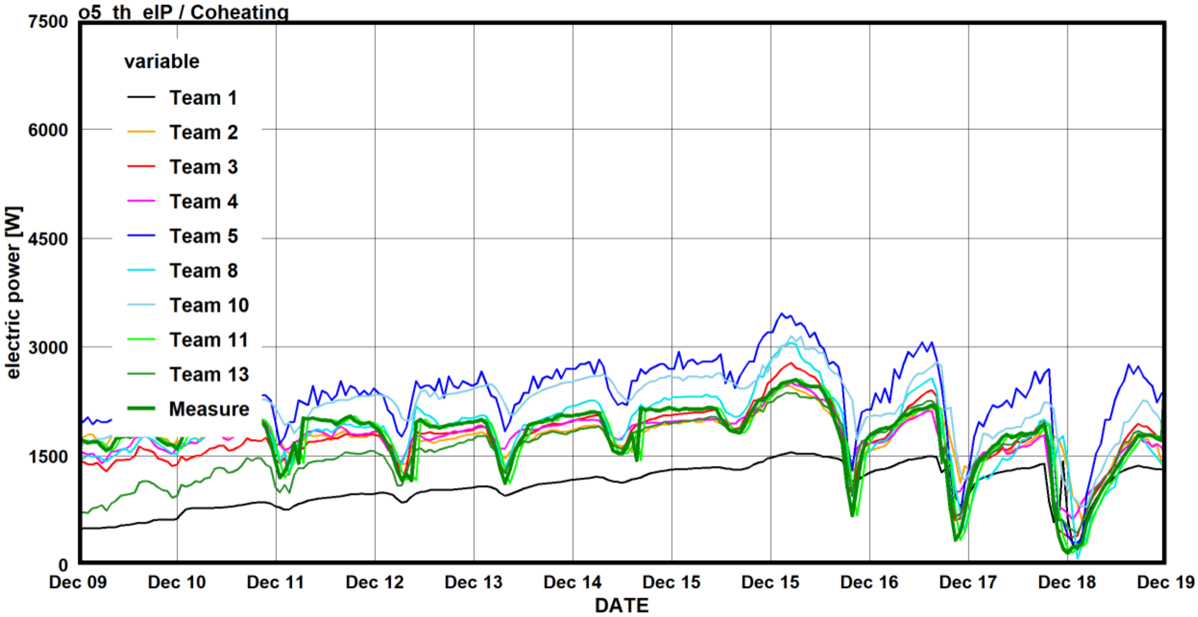


Figure 40. Electrical power of the entire O5-house during the Co-heating period. Top: Blind phase / Bottom: Open phase.

Table 20. Mean deviation between measurement and simulation during Co-heating period. Top: Blind phase / Bottom: Open phase. The highest value are coded orange, the lowest blue and "0" green; to consider the values of the different groups to colour-coding is done for the air temperatures and electrical heating powers separately.

	team								
value	**team_01**	**team_02**	**team_03**	**team_04**	**team_05**	**team_08**	**team_10**	**team_11**	**team_13**
n2_th_AT									
o5_th_AT									
n2_th_elP									
o5_th_elP									
n2_gf_elP									
o5_gf_elP									
n2_att_elP									
o5_att_elP									
n2_aroom_bath_heat_elP									
o5_aroom_bath_heat_elP									
n2_aroom_bed_heat_elP									
o5_aroom_bed_heat_elP									
n2_aroom_child1_heat_elP									
o5_aroom_child1_heat_elP									
n2_aroom_child2_heat_elP									
o5_aroom_child2_heat_elP									
n2_aroom_dining_heat_elP									
o5_aroom_dining_heat_elP									
n2_aroom_kitchen_heat_elP									
o5_aroom_kitchen_heat_elP									
n2_aroom_living_heat_elP									
o5_aroom_living_heat_elP									

	team								
value	**team_01**	**team_02**	**team_03**	**team_04**	**team_05**	**team_08**	**team_10**	**team_11**	**team_13**
n2_th_AT	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	-0.1	0.0
o5_th_AT	-5.7	0.0	0.0	0.0	0.0	0.0	0.0	-1.5	0.0
n2_th_elP	1950.1	-116.7	-19.5	34.1	423.3	58.8	307.9	-819.5	29.9
o5_th_elP	-700.6	-13.6	-54.4	-23.5	559.6	59.4	419.1	-5.6	-210.6
n2_gf_elP	1484.4	-118.2	-58.8	-31.6	174.1	-53.1	47.1	-446.0	52.7
o5_gf_elP	-259.4	-14.2	-66.4	-52.7	307.7	-20.3	161.0	-3.3	-184.6
n2_att_elP	465.7	1.5	39.2	65.6	249.2	111.9	260.7	-373.6	-22.8
o5_att_elP	-441.2	0.7	12.0	29.2	251.9	79.6	258.0	-2.3	-26.1
n2_aroom_bath_heat_elP	165.6	-13.5	8.7	-1.2	-86.0	-6.5	19.3	-14.0	5.0
o5_aroom_bath_heat_elP	-75.3	-6.4	-5.0	-5.0	23.1	-2.9	24.3	0.0	-46.1
n2_aroom_bed_heat_elP	235.0	-35.1	-3.5	-1.5	58.6	0.1	17.6	-27.6	12.2
o5_aroom_bed_heat_elP	-167.2	-43.3	-27.5	5.1	37.2	-18.1	14.1	-0.5	-73.2
n2_aroom_child1_heat_elP	148.1	-36.9	-17.8	-32.5	152.6	2.7	76.3	35.4	-59.0
o5_aroom_child1_heat_elP	-248.1	-25.9	-30.1	-1.0	131.8	-19.5	62.4	-0.4	-77.2
n2_aroom_child2_heat_elP	253.4	-3.6	1.6	39.8	124.2	69.3	119.2	-381.3	-2.6
o5_aroom_child2_heat_elP	-185.7	-23.9	-28.3	37.7	104.9	33.5	110.5	-1.3	-15.2
n2_aroom_dining_heat_elP	191.4	-47.3	-27.5	-16.7	-85.1	-16.6	-25.6	-73.3	-13.4
o5_aroom_dining_heat_elP	-103.3	2.4	25.9	6.9	80.4	30.5	43.7	-0.1	-38.2
n2_aroom_kitchen_heat_elP	144.9	-61.9	-55.4	-47.7	-34.5	-64.5	-50.6	-125.9	9.2
o5_aroom_kitchen_heat_elP	-224.2	-83.0	-96.8	-84.1	-24.2	-104.5	-67.8	-1.4	-15.6
n2_aroom_living_heat_elP	475.5	25.7	30.8	47.7	193.6	79.4	61.0	-122.4	45.3
o5_aroom_living_heat_elP	411.8	95.0	64.0	51.6	203.8	117.1	145.4	-0.8	14.5

Table 21. Spearman's rank correlation between measurement and simulation during Co-heating period: Top: Blind phase / Bottom: Open phase.

value	team								
	team_01	team_02	team_03	team_04	team_05	team_08	team_10	team_11	team_13
n2_zh_AT	65%	97%	86%	96%	35%	86%	97%	92%	97%
o5_zh_AT	2%	86%	29%	87%	7%	72%	86%	86%	86%
n2_zh_elP	72%	84%	77%	86%	87%	78%	78%	63%	68%
o5_zh_elP	50%	84%	76%	84%	84%	86%	78%	63%	58%
n2_gf_elP	80%	65%	83%	88%	93%	70%	83%	59%	77%
o5_gf_elP	66%	63%	84%	84%	90%	83%	84%	47%	58%
n2_att_elP	46%	70%	65%	73%	60%	60%	50%	60%	52%
o5_att_elP	15%	61%	52%	72%	52%	52%	41%	55%	56%
n2_aroom_bath_heat_elP	73%	60%	73%	61%	60%	70%	72%	71%	44%
o5_aroom_bath_heat_elP	100%	60%	52%	55%	55%	81%	64%	71%	38%
n2_aroom_bed_heat_elP	77%	84%	79%	67%	77%	80%	63%	89%	86%
o5_aroom_bed_heat_elP	100%	86%	80%	68%	78%	77%	66%	89%	79%
n2_aroom_child1_heat_elP	36%	69%	77%	62%	62%	56%	46%	45%	27%
o5_aroom_child1_heat_elP	7%	76%	73%	82%	50%	37%	23%	39%	12%
n2_aroom_child2_heat_elP	84%	83%	81%	68%	82%	83%	68%	79%	65%
o5_aroom_child2_heat_elP	56%	75%	69%	56%	74%	82%	63%	66%	49%
n2_aroom_dining_heat_elP	74%	64%	68%	67%	67%	72%	69%	68%	62%
o5_aroom_dining_heat_elP	100%	87%	84%	85%	77%	95%	86%	87%	63%
n2_aroom_kitchen_heat_elP	100%	0%	86%	3%	9%	75%	59%	69%	85%
o5_aroom_kitchen_heat_elP	100%	33%	47%	33%	11%	55%	63%	65%	45%
n2_aroom_living_heat_elP	58%	68%	75%	78%	81%	55%	76%	29%	45%
o5_aroom_living_heat_elP	58%	59%	91%	65%	78%	79%	86%	33%	47%

value	team								
	team_01	team_02	team_03	team_04	team_05	team_08	team_10	team_11	team_13
n2_zh_AT	49%	97%	80%	96%	60%	83%	97%	68%	97%
o5_zh_AT	16%	86%	35%	87%	9%	74%	86%	37%	86%
n2_zh_elP	75%	84%	86%	83%	87%	78%	76%	84%	73%
o5_zh_elP	48%	82%	86%	87%	84%	87%	76%	90%	73%
n2_gf_elP	83%	66%	91%	89%	91%	67%	83%	85%	86%
o5_gf_elP	60%	61%	92%	87%	89%	81%	84%	92%	85%
n2_att_elP	46%	70%	70%	61%	61%	78%	45%	43%	42%
o5_att_elP	5%	66%	57%	78%	50%	73%	35%	88%	35%
n2_aroom_bath_heat_elP	74%	64%	81%	74%	18%	77%	76%	61%	41%
o5_aroom_bath_heat_elP	100%	62%	69%	67%	58%	79%	67%	89%	27%
n2_aroom_bed_heat_elP	79%	85%	90%	77%	87%	79%	67%	72%	82%
o5_aroom_bed_heat_elP	100%	85%	91%	63%	77%	78%	69%	91%	76%
n2_aroom_child1_heat_elP	38%	73%	78%	67%	63%	77%	38%	34%	36%
o5_aroom_child1_heat_elP	19%	81%	70%	81%	47%	84%	15%	90%	11%
n2_aroom_child2_heat_elP	84%	84%	85%	81%	84%	83%	71%	72%	82%
o5_aroom_child2_heat_elP	47%	76%	76%	63%	74%	82%	65%	87%	70%
n2_aroom_dining_heat_elP	74%	65%	74%	67%	76%	65%	69%	71%	60%
o5_aroom_dining_heat_elP	100%	88%	90%	89%	79%	94%	86%	94%	79%
n2_aroom_kitchen_heat_elP	79%	1%	89%	15%	19%	69%	63%	53%	51%
o5_aroom_kitchen_heat_elP	100%	33%	58%	27%	15%	53%	61%	89%	21%
n2_aroom_living_heat_elP	72%	66%	81%	83%	78%	62%	75%	82%	72%
o5_aroom_living_heat_elP	52%	58%	93%	90%	82%	78%	85%	94%	86%

100 % - 80 %	80 % - 70 %	70 % - 60 %	60 % - 35 %	< 35 %

7.3. Trend treatment

In the User-1 and User-2 periods, teams were asked to use the measured heating power (or measured flow rates and supply temperatures in the case of underfloor heating in the O5 house) as a modelling input and predict internal room temperatures. As can be seen in Figure 41 even in the Open phase some teams, e.g. team 10, are accumulating a temperature deviation. This is an aspect of the chosen experimental design, providing the heating inputs and not requiring any control. This means that even a relatively small deviation in a model's heat balance, causing a deviation in the predicted temperature, accumulates to a large deviation over time. During the visual inspection of the simulation results and the evaluation of bias indicators this accumulated temperature deviation can lead to the impression that the evaluated models are a poor representation of measured performance. To compensate for this accumulation effect, a method was developed to eliminate the accumulation trend by applying a square root based trend function according to equation (7.3) and applying this separately to the User-1 and User-2 periods. The resulting compensated trend lines can be seen in Figure 42. Using this compensation a visual inspection of the remaining deviation in dynamic response becomes much easier. However, the decision was made not to apply this compensation in the analysis because it was found that this bias treatment also has an undesired influence on Spearman's rank correlation shape metric.

$$\Delta\theta(t) = a * \sqrt{t} + b \tag{7.3}$$

$\Delta\theta$	: Time dependent temperature trend	[K]
a, b	: Function's Coefficient to be identified	[$h^{-0,5}$, -]
t	Time since the start of the experimental period	[h]

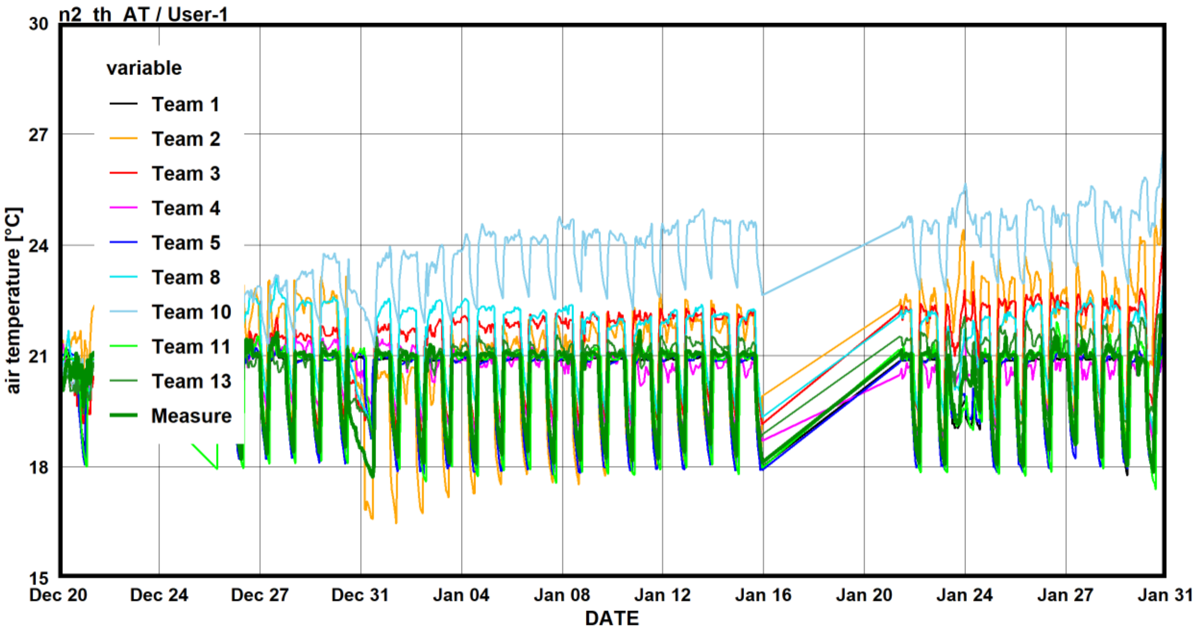


Figure 41. Uncompensated trend line of the N2 house volume-weighted air temperatures during User-1 period in the Open phase.

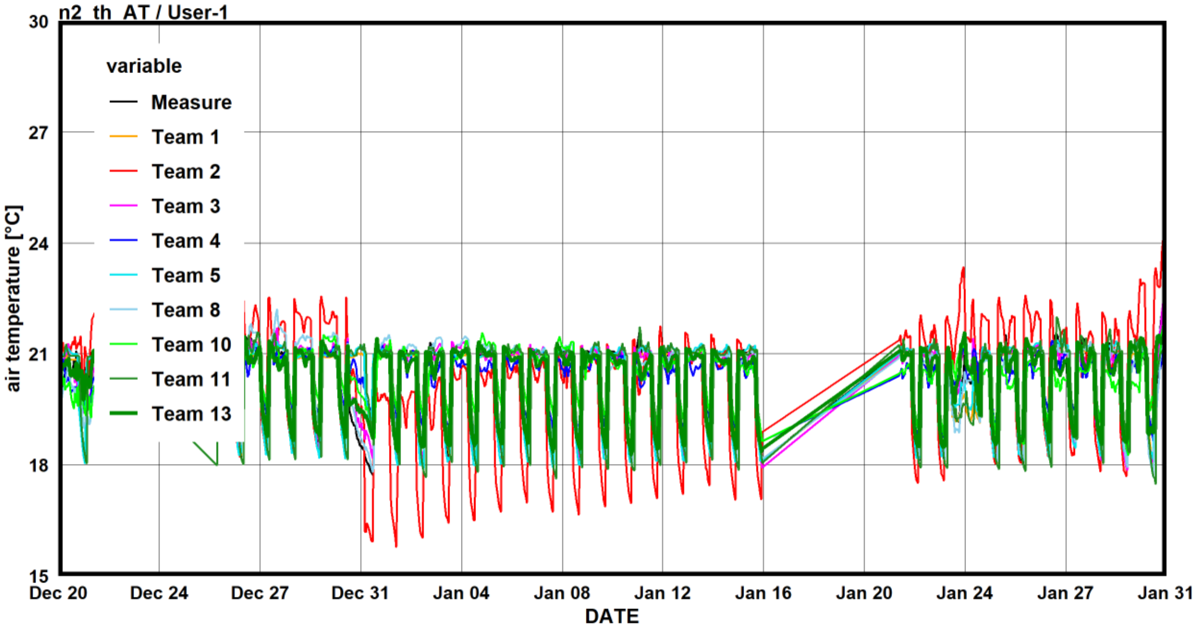


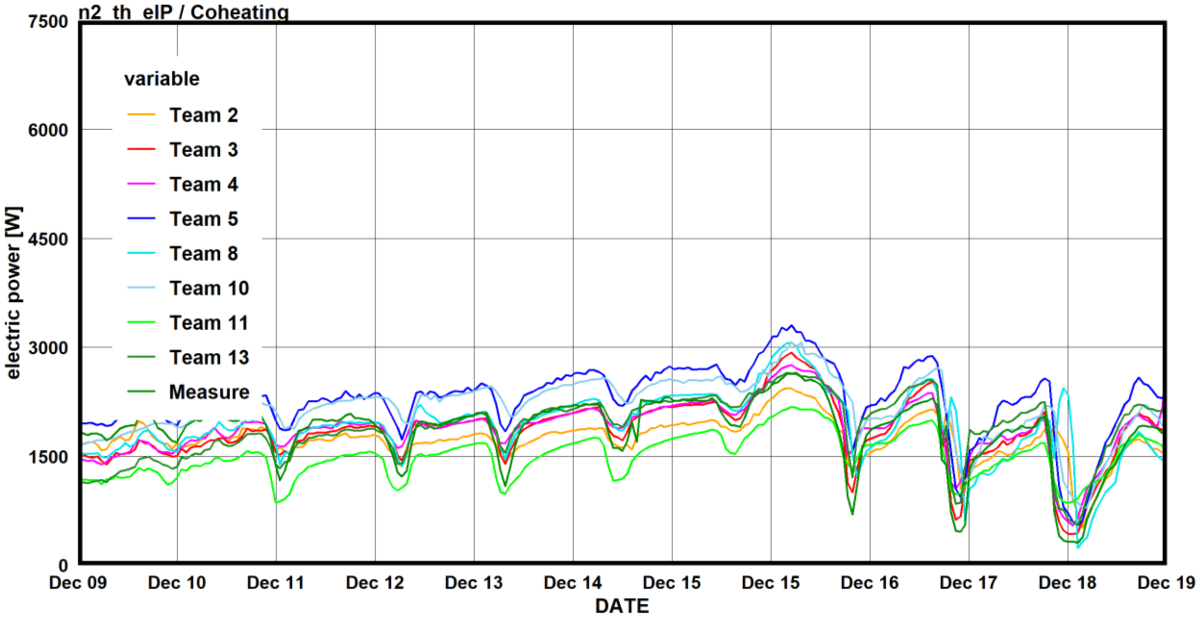
Figure 42. Compensated trend line of the N2 house volume-weighted air temperatures during User-1 period in the Open phase.

7.4. Co-heating period (Main Experiment)

During the Co-heating period both Twin Houses are electrically heated to a constant temperature. No synthetic occupants are present. A detailed description of this period can be found in section 4.2.

As can be seen in Figure 43 most teams have reached a good agreement with the measured consumption while some still show substantial deviations. The related mean air temperatures, shown in Figure 44, reveal that even in the Open phase the teams 1 and 11 still suffer major modelling errors in the O5 house. This becomes apparent when looking at the O5 air temperatures on the bottom of Figure 44. Since the analysis of modelling errors is not within the scope of this research these results will be excluded.

When assessing the deviations between simulation results and measurement the uncertainty of the measurement and the experiment must alyways be considered. In case of the Co-heating period the conventional co-heating analysis from section 3.2.3 provides some inputs to these considerations. Here for the Twin Houses HLCs of 103 and 107 W/K, using hourly mean values (107 / 112 W/K for daily means) were calculated from the measurment data. Theoretical calculations using the specified materials' properties give a HLC of 109 W/K. The range of all HLCs available indicates an uncertainty of 9 W/K (~10 %).



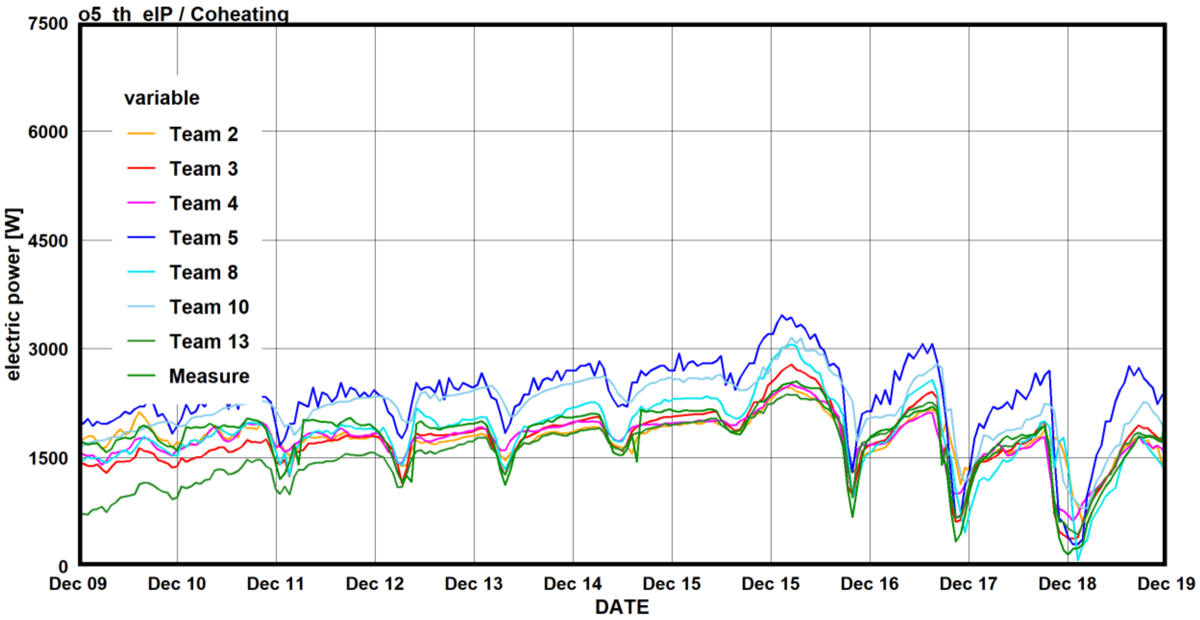


Figure 43. Electrical consumption and demand for the entire N2 house (top) and O5 house (bottom) during the Co-heating period.

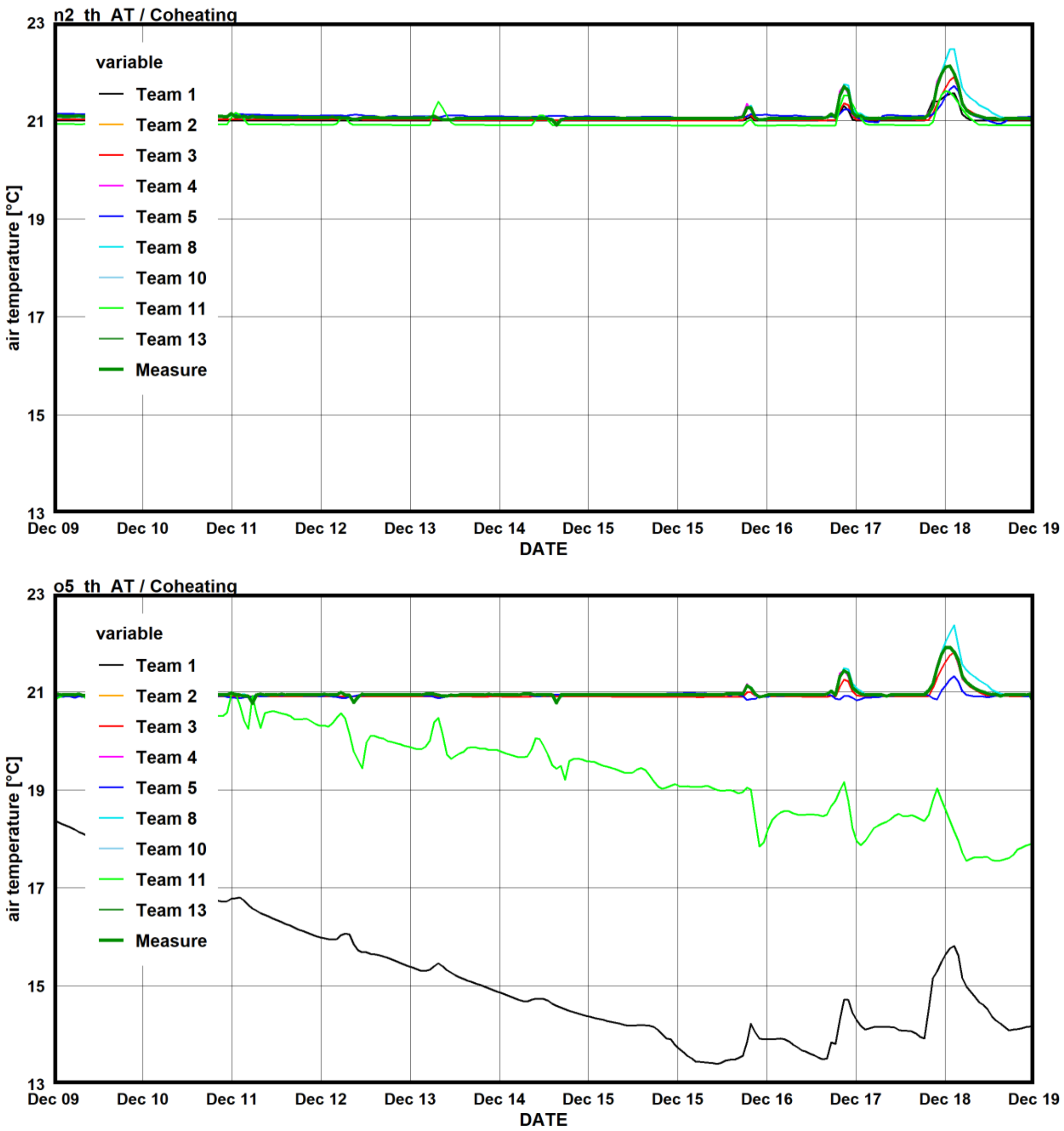


Figure 44. Average air temperature during the Co-heating period for the N2 house on the top and for O5 on the bottom.

Table 22 shows the resulting metrics for the Co-heating period after the remodelling during the Open phase. Here the same effects as just discussed can be seen. It also becomes apparent that the results for the entire building are better than for single rooms (as discussed in Section 7.2). As for most buildings the Twin Houses' envelopes are designed to minimize heat flows through them. For internal partitions this is true only to a certain extent and certainly it's not the case for open internal doors, allowing for air flow between the zones. So high internal heat flow between single rooms are caused by minimal temperature differences. This shifting of heating loads between individual rooms poses a substantial difficulty when modelling a room's heating load and can cause high deviation in the comparison with measured room-wise heating demand. As explained above team 11 will be excluded for O5 and team 1 for both houses. In the Co-heating period the set temperatures and the measured room air temperatures were given and the modelling teams were free to choose what to use as the model input. The chosen input is documented in Table 22.

Table 22. Mean deviation (top) and Spearman's rank correlation (bottom) between measurement and simulation during Co-heating (Open phase). Blank fields occur when no values are provided because results are excluded. "T_{set}" indicates that the set temperatures were chosen as model input, "T_{meas}" indicates measured temperatures. For the mean deviation the highest value are coded orange, the lowest blue and "0" green; to consider the values of the different groups to colour-coding in done for the air temperatures and electrical heating powers separately.

value	mean deviation								
	team_01 (-)	team_02 (T_{meas})	team_03 (T_{meas}[1])	team_04 (T_{set})	team_05 (T_{set})	team_08 (T_{meas})	team_10 (T_{meas})	team_11 (T_{meas})	team_13 (T_{set})
n2_th_AT		0,0	-0,1	0,0	0,0	0,0	0,0	-0,1	0,0
o5_th_AT		0,0	0,0	0,0	0,0	0,0	0,0		0,0
n2_th_elP		-117	-20	34	423	59	308	-820	30
o5_th_elP		-14	-54	-24	560	59	419		-211
n2_gf_elP		-118	-59	-32	174	-53	47	-446	53
o5_gf_elP		-14	-66	-53	308	-20	161		-185
n2_att_elP		1	39	66	249	112	261	-374	-23
o5_att_elP		1	12	29	252	80	258		-26

value	Spearman's rank correlation								
	team_01	team_02	team_03	team_04	team_05	team_08	team_10	team_11	team_13
n2_th_AT		97%	80%	96%	60%	83%	97%	68%	97%
o5_th_AT		86%	35%	87%	9%	74%	86%		86%
n2_th_elP		84%	86%	83%	87%	78%	76%	84%	73%
o5_th_elP		82%	86%	87%	84%	87%	76%		73%
n2_gf_elP		66%	91%	89%	91%	67%	83%	85%	86%
o5_gf_elP		61%	92%	87%	89%	81%	84%		85%
n2_att_elP		70%	70%	61%	61%	78%	45%	43%	42%
o5_att_elP		66%	57%	78%	50%	73%	35%		35%

100 % - 80 %	80 % - 70 %	70 % - 60 %	60 % - 35 %	< 35 %

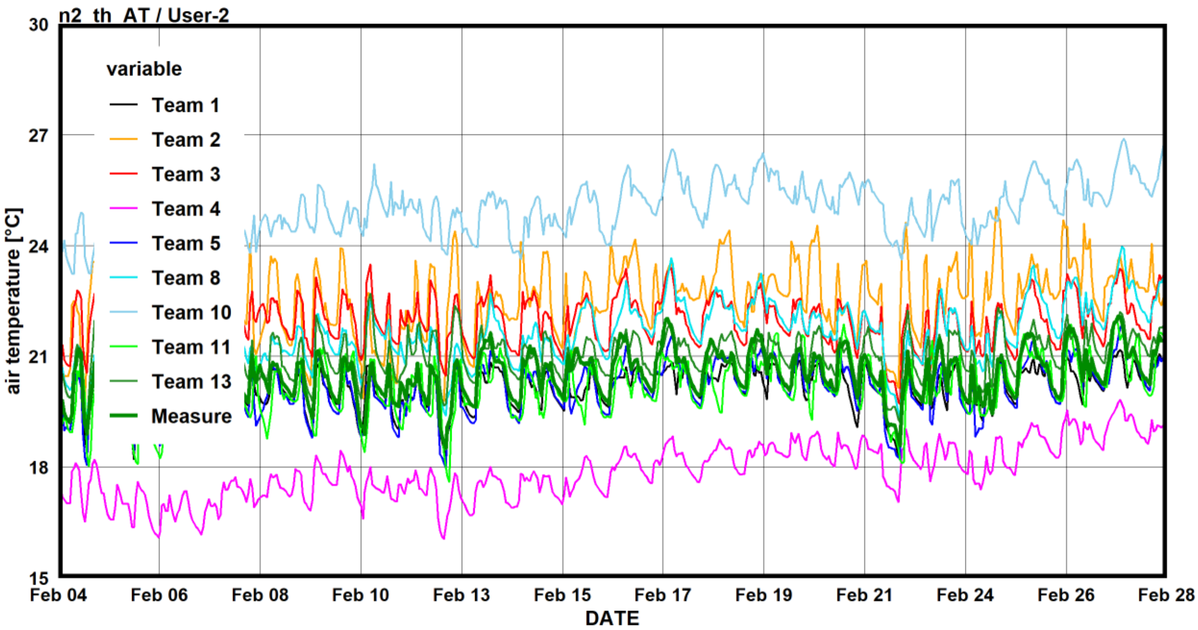
7.5. User-1 and User-2 periods

In the User-1 and User-2 periods both buildings are occupied by synthetic users; the User-2 period has the more complex usage profile. The O2 house is heated with an underfloor heating system (UFH), while the N2 house is heated with electrical convectors, as during the Co-heating period. Mixing fans are not in operation. In these periods the power inputs of the internal heat gains and the heating power are given while the resulting air temperatures are the validation goals.

In Figure 45 the trend lines of both houses' volume weighted mean air temperatures for the User-2 period can be compared to the measurements. Similar to the Co-heating period it can be seen that even in the Open phase, after the remodelling, some teams still show substantial deviations while some reach good agreement with the measurements. Table 23 gives the metrics for the User-1 and User-2 periods. Here it can be observed that the UFH-equipped O5 house is modelled a little more accurately than N2 with electrical heating. On the one hand this seems surprising because the mathematical models to represent an UFH system are much more complex than the modelling of a nearly ideal electrical heater. On the other hand the electrical heaters create a plume of hot air, rising to the ceiling and creating stratification in the room. The greater the electrical heating power, the more distinct is this plume. The children's rooms have the highest stratification because of their high heating load and the room height. Figure 46 shows a comparison of the stratification in both houses during the User-1 period. While the Child-1 room with UFH in house O5 has a stratification of about 1 K, the electrically heated house N2 reaches a difference of 6 K between the top and the bottom temperature probe. Since most simulation models assume fully mixed air inside a zone it becomes apparent that some important heat flows have very different temperatures as the driving force. For example, the thermal transmission though ceiling and roof surfaces as well as extract air losses (extracts are located at the top of the rooms) have a temperature well above the mean air temperature in the O5 house and heat losses through the lower parts of rooms

[1] Average of measured room-wise air temperatures as fixed input

are driven by lower temperature differences. So it is likely that the better modelling representation of the O5 house with UFH isn't cause by superior UFH model quality but by a better mixing of air in the rooms.



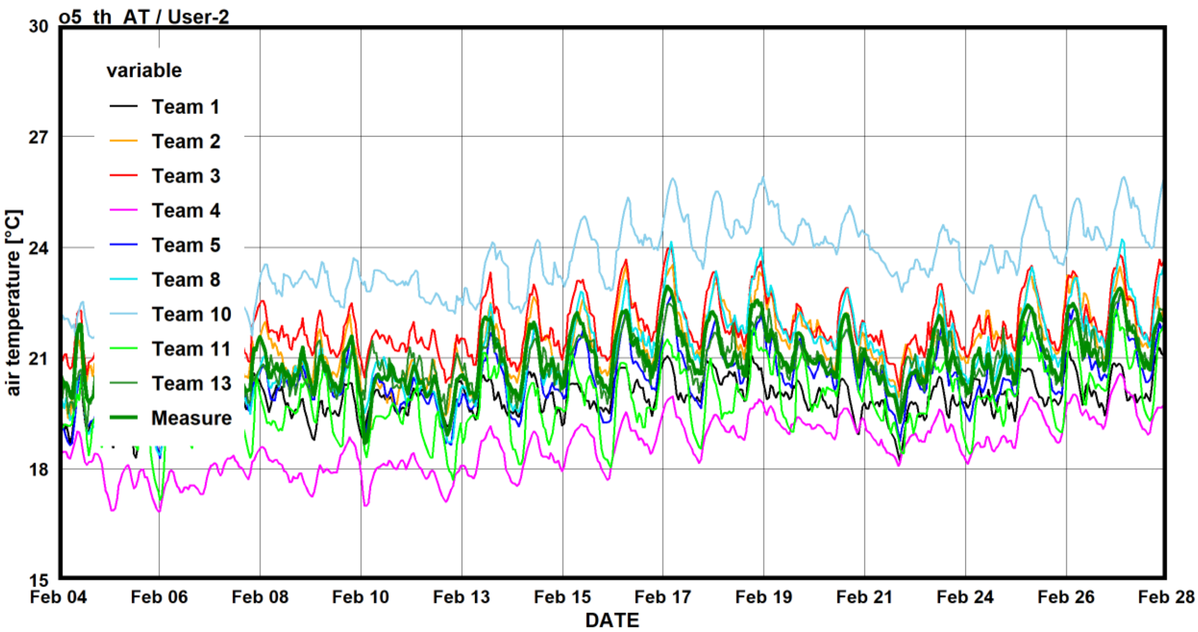


Figure 45. Average air temperatures during the User -2 period of the Open phase for the N2 house on the top and for O5 at the bottom.

Table 23. Mean deviation (top) and Spearman's rank correlation (bottom) between measurement and simulation during User-1 and User-2 periods (Open phase). "(T_{set})" indicates that a team used the set temperatures and not the provided supply temperature and flowrate.

value	Period	mean deviation								
		1 (T_{set})	2	3	4 (T_{set})	5 (T_{set})	8	10	11 (T_{set})	13
n2_zh_AT	User-1	-0.1	0.8	0.9	0.2	-0.1	1.1	3.2	-0.1	0.2
	User-2	-0.4	1.9	1.5	-2.6	-0.3	1.1	4.5	-0.3	0.5
o5_zh_AT	User-1	-0.8	-0.5	0.6	-0.5	0.1	-0.4	1.8	-0.3	-0.1
	User-2	-1.0	0.4	0.9	-2.3	-0.5	0.1	2.6	-1.1	-0.1
n2_gf_AT	User-1	-0.2	1.1	1.4	0.1	-0.2	2.0	2.5	-0.1	0.2
	User-2	-0.5	1.4	1.9	-2.2	-0.5	2.0	4.6	-0.2	0.6
o5_gf_AT	User-1	-0.9	-0.5	0.6	-0.7	-0.1	-0.2	1.9	0.0	-0.6
	User-2	-1.3	0.4	1.1	-1.5	-0.7	0.8	3.1	-0.7	0.1
n2_att_AT	User-1	0.1	0.4	0.0	0.2	-0.1	-0.1	4.1	0.0	0.3
	User-2	-0.2	2.7	0.9	-3.1	-0.1	-0.2	4.3	-0.4	0.4
o5_att_AT	User-1	-0.7	-0.6	0.6	-0.3	0.4	-0.7	1.6	-0.7	0.5
	User-2	-0.7	0.4	0.6	-3.5	-0.1	-0.8	1.9	-1.5	-0.3
n2_aroom_living_110_AT	User-1	0.0	0.7	1.1	-0.2	-0.3	1.7	0.4	-0.2	0.0
	User-2	-0.3	1.1	1.6	-2.5	-0.6	1.8	2.3	-0.2	0.4
o5_aroom_living_110_AT	User-1	0.0	-0.9	0.3	-1.7	-0.3	-0.5	0.5	-0.4	-0.6
	User-2	0.1	0.0	0.9	-2.0	-1.1	0.6	1.6	-0.8	0.0
n2_aroom_dining_110_AT	User-1	-0.4	1.9	2.5	0.0	-0.4	2.7	6.8	-0.5	1.0
	User-2	-0.9	1.7	2.6	-3.3	-0.8	2.3	9.2	-1.1	1.2
o5_aroom_dining_110_AT	User-1	-1.0	-0.5	0.3	-0.3	0.0	-0.5	3.5	-0.2	-0.8
	User-2	-1.5	0.0	0.9	-1.9	-0.8	0.5	5.6	-1.5	0.0
n2_aroom_kitchen_110_AT	User-1	0.1	1.4	1.7	1.1	0.2	2.6	3.6	0.9	0.1
	User-2	-0.3	2.5	2.2	-0.8	0.1	2.8	5.3	1.8	0.6
o5_aroom_kitchen_110_AT	User-1	-0.1	0.2	1.4	-0.4	0.5	0.5	3.8	1.0	-0.2
	User-2	-0.4	1.9	2.1	-0.1	0.1	1.8	4.4	1.3	0.4
n2_aroom_bath_110_AT	User-1	-0.2	1.0	1.4	0.3	-0.2	1.8	6.0	-0.2	0.1
	User-2	-1.1	1.3	2.0	-2.5	-0.5	1.8	8.6	-1.0	0.9
o5_aroom_bath_110_AT	User-1	-0.6	-0.1	1.0	0.6	0.1	0.0	4.9	0.0	-0.7
	User-2	-2.3	0.4	1.3	-1.2	-0.5	0.9	6.8	-1.3	0.4
n2_aroom_bed_110_AT	User-1	-0.1	1.2	1.4	0.2	-0.1	1.8	1.8	0.1	0.2
	User-2	-0.2	1.5	1.6	-1.4	-0.1	1.5	4.0	-0.2	0.2
o5_aroom_bed_110_AT	User-1	-1.2	0.1	1.1	0.9	0.1	0.2	1.9	0.3	-0.2
	User-2	-2.1	0.8	1.2	-0.5	-0.2	0.9	2.6	-0.5	-0.1
n2_aroom_child1_110_AT	User-1	0.3	0.9	0.4	1.1	0.1	0.2	1.3	0.2	0.9
	User-2	0.1	3.6	1.3	-2.9	0.0	-0.2	-0.4	-0.2	0.7
o5_aroom_child1_110_AT	User-1	0.4	-0.4	0.7	-0.3	0.4	-0.6	-1.5	-0.7	0.8
	User-2	0.9	1.1	1.1	-3.6	-0.2	-0.9	-2.6	-1.9	-0.4
n2_aroom_child2_110_AT	User-1	-0.1	0.0	-0.2	-0.9	-0.1	-0.5	7.7	-0.1	-0.2
	User-2	-0.4	1.9	0.6	-3.4	-0.2	-0.3	9.6	-0.5	0.2
o5_aroom_child2_110_AT	User-1	-0.7	-0.8	0.5	-0.2	0.3	-0.8	4.7	-0.7	0.2
	User-2	-1.2	-0.3	0.1	-3.7	-0.1	-0.9	6.3	-1.2	-0.4

Absolute deviation	< 1 K	1 - 2 K	2 - 4 K	4 - 8 K	> 8 K

value	Period	Spearman's rank correlation								
		1 *(T_{set})*	2	3	4 *(T_{set})*	5 *(T_{set})*	8	10	11 *(T_{set})*	13
n2_zh_AT	User-1	73%	57%	70%	73%	71%	80%	36%	55%	76%
	User-2	86%	54%	88%	61%	90%	78%	62%	65%	76%
o5_zh_AT	User-1	79%	86%	93%	78%	70%	96%	84%	70%	76%
	User-2	77%	84%	95%	77%	89%	84%	70%	79%	79%
n2_gf_AT	User-1	79%	51%	62%	68%	76%	63%	20%	60%	72%
	User-2	95%	68%	94%	71%	92%	84%	69%	73%	87%
o5_gf_AT	User-1	77%	77%	85%	45%	76%	86%	60%	68%	80%
	User-2	97%	91%	97%	83%	90%	76%	69%	84%	92%
n2_att_AT	User-1	60%	55%	71%	74%	59%	72%	46%	35%	71%
	User-2	73%	31%	53%	55%	88%	49%	36%	57%	68%
o5_att_AT	User-1	80%	90%	94%	90%	59%	95%	88%	59%	63%
	User-2	28%	41%	73%	63%	79%	75%	49%	71%	47%
n2_aroom_living_110_AT	User-1	88%	53%	72%	74%	79%	76%	48%	66%	80%
	User-2	96%	71%	96%	78%	92%	90%	69%	80%	90%
o5_aroom_living_110_AT	User-1	86%	81%	91%	55%	79%	91%	63%	70%	83%
	User-2	97%	92%	98%	88%	90%	82%	73%	85%	94%
n2_aroom_dining_110_AT	User-1	86%	50%	61%	57%	63%	59%	30%	51%	68%
	User-2	90%	52%	75%	53%	82%	72%	57%	58%	70%
o5_aroom_dining_110_AT	User-1	63%	67%	79%	34%	62%	73%	33%	62%	71%
	User-2	90%	94%	96%	82%	90%	77%	60%	75%	94%
n2_aroom_kitchen_110_AT	User-1	83%	63%	71%	73%	82%	70%	29%	44%	55%
	User-2	90%	76%	92%	71%	92%	88%	61%	55%	72%
o5_aroom_kitchen_110_AT	User-1	76%	69%	78%	62%	75%	81%	41%	68%	74%
	User-2	81%	75%	85%	72%	83%	74%	65%	76%	81%
n2_aroom_bath_110_AT	User-1	86%	48%	50%	64%	69%	49%	16%	54%	60%
	User-2	88%	77%	95%	57%	93%	78%	54%	63%	92%
o5_aroom_bath_110_AT	User-1	58%	70%	74%	35%	62%	79%	43%	58%	60%
	User-2	76%	91%	96%	65%	90%	75%	59%	76%	89%
n2_aroom_bed_110_AT	User-1	73%	48%	35%	55%	59%	29%	5%	26%	50%
	User-2	92%	67%	88%	66%	82%	90%	47%	41%	83%
o5_aroom_bed_110_AT	User-1	33%	54%	49%	10%	35%	44%	6%	5%	42%
	User-2	65%	70%	93%	70%	87%	76%	48%	29%	81%
n2_aroom_child1_110_AT	User-1	79%	50%	73%	57%	64%	75%	59%	59%	71%
	User-2	70%	26%	62%	64%	89%	63%	58%	46%	69%
o5_aroom_child1_110_AT	User-1	78%	91%	95%	90%	58%	96%	81%	60%	62%
	User-2	17%	32%	82%	70%	84%	82%	62%	67%	65%
n2_aroom_child2_110_AT	User-1	73%	61%	73%	69%	59%	76%	26%	54%	73%
	User-2	82%	42%	57%	50%	76%	53%	1%	55%	63%
o5_aroom_child2_110_AT	User-1	86%	87%	92%	89%	60%	93%	31%	56%	58%
	User-2	59%	50%	58%	47%	68%	65%	17%	60%	16%

100 % - 80 %	80 % - 70 %	70 % - 60 %	60 % - 35 %	< 35 %

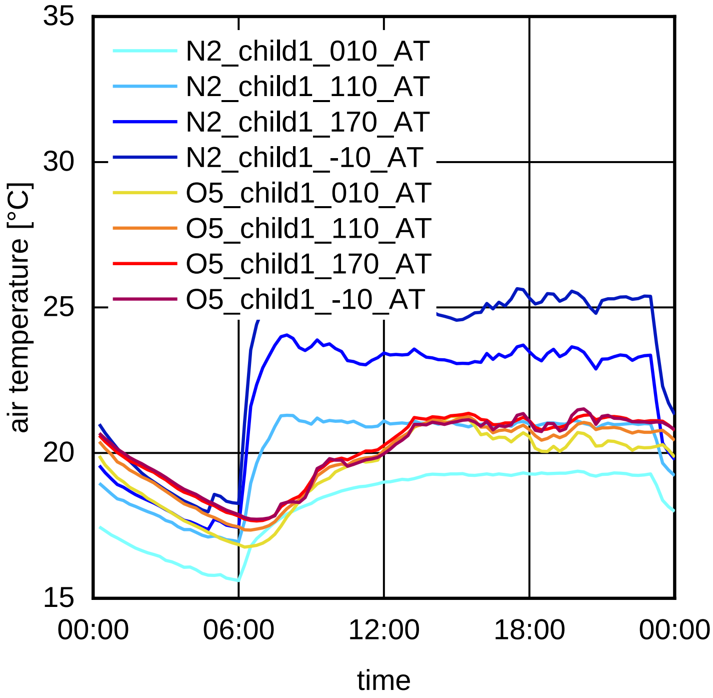


Figure 46. Comparison of the stratification between the UFH and the electrically heated Twin Houses in the Child-1 room on the 12th of January 2019.

7.6. Extended Experiment

In the Extended Experiment, instead of the underfloor heating in the O5 house internal moisture sources (section 3.17.3) are added to the living room as the differentiating element between both houses. It consists of three experimental periods. In the User-3 period, described in section 4.6, the Twin Houses are also occupied by synthetic users similar to the User-2 period of the Main Experiment. The User-3 period provides realistic boundaries but with internal moisture sources. In the PRBS period, described in section 4.7, the heat inputs consist of a strong binary heat signal instead of representative user gains and heating inputs. During the Free-Floating period synthetic users are included but no heating is considered, as explained in section 4.8. Table 24 provides the metrics for these three periods. Here the results for the entire building, the two separate floors and the living room (location of moisture injection) are displayed.

First it can be seen that the Extended Experiment's results for room air temperatures (Table 24, left), compared to the Main Experiment, are more accurate regarding the mean deviation, especially for teams 8 and 11 The shape fits, indicated by the Spearman's rank correlation, are substantially better for all teams. This is also true for the N2 House, where there were no experimental differences between the User-2 and User-3 periods. The modelling reports offer no conclusive reason for this improvement. The measured and simulated mean air temperatures for both houses are displayed in Figure 47. It can be seen that the O5 house is a little warmer than N2. The reason for this is temperature raise in the living room's supply air by the moisture injection system, as explained in section 3.17.3.

In general the predictions for the room air's relative humidity at 110 cm height (Table 24, right) are good, although teams 8 and 11 have some problems with the shape of the humidity time series. These are the same teams having the highest mean deviations regarding the air temperatures. Figure 48 shows the trend lines of the living rooms' relative humidity. Here the living rooms and not the entire buildings are chosen because all moisture inputs are injected here and so the most significant effects can be expected.

The goal of the side-by-side design in the Extended Experiment was to check if teams do better or worse when the IMS was added. The temperatures' mean deviations show a minor (unexpected) increase in O5 results' agreement, the SRC gives a little better results on the dry N2 house. Regarding the living room relative air humidity the results of the N2 House are better than for O5.

Table 24. Mean deviation (top) and Spearman's rank correlation (bottom) between measurement and simulation during the User-3, PRBS and Free-Floating periods (Open phase). Air temperatures are on the left, and relative humidity on the right.

value	Team 3	4	5	8	11	13
n2_zh_AT						
User-3	0.7	0.2	-0.1	1.9	0.5	0.5
PRBS	1.2	1.0	0.7	2.9	2.5	0.8
FreeF	0.9	2.4	0.4	2.7	2.7	1.0
o5_zh_AT						
User-3	0.5	-0.7	-0.2	1.5	0.1	0.0
PRBS	0.8	-0.1	0.1	2.8	2.1	0.5
FreeF	0.4	1.3	-0.4	2.5	2.0	0.6
n2_gf_AT						
User-3	0.9	0.8	0.0	2.5	1.1	0.5
PRBS	2.1	1.6	1.7	4.0	4.7	1.2
FreeF	1.6	2.7	0.9	3.3	4.3	1.1
o5_gf_AT						
User-3	0.6	-0.3	-0.1	2.0	0.4	0.0
PRBS	1.5	0.2	1.1	3.8	4.0	0.8
FreeF	0.9	1.4	0.1	3.0	3.3	0.6
n2_att_AT						
User-3	0.4	-0.6	-0.1	1.0	-0.3	0.5
PRBS	0.0	0.1	-0.8	1.3	-0.6	0.1
FreeF	0.0	1.9	-0.4	1.7	0.4	0.8
o5_att_AT						
User-3	0.2	-1.2	-0.2	0.8	-0.4	0.0
PRBS	-0.2	-0.5	-1.2	1.2	-0.6	0.1
FreeF	-0.4	1.2	-1.0	1.7	0.3	0.6
n2_aroom_living_110_AT						
User-3	0.7	0.4	0.0	2.5	1.3	0.6
PRBS	1.3	0.9	1.4	3.5	4.4	1.0
FreeF	1.4	2.6	0.9	3.3	4.6	1.3
o5_aroom_living_110_AT						
User-3	0.6	-0.9	-0.2	1.9	0.7	0.1
PRBS	0.8	-0.7	0.7	3.2	3.5	0.4
FreeF	0.8	1.2	0.1	2.8	3.5	0.7

value	Team 3	4	5	8	11	13
n2_zh_RH						
User-3	3.0		2.7	-0.4	2.0	3.6
PRBS	2.0		1.2	-1.9	-1.0	2.8
FreeF	4.9		3.8	-1.3	-1.2	4.4
o5_zh_RH						
User-3	3.4		3.6	0.2	3.1	4.0
PRBS	1.6		1.6	-2.6	-0.3	2.7
FreeF	3.1		3.9	-3.1	-1.0	3.3
n2_gf_RH						
User-3	2.3		2.5	-1.6	0.8	3.4
PRBS	0.3		-0.6	-3.4	-4.2	1.6
FreeF	3.1		2.6	-2.4	-4.4	3.8
o5_gf_RH						
User-3	2.7		6.5	-0.6	1.6	5.6
PRBS	-0.4		1.0	-4.5	-3.7	1.8
FreeF	-0.3		5.1	-5.1	-5.7	3.6
n2_att_RH						
User-3	3.9		3.0	1.3	3.7	3.8
PRBS	4.4		3.8	0.3	3.5	4.5
FreeF	7.4		5.4	0.2	3.3	5.3
o5_att_RH						
User-3	4.4		-0.5	1.4	5.3	1.8
PRBS	4.4		2.3	0.1	4.6	3.9
FreeF	8.0		2.1	-0.3	5.6	2.9
n2_aroom_living_110_RH						
User-3	3.5		3.1	-0.9	1.0	4.2
PRBS	2.2		0.4	-2.5	-3.4	3.2
FreeF	3.5		2.4	-2.7	-5.3	4.4
o5_aroom_living_110_RH						
User-3	4.0		8.5	0.6	1.4	5.7
PRBS	1.4		3.2	-3.1	-3.1	3.1
FreeF	0.8		7.0	-4.0	-6.3	4.2

Absolute deviation: < 1 K | 1 - 2 K | 2 - 4 K | 4 - 8 K | > 8 K (temperature); < 5 % | 5 - 10 % | 10 - 20 % | 20 - 30 % | > 30 % (humidity)

value	Team					
	3	4	5	8	11	13
n2_zh_AT						
User-3	0.91	0.92	0.97	0.93	0.64	0.90
PRBS	0.98	0.91	0.99	0.98	0.87	0.97
FreeF	0.93	0.84	0.98	0.96	0.88	0.96
o5_zh_AT						
User-3	0.94	0.93	0.97	0.92	0.75	0.93
PRBS	0.98	0.90	0.99	0.97	0.88	0.96
FreeF	0.94	0.79	0.97	0.92	0.85	0.94
n2_gf_AT						
User-3	0.94	0.88	0.96	0.88	0.63	0.92
PRBS	0.97	0.90	0.98	0.95	0.86	0.97
FreeF	0.82	0.86	0.91	0.91	0.82	0.95
o5_gf_AT						
User-3	0.98	0.93	0.97	0.90	0.73	0.95
PRBS	0.98	0.92	0.99	0.95	0.88	0.96
FreeF	0.83	0.82	0.89	0.88	0.77	0.92
n2_att_AT						
User-3	0.72	0.76	0.86	0.79	0.42	0.61
PRBS	0.98	0.92	0.98	0.96	0.92	0.89
FreeF	0.98	0.81	0.97	0.95	0.82	0.90
o5_att_AT						
User-3	0.75	0.77	0.85	0.82	0.44	0.61
PRBS	0.97	0.87	0.97	0.96	0.90	0.83
FreeF	0.97	0.77	0.96	0.91	0.80	0.88
n2_aroom_living_110_AT						
User-3	0.97	0.92	0.97	0.92	0.73	0.94
PRBS	0.97	0.91	0.97	0.94	0.86	0.98
FreeF	0.92	0.81	0.94	0.94	0.86	0.96
o5_aroom_living_110_AT						
User-3	0.98	0.94	0.98	0.90	0.79	0.95
PRBS	0.98	0.92	0.98	0.92	0.88	0.96
FreeF	0.91	0.76	0.91	0.89	0.81	0.92

value	Team					
	3	4	5	8	11	13
n2_zh_RH						
User-3	0.93		0.91	0.92	0.81	0.90
PRBS	0.97		0.95	0.95	0.84	0.96
FreeF	0.96		0.95	0.96	0.82	0.93
o5_zh_RH						
User-3	0.88		0.86	0.60	0.81	0.87
PRBS	0.95		0.95	0.64	0.84	0.95
FreeF	0.91		0.95	0.45	0.94	0.96
n2_gf_RH						
User-3	0.94		0.91	0.89	0.81	0.91
PRBS	0.98		0.96	0.96	0.79	0.96
FreeF	0.96		0.95	0.96	0.88	0.96
o5_gf_RH						
User-3	0.83		0.81	0.43	0.76	0.83
PRBS	0.91		0.90	0.50	0.77	0.86
FreeF	0.94		0.96	0.49	0.94	0.95
n2_att_RH						
User-3	0.91		0.89	0.89	0.81	0.88
PRBS	0.96		0.91	0.91	0.88	0.89
FreeF	0.91		0.80	0.77	0.67	0.82
o5_att_RH						
User-3	0.90		0.82	0.79	0.81	0.84
PRBS	0.94		0.79	0.78	0.86	0.85
FreeF	0.82		0.68	0.51	0.70	0.80
n2_aroom_living_110_RH						
User-3	0.94		0.93	0.88	0.83	0.92
PRBS	0.97		0.96	0.94	0.80	0.97
FreeF	0.95		0.96	0.95	0.87	0.95
o5_aroom_living_110_RH						
User-3	0.87		0.87	0.44	0.79	0.83
PRBS	0.90		0.89	0.41	0.78	0.87
FreeF	0.93		0.97	0.45	0.93	0.95

1.0 - 0.8	0.8 - 0.7	0.7 - 0.6	0.6 - 0.35	< 0.35

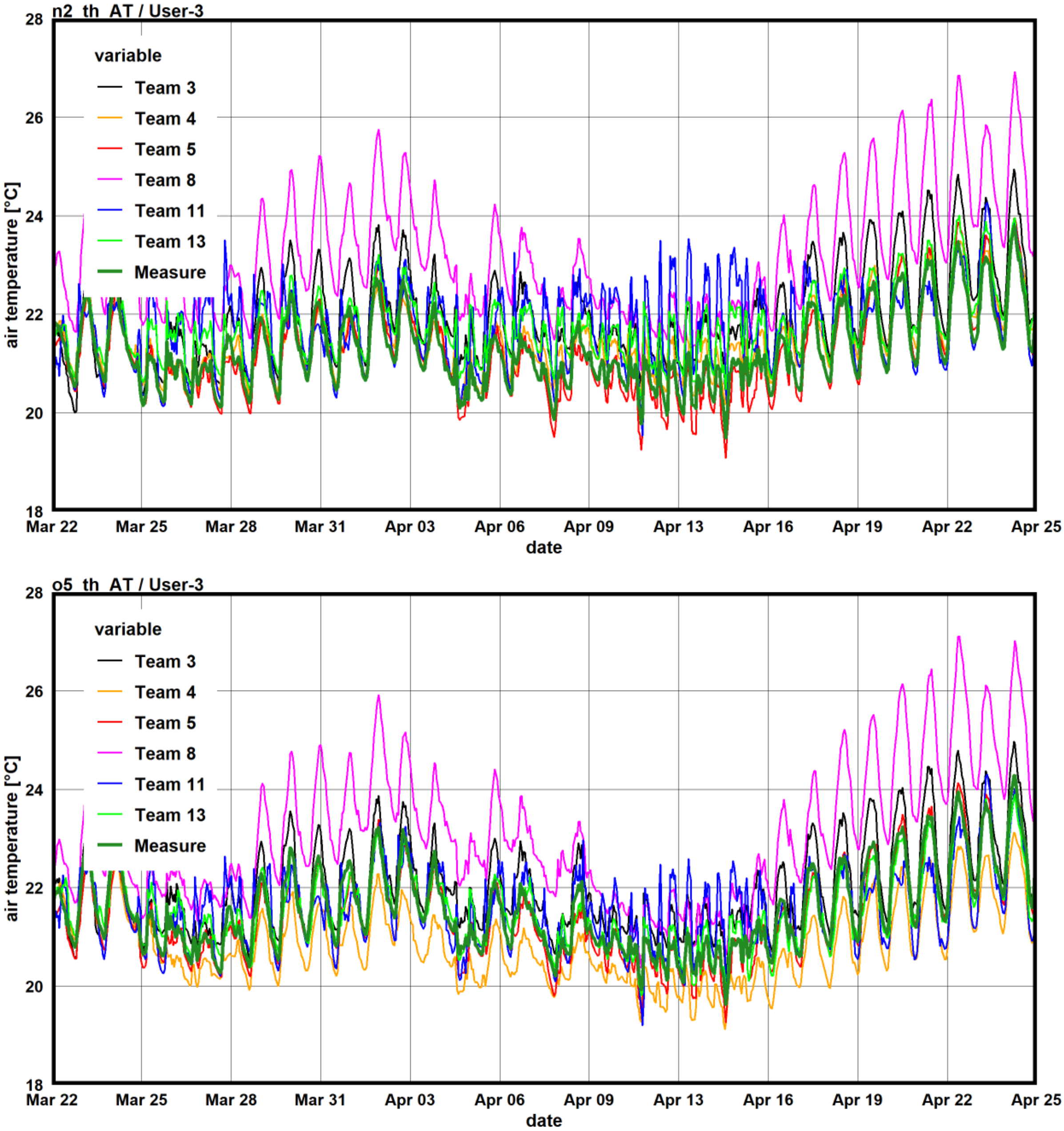


Figure 47. Average air temperatures during the User-3 period (Open phase) for the N2 house on the top and the O5 house at the bottom.

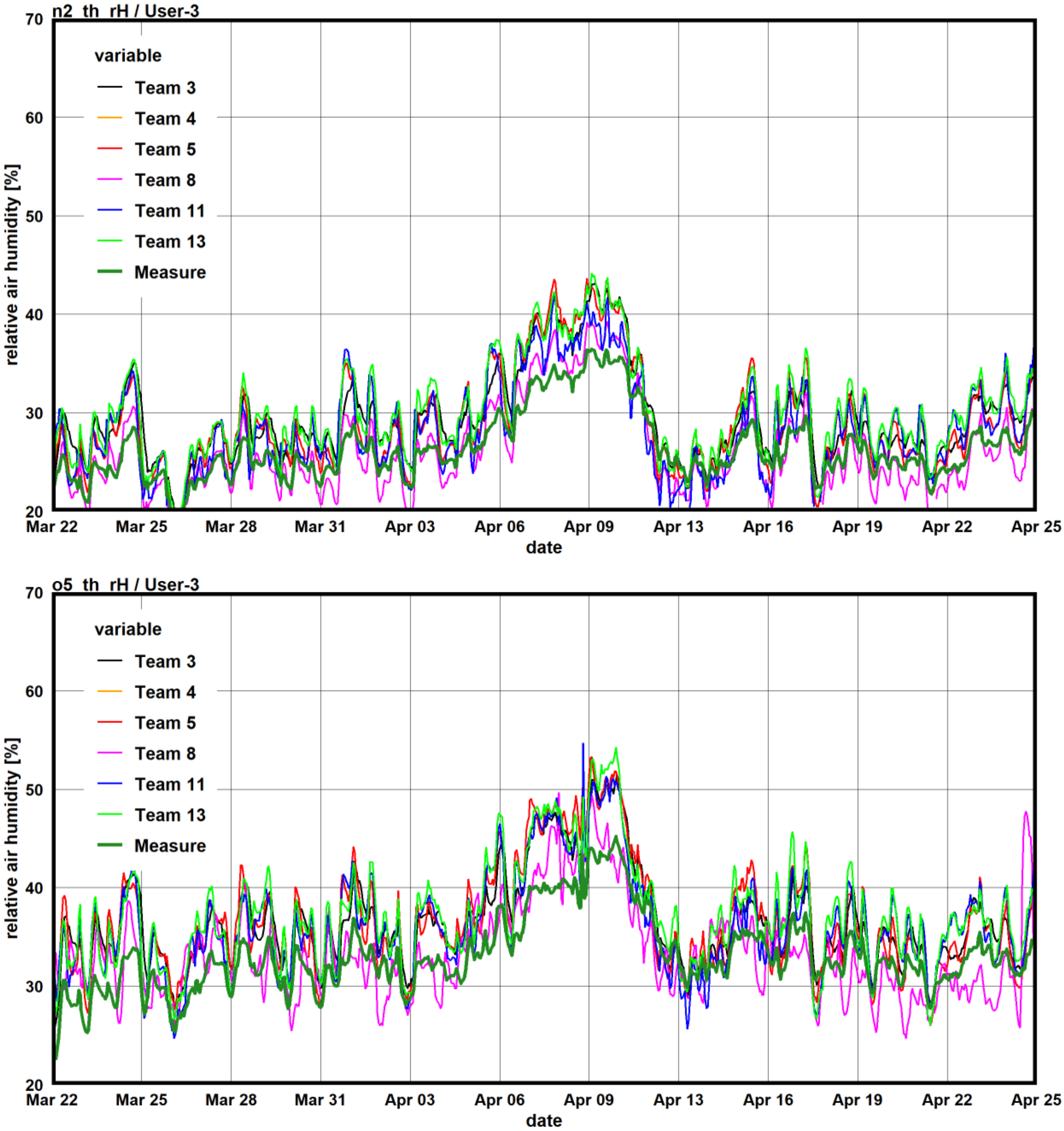


Figure 48. Living room relative humidities during the User-3 period (Open phase) for the N2 house on the top and the O5 house at the bottom.

To determine the reason for the different behaviours between the Main and Extended Experiments some parameters that are expected to have a significant influence on the results' quality were investigated in further detail. In Figure 49 the stratification occurring during the different experimental periods in both houses can be seen. Here it is apparent that the stratification in N2 during the User-1 and User-2 periods is higher than during the User-3 period in both houses. Stratification has an important influence on modelling predictions, as discussed in Section 7.5. Figure 50 shows lower solar gains during the User-3 period than during the User-2 period. The User-1 period also has lower solar gains but the synthetic users' behaviour is simpler than during the User-2 and User-3 periods. Significant differences regarding the wind speeds cannot be identified in Figure 51.

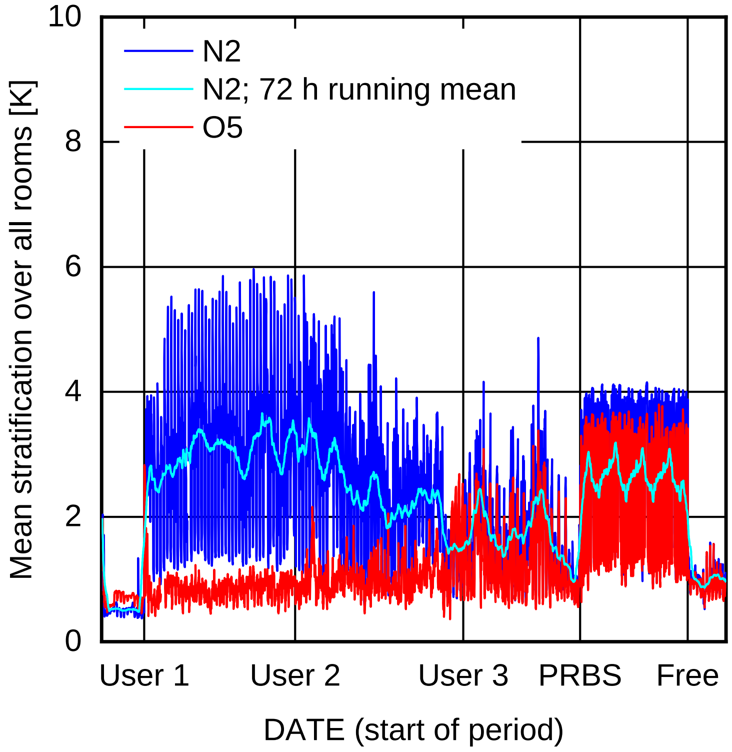


Figure 49. Average stratification (hourly means) in all rooms inside the Twin Houses depending on the experimental period.

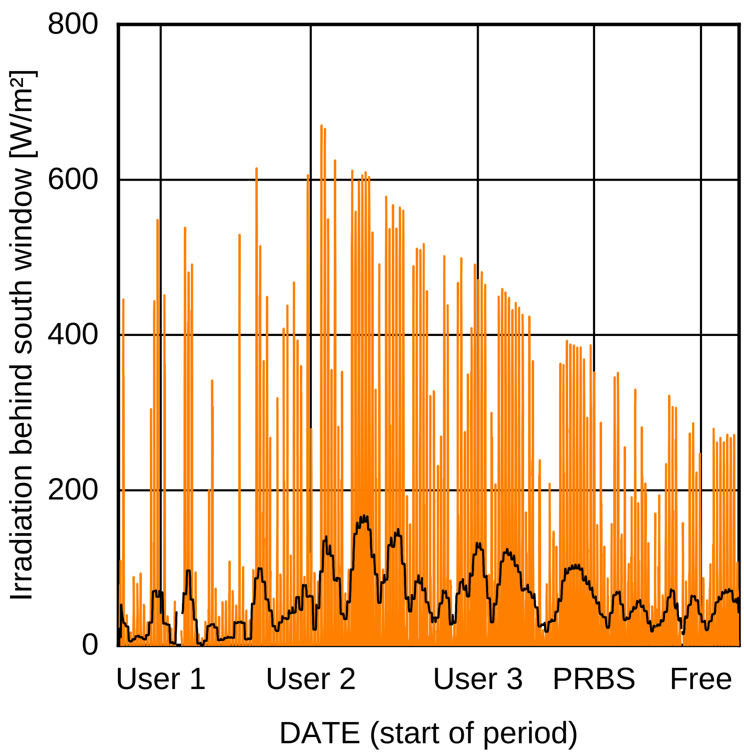


Figure 50. Solar irradiation inside behind the south windows (hourly means, measured in the O5 house). The black line represents the 72 hour running mean value.

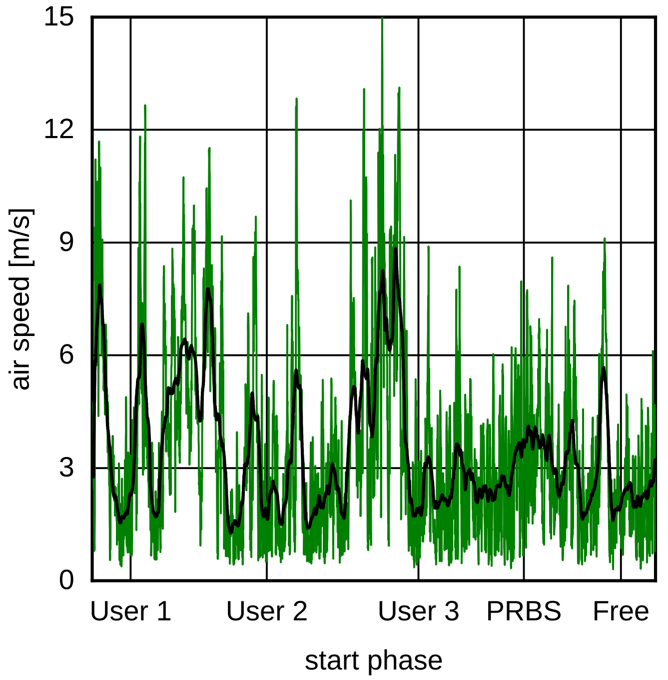


Figure 51. Wind speeds (hourly means) prevailing during the Annex 71 BES model validation experiment. The black line represents the 72 hour running mean value.

7.7. Radiation processes

Figure 52 and Table 25 show the agreement between the simulated solar irradiation on the facades and the radiation intensities measured at the IBP's weather station. Large deviations can be seen particularly for the south facing façade featuring relative large glazing areas. It is assumed that the simulation programs' radiation algorithms are not responsible for the observed deviations, but rather it is the treatment of solar radiation reflected from the ground (Table 25, bottom). Team 3, using the measured downwards radiation to calculate a dynamic albedo shows the best results in terms of solar radiation. Team 8 also uses measurement values but doesn't consider the two pyranometers that are used to calculate time-varying albedo have a high uncertainty during low irradiation intensities around sunrise and sunset. This leads to systematic overestimations of the albedo during these times. Other teams like 5 and 10 use two fixed albedo values to take into account snow cover and reach irradiation accuracies comparable to those of team 8. The results obtained by programs using a single fixed albedo show the highest deviations.

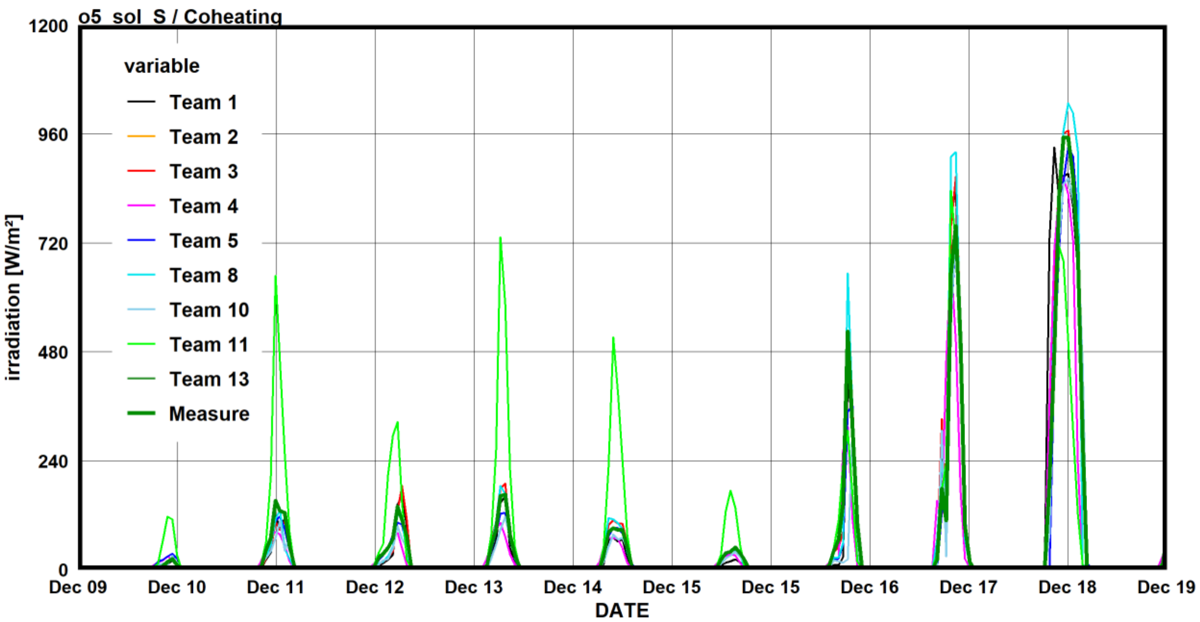


Figure 52. South-facing external incident solar irradiation during the Co-heating period.

Table 25. Mean Deviation (top), absolute mean value (middle) and relative deviation (bottom) of the outside solar irradiation for all four facades during Co-heating.

Mean Deviation							
	team_01	team_03	team_04	team_05	team_08	team_10	team_11
n2_sol_E							
User-1	-11.0	3.0	-5.4	5.8	-8.9	3.1	-15.6
User-2	-29.2	4.8	-25.2	25.4	-29.3	17.1	-74.7
n2_sol_N							
User-1	-12.0	3.3	-2.9	3.0	-8.6	5.7	-6.4
User-2	-33.3	1.7	-13.7	6.8	-27.4	23.5	-1.7
n2_sol_W							
User-1	-16.0	0.8	-7.4	-4.8	-9.0	2.4	104.4
User-2	-48.4	-10.5	-27.0	-30.4	-30.9	9.2	170.4
n2_sol_S							
User-1	-10.5	2.6	-13.2	-6.4	-9.6	-1.9	1.9
User-2	-40.5	-4.5	-40.1	-28.2	-35.4	3.5	-106.6
Absolute mean value							
	team_01	team_03	team_04	team_05	team_08	team_10	team_11
n2_sol_E							
User-1	14.8	28.8	20.4	31.6	16.9	28.9	10.2
User-2	67.6	101.6	71.6	122.2	67.5	113.9	22.1
n2_sol_N							
User-1	6.1	21.5	15.3	21.1	9.5	23.8	11.8
User-2	9.1	44.1	28.7	49.2	15.0	65.9	40.7
n2_sol_W							
User-1	14.7	31.5	23.3	25.9	21.7	33.1	135.1
User-2	56.3	94.2	77.7	74.3	73.8	113.9	275.1
n2_sol_S							
User-1	49.8	62.9	47.1	54.0	50.7	58.4	62.2
User-2	174.7	210.7	175.1	187.0	179.8	218.7	108.6
Relative deviation – related to the simulated value							
	team_01	team_03	team_04	team_05	team_08	team_10	team_11
n2_sol_E							
User-1	-75%	10%	-27%	18%	-53%	11%	-152%
User-2	-43%	5%	-35%	21%	-43%	15%	-337%
n2_sol_N							
User-1	-197%	15%	-19%	14%	-91%	24%	-54%
User-2	-365%	4%	-48%	14%	-182%	36%	-4%
n2_sol_W							
User-1	-108%	3%	-32%	-18%	-41%	7%	77%
User-2	-86%	-11%	-35%	-41%	-42%	8%	62%
n2_sol_S							
User-1	-21%	4%	-28%	-12%	-19%	-3%	3%
User-2	-23%	-2%	-23%	-15%	-20%	2%	-98%
Albedo method	Estimate snow cover	Measured only above 15 W/m²	Fixed 0.22	Fixed 0.23 / 0.7	Measured max=1.0	Fixed 0.23 / 0.9	Fixed 0.2

7.8. Underfloor heating models

Table 26 shows the mean deviations in the calculated return temperatures of the underfloor heating. Since several teams did not use the provided flow rates but use the set temperatures to feed their own control it doesn't make sense to compare the dynamics (Spearman's rank correlation) since every control results in an individual dynamic behaviour. First it becomes apparent that most teams reach a higher precision modelling the attic's dry screed system than modelling the ground floor's conventional concrete screed system. This is unexpected since most UFH models are expected to be developed for conventional UFHs. A systematic difference between teams using individual controls with provided setpoint and teams using the provided supply temperatures and flow rates can't be observed.

Table 26. Mean deviation of the underfloor heating return temperatures of the living room, dining room and child 1 during the Open phase.

	Team							
	1	2	3	4	5	8	10	11
o5_UFH_Child1_Tret								
User-1	-3.2	-0.5	-4.6	-1.2	8.1	-1.3	-0.5	8.2
User-2	-4.2	0.3	-3.9	-2.1	6.1	-1.5	-0.8	7.0
o5_UFH_Dining_Tret								
User-1	-4.8	-5.9	-5.3	-4.7	4.3	-5.9	-2.6	3.0
User-2	-5.9	-7.6	-6.6	-9.5	1.0	-7.3	-5.3	1.8
o5_UFH_living_Tret								
User-1	-5.6	-4.6	-4.8	-4.8	7.4	-5.5	-3.6	-2.4
User-2	-7.4	-5.8	-5.2	-8.4	4.8	-6.9	-5.7	-4.6

7.9. Modelling Reports and Questionnaire for Main Experiment

Information on the modelling approaches and assumptions made by the various teams were obtained from three sources: the modelling report submitted as part of the Blind phase modelling, the updated report detailing differences in models between the Blind and Open phases, and a follow-up questionnaire asking for more details on specific topics that were considered influential.

Some of the key findings from the modelling reports and questionnaire that are considered to be important determinants of energy performance of the Twin Houses are as follows.

1. **Modelling with temperature or heat inputs.** In the Co-heating period, predictions by teams using setpoint temperatures for control were generally better than those using measured temperatures. Using measured temperatures when there was a rapid increase in solar radiation sometimes resulted in a predicted cooling spike, due to the predicted impact on air temperatures of the solar radiation being faster than in practice. On the other hand, some teams using the setpoint temperature for control underpredicted overheating. In principle, controlling with the measured temperatures should be the most accurate method, but it may require more attention paid to the response time for solar radiation entering the room on the air temperature. In the User-1 and User-2 periods, some teams used measured setpoint temperatures to predict heat inputs; others used measured heat inputs to predict temperatures (although modelling guidelines asked teams to predict the temperatures
2. **Thermal bridge modelling**. There was a large variation in the modelling of thermal bridges. Some teams did not include these, others include only external thermal bridges, others modelled some of the bridges and not others. The way the bridges were modelled also varied. Some teams used additional constructions in their models and adjusted thermophysical properties to match the calculated linear and point thermal bridges, others added an additional heat loss path between the internal air node and the external temperature.
3. **Stratification**. A common modelling assumption is that each room is modelled as a thermal zone in which the air is fully mixed. Two teams attempted to model stratification by splitting each room into two thermal zones. Heat injections were to the upper zone, with an air exchange between the upper and lower zones, with underlying theory based on a transient natural ventilation analysis for a thermal plume above the electric heater and a stable stratification outside the plume.
4. **Infiltration modelling**. Most programs used an airflow network flow model to predict the air flows resulting from infiltration and mechanical ventilation. Some used empirical correlations for window and door openings superimposed on the mechanical ventilation flow rate. There were differences in the assumptions regarding leakage distribution for infiltration. The blower door tests only give the whole-house infiltration rate, and do not

distinguish between flow from the outside or the cellar, or through individual doors and windows on the different facades.

5. **Ground albedo**. Snow cover has a large impact on ground albedo. There were many different approaches adopted by the modelling teams: some used measured vertical solar on each façade (which takes into account the reflected solar radiation), others used time-varying measured albedo, others used a single fixed value and others used banded values.
6. **Underfloor Heating System modelling**. Again, there were significant differences in modelling approaches. Some programs had detailed models of the embedded heating loops (with different models for the wet ground floor system and dry attic system) and used the measured supply temperatures and flow rates to predict the heat injection and return temperatures for each loop (14 separate circuits in total). Other teams combined some loops as a simplification, and other assumed a fixed return temperature (in the Blind phase) to calculate heat injection and known heat input based on temperature differentials and flow rates for the Open Phase.

Several other differences in modelling approaches were noted, but are considered to be of lesser importance. These include the following.

7. **External longwave radiation.** Some models used measured net longwave radiation, others used internal algorithms.
8. **Shading**. Some included shading from surrounding buildings (minimal); some included window reveal shading; some did not model shading.
9. **Mechanical ventilation**. Some modellers used fixed values, others used measured values (these were stable except for rare experimental problems).
10. **Window modelling**. Most programs used similar models with angular dependent optical properties; some teams used g-values for thermal transmission, others used detailed modelling of convective/radiant transfer.
11. **Duct heat transfer**. Although the ductwork in the kitchen was insulated, there are still some losses, which some modellers included.
12. **Open trapdoor modelling**. Different opening algorithms used.

Several programs reported modelling difficulties. Some examples of individual responses:

- Thermal bridges between the ground floor and attic were not taken into due to difficulties in the modelling procedure.
- As the implementation of underfloor heating systems is currently under work there is no proper method to model the O5's heating system at the moment.
- Snow cover is not taken into account, as it requires a newly written code (which the software would allow), however, due to time constraints this was not possible.
- Remaining specified thermal bridges (mainly roof specifications) could not be employed due to the limitations of the software.

After the Blind phase, when all measured data was released, some (except for two teams in the Extended Experiments) of the modelling teams undertook a comprehensive evaluation by fixing modelling errors, as documented in their updated modelling reports. The reports give some confidence that the models weren't calibrated. As was pointed out by several modellers when comparing their models with experimental measurements, the complexity of the experiment was high, so adjusting one input parameter could improve results in one part of the experiment but make the comparison worse at others. There are also some experimental uncertainties. One modeller compared the U-value of the West wall based on the heat flux measurements and found that it exceeded the value in the specification by 18 % for the N2 house and 32 % for the O5 house.

As outlined in this section, there were a range of modelling approaches and assumptions made by the various teams, some of these important in predictions. However, it was not possible to state definitively which particular set of assumptions led to the most accurate predictions compared to the measurements. For example, it is not possible to say that modellers who included, for example, thermal bridges, got better results than those who didn't, because they maybe did or did not also include stratification or snow cover modelling.

It was noted from the experimental design, modelling report and questionnaire responses that key factors where there were significant differences in approach and assumptions were thermal bridges, stratification, albedo (due to snow cover), underfloor heating system modelling and infiltration paths. Other important factors, such as mechanical ventilation, fabric heat conduction and solar processes are thought to be modelled relatively consistently and accurately (based on Annex 58 validation experiment results (Kersken & Strachan, 2020) and other validation studies). One way of helping to disentangle the various factors is by undertaking sensitivity analysis on these key factors by the modelling teams. It is expected that further work on sensitivity analysis, together with additional analysis with the comprehensive dataset using information on surface temperatures, heat flux measurements and tracer gas measurements, will continue. In the near future the experimental team conducting this validation study will use sensitivity analyses, provided by some of the modelling teams, to compile an overview of the impact on the simulation results when one factor at a time (OAT) is changed.

7.10. Comparison with the Annex 58 results

The BES validation described in this report is the successor to the previous validation conducted within the IEA EBC Annex 58, as detailed in section 1.2. The increased realism in the experimental design of this validation, described in section 1.3, makes a systematic difference in the quality range of submitted results likely. Considering this, it is of interest to compare the range of submitted results between both validations.

To compare the results of this validation with the results from the previous IEA EBC Annex 58, boundaries must be considered to select valid comparisons. In Annex 58 only a room-wise evaluation was done, so the comparison of the two Annex's results is also limited to room level. This comparison focuses on the living room, since it is the largest room considered in the Annex 58, as the attic was not part of the Annex 58 experimental design. Also only periods with identical validation goals (heating power or air temperature) can be compared. These considerations allow comparisons listed in Table 27.

Table 27. Possible and selected comparisons between Annex 71 and Annex 58 periods.

selected	Annex 71 period	Annex 58 period
	heating energy	
	Co-heating	Constant temperature (30°C)
x	Co-heating	Re-initialisation (25°C)
	room air temperature	
x	PRBS	ROLBS
x	Free-Float	Free-float
	User-1 (N2 only)	ROLBS
x	User-2 (N2 only)	ROLBS
	User-3 (N2 only)	ROLBS

Figure 53 compares the overall living room results' quality of all participating modelling teams between the IEA EBC Annexes 58 and 71 for Constant Temperature / Co-heating periods. Figure 54 does the same for the ROLBS / PRBS periods. All these displayed periods are heated electrically only. It can be seen that the results for the simpler Annex 58 perform slightly better. The range of mean deviations for the Annex 71 Co-heating period is smaller than in Annex 58 but also fewer teams participated in Annex 71 and the median is closer to the zero deviation. Also the Annex 71 Co-heating period's (Annex 58 Constant temperature) range of power shape fit values is smaller but again the median is closer to one, indicating a better fit. For the PRBS periods the Annex 58 results are closer to the ideal fit and have a smaller range too. When interpreting these findings it must also be considered that the simulations were partly done by different modelling teams, and the modelling of the experiments in Annex 71 was more complex.

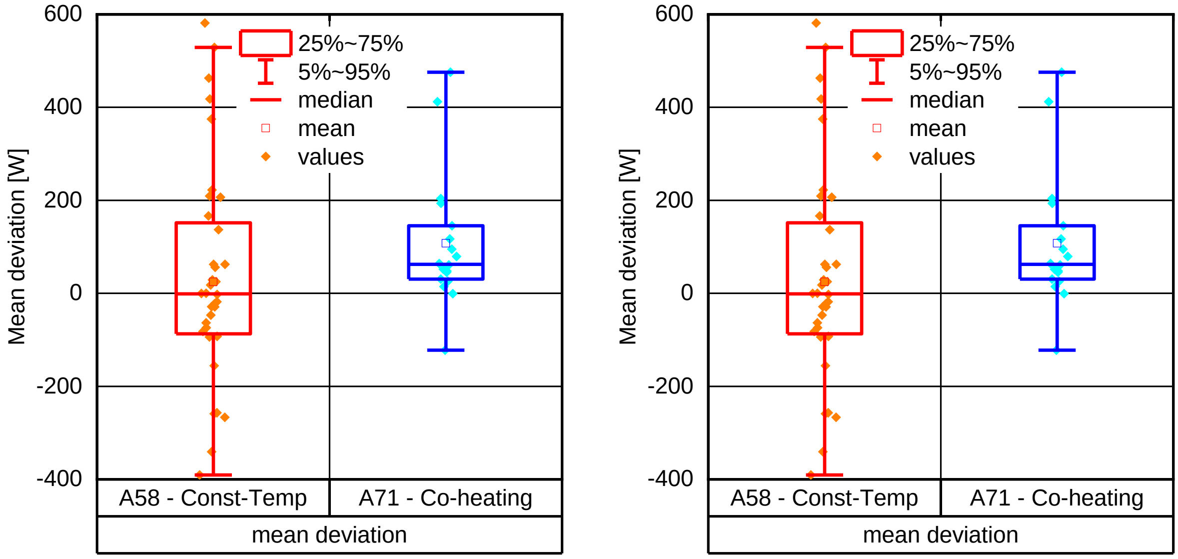


Figure 53. Comparison of the mean deviation and the Spearman's Rank Correlation between the Annex 58 Constant Temperature period (25°C) and the Annex 71 Co-heating period.

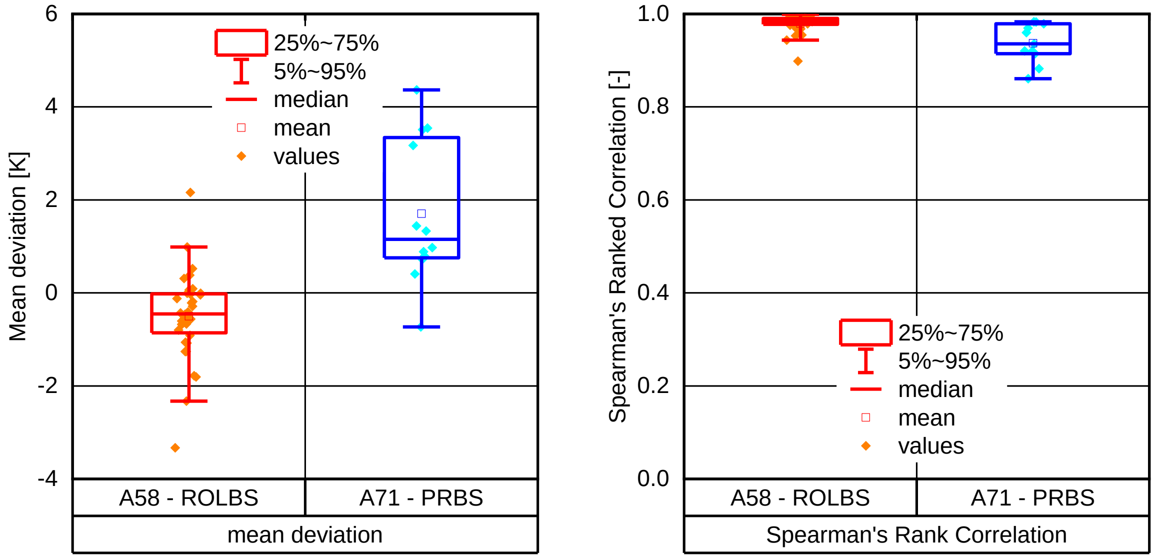


Figure 54. Comparison of the mean deviation and the Spearman's Rank Correlation between the Annex 58 ROLBS period and the Annex 71 PRBS period.

Figure 55 compares the electrically heated Annex 58 ROLBS results with the Annex 71 User-2 period, separately for the electrically heated N2 house and the O5 house with underfloor heating. Here again it can be seen that the Annex 58 results are better than for the Annex 71 N2 house. The underfloor heated O5 house however has the lowest (best) mean deviation and the temperature shape fit, measured by the Spearman's Rank Correlation, is between Annex 58 and the Annex 71 N2 house.

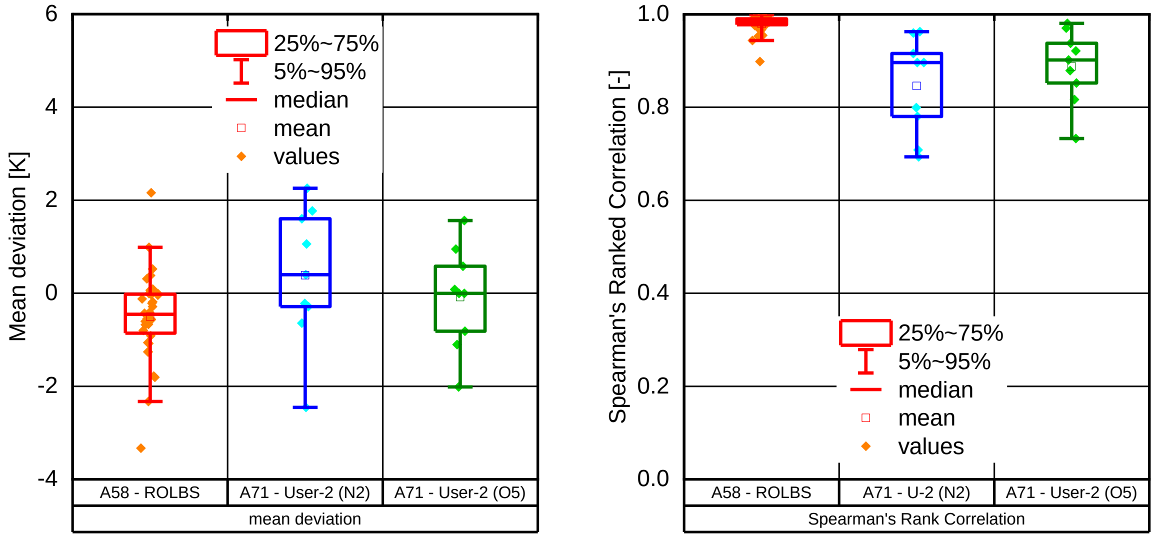


Figure 55. Comparison of the mean deviation and the Spearman's Rank Correlation between the Annex 58 ROLBS period and the Annex 71 User-1 period (N2 house only).

Results for the comparison of the mean deviation and the Spearman's Rank Correlation between the Annex 58 and the Annex 71 Free-Floating periods are similar to those for the ROLBS/PRBS comparison of Figure 54.

8. Conclusion and discussion

As a basis for this validation exercise for Building Energy Simulation (BES) programs a well-documented measurement dataset with synthetic users was created. This dataset has been made publicly available (Kersken & Strachan, 2020) and can be used for further validations, teaching and educational purposes and further research, especially focusing on the modelling of wet and dry screed underfloor heating systems, air source heat pump systems including domestic hot water, profiled internal heat and moisture gains and internal air flows through open doors and trap doors. There are no other comparable whole-house datasets with such detailed specifications publicly available. So this new dataset itself is a valuable contribution to research and improvement of confidence in building simulation, as well as an important resource for model developers. The dataset is suitable for whole building modelling, but subsets could also be used to check sub-systems such as dynamic occupancy profiling or underfloor heating systems modelling. As was the case for the IEA Annex 58 datasets, future research publications are expected, including reporting of the sensitivity analyses currently being progressed by the experimental team and modellers The datasets created were also used by Subtasks 2 and 3 of this Annex as development cases ("Common Exercises") for their work on model predictive control (MPC), fault detection and diagnosis (FDD) and regarding the identification of building standard metrics, particularly the heat loss coefficient (HLC), from transient field data. To evaluate the teams' results handed in for the validation study two different metrics were chosen to be able to determine the results' bias (by mean deviation) and the dynamics' fit (by Spearman's ranked correlation) separately. For all experimental periods the relevant validation goal is analysed for the entire buildings' mean, for ground floor and attic and room-wise.

The detailed and realistic validation experiment created within this IEA EBC Annex 71 contains numerous aspects that need to be / can be considered when modelling. These start with thermal bridges through the envelope and between the individual rooms and the cellar, internal air flow with operated internal doors, infiltration and natural ventilation by an operated window. Considering the electrical convector heaters, the dry and the wet screed underfloor heating, three heating systems need to be modelled together with a balanced mechanical ventilation system. Real outside weather conditions including time varying ground reflectance due to snow cover pose an additional challenge. A large number of time dependent inputs like set temperatures, heat and moisture inputs, ventilation rates, window and door operation schedules, etc. have to be included into the model, considering different operation modes for the six periods of the experiment.

This complexity, allowing for the validation of many modelling aspects under realistic but still well-known conditions on the one hand is an additional challenge on the other hand. All the different modelling aspects interact with the deviations and dynamics in multiple rooms. These interactions pose a difficulty when trying to identify one or more particular causes for observed differences between modelling and predictions. This makes it difficult for an individual modelling team to determine which aspects of the modelling need improvement. From the perspective of the analysts attempting to assess the performance of all the modelling teams' predictions, it is difficult to isolate the various approaches used by the modelling teams as a contributory factor to better or poorer predictive performance. Arguably, the limit of feasible complexity has been reached in this validation experiment. It is recommended that future validation studies should be designed with a reduced complexity. This does not necessarily mean reduced realism, but the experimental design should ensure a reduction in the number of parallel modelling changes at each step of the experimental schedule, by focusing more on specific effects with realistic boundary conditions. Most previous empirical validation studies used test rooms and test cells which are as simple as possible outside a laboratory context. IEA Annex 58 was a step up in terms of complexity by focusing on the envelope and solar aspects of a whole house, but in a simplified manner with no systems or variable occupancy profiles. It was shown that, with care, modelling could be successful and the Annex provided useful empirical validation datasets. IEA Annex 71 increased complexity with synthetic occupancy and systems. It was found that modelling, with much effort, could produce reasonable agreement with experimental data, but that the complexity (e.g. the number of dynamic model inputs required using measured data, which is not usual in design use) meant that user input errors became significant. It is not considered feasible to construct a suitable empirical validation experiment that increases complexity to a fully realistic building with real occupants.

Another aspect related to the experimental design is the observed fact that the Open phase usually shows an improvement compared to the Blind phase but still shows significant deviations. This is another indicator that the chosen experimental design approaches a level of complexity that is challenging to meet even for experienced modellers. This should not be taken as an indication that BES tools aren't able to accurately represent complex situations: it is important to be aware that the modelling requirement in this experiment involves a high number of measured time-varying inputs, different modes of operation and provides a lot of necessary details in the experimental specification that of course all come with an uncertainty. As mentioned, with this complexity, it is also a big challenge to identify the single effect or submodel that causes a certain deviation. Additionally, it should be mentioned that it is very challenging for the experimental team to perform such a complex experiment as a continuous, uninterrupted time series, as is required for modelling such a time series accurately.

In spite of the difficulties just described in general it can be stated that most modelling teams / programs were able to reach a good degree of accuracy in their simulations. Interestingly, the results for the electrical convectors equal the accuracy of the results for the more complex underfloor heating. The additional complexity of the underfloor systems is most probably compensated by strong stratification created by the convectors. The results for the User-1 period are more accurate than for the User-2 period, because the User-2 period has the more complex synthetic user profiles. For these User periods some teams for various reasons did not use the provided supply temperatures and flow rates but they used the rooms' set temperatures together with an individual control. Regarding the room air temperatures (the validation goal of the User periods), there is no clear advantage to either of the approaches adopted. In the Extended Experiment the O5 house features internal moisture gains instead of the underfloor heating. It is apparent that the results for this Extended Experiment, also regarding the relative humidity, are quite good. This is also true for the N2 building where no change between the two experiments was made. The reason for this is not certain – possibly due to modelling teams having results from the Main Experiment, or possibly because the weather conditions were different between the two experiments.

Concerning the modelling, it was interesting to compare program capabilities and the approaches adopted. For many of the heat transfer paths, the modelling approach was similar, e.g. for mechanical ventilation, fabric heat conduction and solar processes. However, there were significant differences in approach and assumptions for thermal bridges, stratification, albedo (due to snow cover), underfloor heating system modelling and infiltration leakage paths. It was noted that modellers often undertook detailed calculations of external shading (for example) which had a minor impact on predictions, but simplified or ignored some of the other important factors (e.g. stratification) which are harder to model. A recommendation from this study is that the modelling of thermal bridges, stratification, albedo, underfloor heating system modelling and infiltration leakage paths should be researched and improved in BES programs.

There are still some unresolved aspects of the research. There are some experimental uncertainties, such as the in-situ construction U-values, which could be addressed by further data analysis, and the leakage distribution and interzonal air exchange, which could be addressed by analysis of the existing (and provided) tracer gas measurements or further experimental room-by-room pressurization testing. Regarding modelling predictions, causes of discrepancies between measurements and predictions could be investigated by additional sensitivity analyses. The extensive dataset gathered will be invaluable in further research to investigate these points, and additional validation research is possible, for example in analysing the heat pump performance and other topics as mentioned at the start of the Conclusion section. In near future the experimental team conducting this validation study will use sensitivity analyses, provided by some of the modelling teams, to compile an overview of the impact on the simulation results when one factor at a time (OAT) is changed. This is also a lesson learned for future application. Aspects that are expected to be critical should be modified OAT in the experimental design. Other aspects, identified to be often subject to poor numerical representation like interzonal air exchange and stratification, might by analyzed by means of detailed and focused experiments or computational fluid dynamics (CFD). For building energy simulation this does only add a value when the information from the CFD is used to derive or improve simplified models that are feasable to be incorporated into BES tools.

Compared to the previous validation of IEA EBC Annex 58 the experimental setup chosen in this validation was comparable but with more realistic boundaries. As this required more details in the modelling this validation's results are a little less accurate in terms of quantifiable metrics, as can be expected. However the visual inspection of the simulation results with the measurements still show a good agreement. One important finding is that results for cases with underfloor heating are accurate; partly exceeding the quality of predictions in Annex 58. Despite the high level of complexity and realism and the difficulties that come along with it, the dataset is still very useful for education or training and to test and investigate various submodels.

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ANNEX 71

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