A dataset to support dynamical modelling of the thermal dynamics of a super-insulated building

A description of the experimental setup, data collection, and resulting dataset

Authors

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Abstract

This document provides a description of the setup of controlled heating experiments for the purpose of control-oriented dynamical modelling. The building studied is the LivingLab at NTNU, which is a super-insulated single-family house. In a first part, the building is presented. In a second part, the dataset is introduced. In a third part control and data acquisition systems are introduced. In the remaining parts, the successive three experiments are described. Appendices contain additional information that may be needed for modelling.

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This work was initiated as part of a collaboration within the IEA EBC Annex 67 "Energy Flexible Buildings"[5].

[3] http://www.zeb.no/
[4] http://fp7-advantage.eu/
[5] http://annex67.org/

Contents

Building layout and description

Location and technologies

The LivingLab at the Norwegian University of Science and Technology (NTNU) in Trondheim[6] was designed to be a zero-emission single family house when accounting for the emissions of construction materials and operation.

Figure 1: South-west view of the building (the main architect of the building was Luca Finocchiaro, NTNU).

The building has a highly insulated envelope (consisting of a wooden frame and rock-wool insulation of thickness 35-40cm[7]), large glazed areas (glass ratio in the range of 0.2) with possible shading on the southern facade (not used in the experiment). Heating is ensured by a heat-pump[8] coupled to either floor, radiator or ventilation heating. Forced ventilation with heat recovery is implemented on the building. Local energy production is available through photovoltaic and solar thermal panels on the roof. Moreover, ninety square meters of phase change material (PCM) boards are installed in the ceiling, behind the wooden cladding at the indoor interface, with the aim to limit indoor temperature fluctuations.

More detailed information about the building and the technologies installed is available in [1], [2] and [3].

Internal layout

The building consists of 7 inhabitable rooms of an area totalling around 100 m^2, and one external technical room, as presented in Figure 2. Areas and denominations of the rooms are summarised in Table 1. Zoning can be made in the building by operating the doors and moving panels, creating 4 zones (bedroom west, bedroom east, bathroom, and main) as depicted in Figure 3.

[6] GPS coordinates of the building are: 63°24'58.6"N 10°24'39.1"E (or in decimal form: 63.416278, 10.410870)

[7] Exact thickness of rockwool insulation layers are 35cm for the walls, 40cm for the floor, 36cm for the flat roof and 40cm for the tilted roof.

[8] The normal heating system of the building was disabled during this experiment (it has not been possible to implement the excitation on it, due to time and technician constraints). Instead, additional electrical radiators were used (see next section).

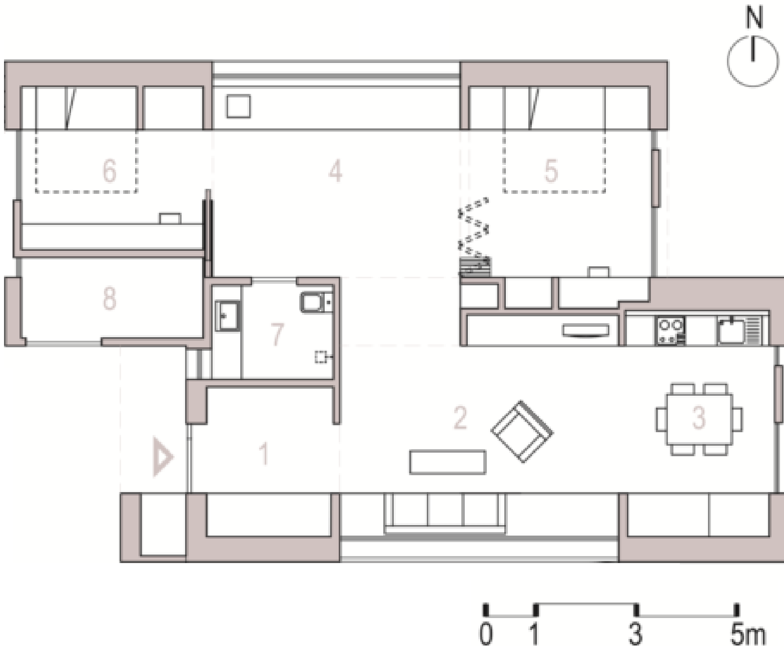

Figure 2: Floor plan of the ground level of the LivingLab. A small bedroom above the bedroom west is not displayed here. (Picture from [1], adapted and reused with permission)

Table 1: Areas within the building corresponding to markings in Fig. 2 (Area values are based upon construction drawings and rounded to the closest unit)

Number	Name	Area (m^2)
1	Entrance	8
2	Living room south	26
3	Kitchen	14
4	Living room north	19
5	Bedroom east	16
6	Bedroom west	12
7	Bathroom	5
8	Technical room	Not considered within the study

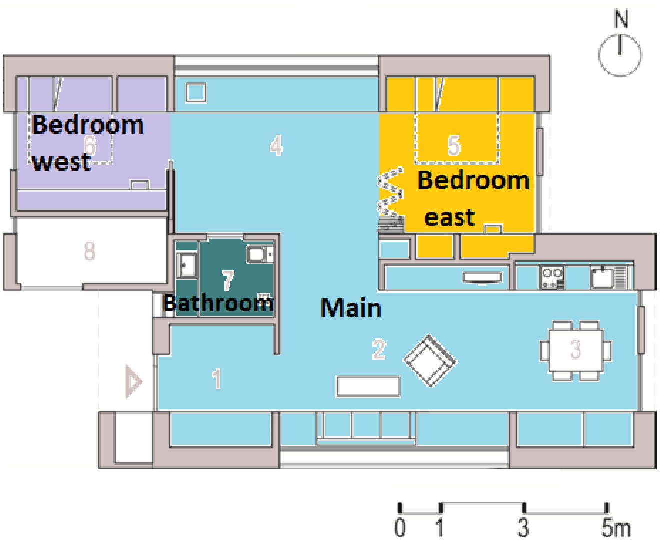

Figure 3: Thermal zones that can be separated using the doors. The small bedroom upstairs (not appearing on this drawing) is part of the 'Main' zone. (Picture from [1], adapted and reused with permission)

Dataset

In this section, experiments and dataset structure are introduced.

Experiments

The data is structured in 3 folders corresponding to the 3 experiments (see Table 1). Further details are presented in later sections of this document[9].

Table 2: Summary of experiments.

Experiment	Dates	Doors to bedrooms	Ventilation supply air set-point (°C)	Ambient temperature (°C) (min / mean / max)
2	18/04/2017 – 20:00 24/04/2017 – 20:00 (6 days)	Open	30	-3.5 2.8 8.8
3	27/04/2017 – 17:00 08/05/2017 –09:30 (11 days)	Closed	18 (30 on the 1st day)	-2.9 6.5 17.2
4	08/05/2017 – 11:00 15/05/2017 – 07:45 (7 days)	Open	18 (disabled the 3 last days)	-2.3 6.3 18.4

For each experiment, the dataset consists of measurements of the following quantities:

- Indoor temperatures (air and operative)
- Power to the radiators (operated using pseudo-random binary sequences (PRBS) as proposed in [4])
- Power to appliances within the building (technical room excluded)
- Ventilation data (temperatures, and estimated flow)
- Environmental conditions (ambient temperature, global solar radiation, wind speed and direction)

Regarding indoor temperatures, individual room values are available (designated below as "zone-averaged" temperatures), as well as an average over the whole building (designated below as "building-averaged" temperatures). Air temperatures were also measured at different heights to allow quantification of the temperature stratification.

Folder structure and documents

The dataset was exported to spreadsheets in .CSV format (for reduced datasets) and .XLSX format (for the comprehensive datasets) to ensure interoperability[10].

[9] Experiment numbering starts from 2 for historical reasons (a first experiment was made, but its resulting dataset was deemed too incomplete to be shared – due to a crash in the data acquisition).

[10] Both .CSV and .XLSX files can be loaded in MATLAB (using the 'readtable' function) and R (using the bstandard function 'read.csv()' for CSV files, and e.g. the function 'read_excel()' from the 'readxl' package for XLSX files).

Experiment are separated in different folders, each of which containing:

- A spreadsheet 'reduced_dataset_XXm.csv', where XX is the sample time of the data (5, 15, 30 or 60 minutes) containing pre-processed data with different sample times, ready to be used in modelling. In terms of denominations, the columns correspond to:
    - Ta: ambient temperature (°C)
    - I_sol_G: global solar radiation (W/m^2)
    - Ws: wind speed (m/s)
    - Wd: wind direction (° - reference to the North, with sign convention such that West lies at 90 °)
    - h_rel: relative humidity of ambient air (%)
    - air_pressure: atmospheric pressure (hPa)
    - Q_ventilation: heat gain from ventilation (W)
    - Q_heating: power to radiator (W)
    - Q_appliances: power to appliances (W)
    - Ti: building-averaged indoor air temperature[11] (°C)
    - Ti_PCA: first principal component of room temperatures[12] (°C)
    - Tv_supply: supply air temperature of the ventilation (°C)
    - Ti_main: zone-averaged indoor air temperature in the *main* zone (°C)
    - Ti_bathroom: zone-averaged indoor air temperature in the *bathroom* zone (°C)
    - Ti_bedroom_east: zone-averaged indoor air temperature in the *bedroom east* zone (°C)
    - Ti_bedroom_west: zone-averaged indoor air temperature in the *bedroom west* zone (°C)
    - To: building-averaged operative temperature[13] (°C)
    - To_main: zone-averaged operative temperature in the *main* zone (°C)
    - To_bathroom: operative temperature in the *bathroom* zone (°C)
    - To_bedroom_east: operative temperature in the *bedroom east* zone (°C)
    - To_bedroom_west: operative temperature in the *bedroom west* zone (°C)
    - Timestamp: timestamp of the measurements (serial date representing the number of days since 00/00/0000)[14]
    - Hour: number of hours elapsed since the beginning of the experiment

- Spreadsheets 'comprehensive_dataset_XXm.xlsx', where XX is the sample time of the data (5, 15, 30 or 60 minutes). Columns are named using similar conventions to the above, with an added extension indicating the height at which the measurements were taken, where relevant.
  These spreadsheets contain the following sheets (details about the data acquisition are provided in the next part of this document):
    - LivingLab DAQ: structured measurements originating from the building-embedded data acquisition (in this sheet, accumulated energy (in Wh) were stored instead of power, as denoted by the "acc" suffix; this is to avoid issues due to high frequencies in power signals)
    - Pt100: Data collected using additional Pt100 sensors
    - Vera Edge: Data collected using a commercial 'smart home' kit
    - iButton: Data collected using additional iButton sensors

[11] Volume considerations were used to compute the weights of each individual measurement for indoor air temperature computation. See [Appendix 1: Building-averaging of indoor temperatures] for more information.
[12] This can be seen as a statistical alternative to averaging emphasizing variations in the indoor temperatures. However, the physical interpretation is questionable. See [Appendix 1: Building-averaging of indoor temperatures] for more information.
[13] The measurements in each room were weighted by the area of the room when computing this average.
[14] This can be used to reconstruct the date and time of the measurements, using e.g. the 'datestr' function in MATLAB.

Control and data acquisition setup

In this section, the data acquisition is presented, together with the materials and heaters used in the experiments.

Embedded data collection and control within the LivingLab

Extensive data collection is implemented in the building, and coupled to a LabView application converting readings to daily TDMS files with a resolution of 30s. Results from this data acquisition are found in sheet 'LivingLab DAQ' of the 'comprehensive_dataset_XXm.xlsx' spreadsheets (where 'XX' denotes the sample time in minutes).

Monitored parameters inside the building on a room level are: indoor air temperature, relative humidity, CO_2 levels, power to sockets and particular appliances, occupancy, and door movements. Air speeds and temperatures within the ventilation system are also monitored. However, the air speed sensors in the ventilation ducts outputted inconsistent values so that a constant value for air flow of 130 m^3/h should be used in modelling whenever the ventilation was running[15].

Regarding indoor temperature metering in each of the rooms (apart from the entrance) several indoor temperature sensors are mounted on the walls (see Figure 4). Corresponding heights for each room are given in Table 3 and spatial positioning of these sensors is displayed with green dots in Figure 13, Figure 15, and Figure 17.

Table 3: Details of wall mounted sensors in the LivingLab (measured to the middle of each box).

Room	Sensor number (and height in m)					
	1	2	3	4	5	6
Living room south	1,6	0,1	0,8	1,6	2,4	3,2
Living room north	1,6	0,1	0,8	1,6	2,4	3,2
Kitchen	1,4	1,6				
Bedroom east	1,4	1,6				
Bedroom west	1,4	1,6				
Bathroom	1,4	1,6				
Entrance	/					

More details about the building data collection can be found in [3]. Moreover, the extensive raw data collected in the experiment was kept by the authors, and can be made available upon request — in the case the data from the detailed dataset is insufficient.

The following weather conditions are also monitored by the building weather station: global horizontal solar irradiance, wind speed and direction, ambient temperature, atmospheric pressure, and relative humidity.

Figure 4: Wall mounted temperature sensors.

[15] More details about this in [Appendix 2: Estimation of heat gains from ventilation] at the end of the document.

Added Pt100 and iButton sensors

Additional measurements were collected using a set of Pt100 connected to wireless transmitters in a Wisensys system (see Figure 5 and Figure 6). This system allows regular collection of air and operative temperatures (using black globes as seen in Figure 7) with a resolution of 0.1 °C. Each sensor is read approximately every 20 s. The base station software then allows exporting average values with a 5 min sample time in one .CSV file for all sensors. This averaging function was used to generate the data in the dataset.

Figure 5: Wisensys base station setup for the data collection from the Pt100.

Figure 6: Pt100 with wireless transmitter used in the experiment.

Figure 7: Black globe for operative temperature measurements using the Pt100 sensors.

For experiments 2 and 3, iButton sensors were also used, due to reduced amount of Pt100 available at that time (see Figure 8). These sensors were setup to collect indoor air temperatures with a 5 min sample time and a resolution of 0.0625 °C. Contrary to the Pt100 system, these measurements must be programmed and read manually, which results in non-synchronous data collected in one .CSV file per sensor.
To ensure high quality of the measurements, sensors with the lowest bias (as measured beforehand in a controlled environment by a technician) were selected from the set of available sensors. In the processing of their output, this individual measured bias (at 20 °C) was then subtracted from the corresponding readings.

Figure 8: iButton sensors used in experiments 1,2,3.

In experiments 2, solar radiation did impact the reading of some of the indoor temperature, as no shading of the sensors was used. This was corrected in experiments 3 and 4 by using dummies to shade the sensors (see Figure 9) while not affecting the solar gains to the building. It is worth noting that this may affect the measurement of the operative temperature, as the part of the outer wall temperature is decreased in the resulting mean radiant temperature).

Figure 9: Shading of the added temperature sensors using dummies.

Relevant data from this data acquisition is found in sheets 'Pt100' and 'iButton' of the spreadsheets 'comprehensive_dataset_XX.xlsx'.

Smart home kit

The control of the heating was done using a set of commercial 'Smart Home' devices relying on the *Z-Wave Plus* communication protocol, presented in Figure 10 (from left to right):

- 1 *Multi-sensor 6* (EU version) from AEOTEC (for measurement of indoor air temperature)[16]
- 1 *VeraEdge* gateway from Vera[17]
- 2 *Smart Switch 6* (EU version) from AEOTEC (for switching ON and OFF the heaters)[18]
- 1 *Micro Smart Plug* from NodOn (for switching ON and OFF the heaters)[19]

Figure 10: 'Smart Home' devices used in the experiment.

To ensure that reasonable temperature limits are kept within the building, the following rules were implemented in the box controller:

- Send a notification to the operator if the indoor air temperature measured by the *multi-sensor* falls below 18 °C (this only happened once during the experiments).
- Stop all the heating if the indoor air temperature measured by the *multi-sensor* rises above 35 °C and send a notification (this never happened during the experiments).

Additionally, collection of power to heater and indoor temperature was made with this kit (using the "DataMine" plug-in) to allow assessing the practical potential of such measurements. Relevant data from this data acquisition is found in sheet 'Vera Edge' of the 'comprehensive_dataset_XX.xlsx' spreadsheets.

Electrical heaters

The excitation was made with a set of 3 electrical radiators in the same location[20], according to combinations of PRBS sequences[21]:

- 2 radiators of 800 W (SIEMENS/Glen Dimplex – model 2NW5 082 4L) with integrated thermostats set to 30 °C (maximum thermostat set-point) to avoid feedback. These are designated as radiators 1 and 2 below, and are shown in Figure 11.
- 1 radiator of 1 kW (Glamox heating, Adax AS, TPS10) with no integrated thermostat (i.e. running full capacity whenever powered). It is designated as radiator 3, which is displayed in Figure 12 below.

In experiment 2 and 3, radiator 3 (1 kW) is used for excitation. In experiment 4, the radiators 1 and 2 are used for excitation (800 W each).

[16] http://aeotec.com/z-wave-sensor/1688-multisensor-6-technical-specifications.html
[17] http://getvera.com/controllers/veraedge/
[18] http://aeotec.com/z-wave-plug-in-switch/1477-technical-specifications.html
[19] http://www.nodon.fr/en/z-wave/micro-smart-plug-z-wave_14-2
[20] This single emitter configuration is in line with the aim of simplifying of the heat distribution system in zero emission buildings (see chapter 2.8 of [11] for more details).
[21] Details of the frequency content of the PRBS sequences is provided in [Appendix 3: Frequency content of the input-output data] at the end of this document. Information on the construction of these sequences are provided in each experiment section below.

Figure 11: Radiators 1 and 2 on their holder.

Figure 12: Electrical radiator 3 (no embedded thermostat).

Experiment 2

The second experiment started on 18/04/2017 – 20:00 and ended on 24/04/2017 – 20:00. The building was unoccupied during the experiment, with internal doors to the bedrooms opened, doors to the bathroom closed. No shading from blinds was used, and the ventilation was activated (the supply air was regulated to a temperature of 30 °C, due to an erroneous previous setting).

Sensor layout

The sensor layout of experiment 2 is summarised in Table 4 and Figure 13 below.

Table 4: Sensor placement for the second experiment.

Sensor name	Type	Temperature	Room	Height (cm)
PT100-V2-41	Pt100	Operative	Bedroom East	65
PT100-V2-42			Entrance	63
PT100-V2-43			Bathroom	65
PT100-V2-44			Bedroom upstairs	70
PT100-V2-45			Living room south	75
PT100-V2-46			Kitchen	70
PT100-V2-47			Living room north	75
PT100-V2-48			Bedroom west	80
PT100-V2-51		Air	Living room north	110
PT100-V2-52			Living room north	170
PT100-V2-53			Living room north	230
PT100-V2-54			Living room north	290
PT100-V2-55			Living room north	350
PT100-V2-57			Living room south (RTD check)	160
PT100-V2-58			Ambient temperature north facade	
PT100-V2-59			Ambient temperature west facade	
PT100-V2-60			Ventilation outlet, bedroom west	
PT100-V2-61			Ventilation outlet, living room south	
PT100-09			Living room south	230
PT100-10			Living room south	280
PT100-11			Living room south	340
PT100-18			Kitchen	345
PT100-19			Living room north	10
PT100-20			Living room north	70
Multi Sensor 6	Multi sensor 6		Living room south	150
CS8	iButton		Bedroom west (RTD check)	160
CS10			Bedroom upstairs	80
CS11			Living room south	12
CS12			Bedroom west	114
CS13			Living room south	130
CS15			Entrance	110
CS16			Kitchen	110
CS21			Bedroom east	105
CS23			Living room south	160
CS28			Bathroom (RTD check)	160
CS33			Kitchen	38
CS40			Bedroom east	154
CS41			Living room north	160
CS42		Surface	Radiator 3	50
CS44		Air	Kitchen	160
CS48		Surface	Radiator 1	47
CS49			Radiator 2	47

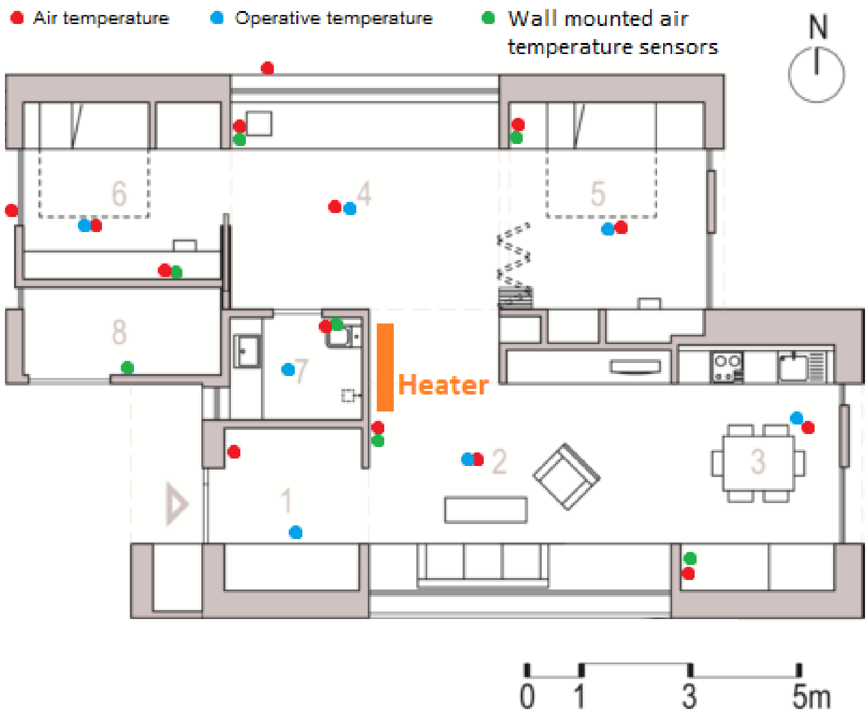

Figure 13: Positioning of the sensors and heater in experiment 2 (Picture from [1]*, adapted and reused with permission).*

Excitation sequence

The heating was operated according to a pre-computed pseudo random binary sequence (PRBS) for the full duration of the experiment. The PRBS was generated using a sample time of 15 minutes and a long time-constant of 2 h in a first part, and 48 h in a second part. This heating schedule, together with the resulting variations in indoor temperature, is shown in Figure 14.

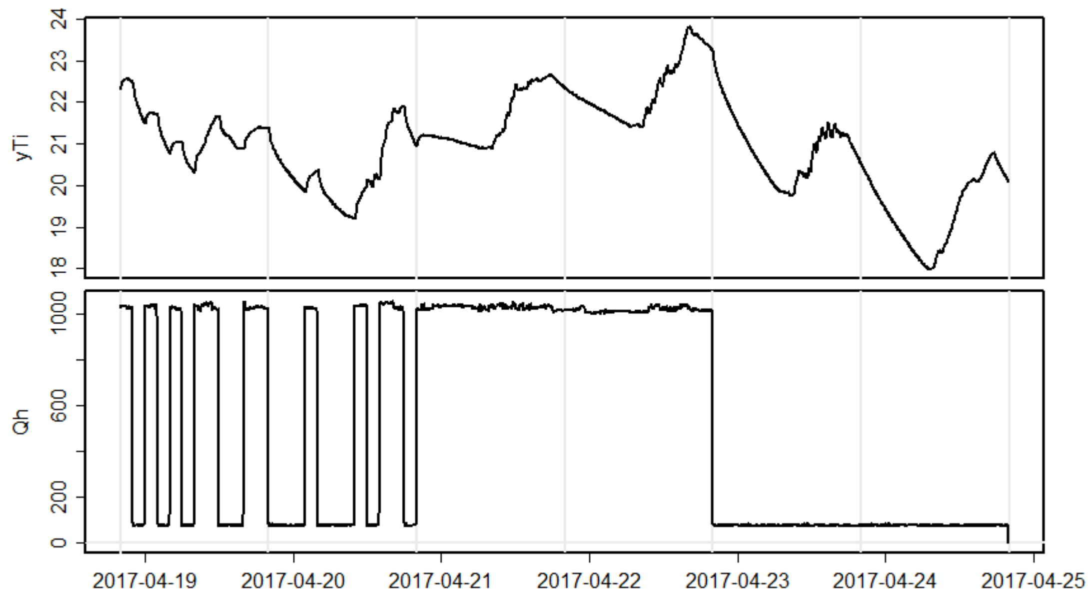

Figure 14: Power to the radiator (lower graph) in experiment 2, and its effect on building-averaged indoor temperature (upper graph).

Access to the building

The building was accessed by one person once during the experiment, on 21/04/2017 – from 09:48 to 09:49.

Experiment 3

The second experiment started on 27/04/2017 – 17:00 and ended on 08/05/2017 – 09:30. The building was unoccupied during the experiment, the door to the bathroom was closed, and no shading from blinds was used.

This time the supply air temperature of the ventilation was regulated to a normal value of 18 °C after 28/04/2017 – 13:20 (and regulated to a temperature of 30 °C until 28/04/2017 – 13:00). Doors to the bedrooms were closed.

Another experiment has been conveyed between experiments 2 and 3, resulting in a significant decrease of the indoor temperature as windows were opened and closed. Therefore, it is expected that the walls were cold at the start of it.

Sensor layout

The sensor layout of experiment 3 is summarised in Table 5 and Figure 15 below.

Table 5: Sensor placement for the third experiment (there is a suspicion that CS8, CS23 and CS41 had been exchanged in the logs, re-labelling presented here was made according to variations in the signal).

Sensor name	Type	Temperature	Room	Height (cm)
PT100-V2-41	Pt100	Operative	Bedroom East	65
PT100-V2-42			Entrance	63
PT100-V2-43			Bathroom	65
PT100-V2-44			Bedroom upstairs	70
PT100-V2-45			Living room south	75
PT100-V2-46			Kitchen	70
PT100-V2-47			Living room north	75
PT100-V2-48			Bedroom west	80
PT100-V2-51		Air	Living room north	110
PT100-V2-52			Living room north	170
PT100-V2-53			Living room north	230
PT100-V2-54			Living room north	290
PT100-V2-55			Living room north	350
PT100-V2-57			Living room south (RTD check)	160
PT100-V2-58			Ambient temperature north facade	
PT100-V2-59			Ambient temperature west facade	
PT100-V2-60			Ventilation outlet, bedroom west	
PT100-V2-61			Ventilation outlet, living room south	
PT100-01_LRS			Living room south	18
PT100-02_LRS			Living room south	95
PT100-03_LRS			Living room south	170
PT100-04			Kitchen	18
PT100-05_K			Kitchen	120
PT100-06_K			Kitchen	215
PT100-07_BR			Bedroom west	170
PT100-08_BR			Bedroom west (RTD check)	175
PT100-09			Living room south	230
PT100-10_BR			Bedroom east (RTD check)	160
PT100-11			Living room south	340
PT100-17_BR			Bedroom east	175
PT100-18			Kitchen	345
PT100-19			Living room north	10
PT100-20			Living room north	70
Multi Sensor 6	Multi sensor 6		Living room south	150

Sensor name (continued)	Type (continued)	Temperature (continued)	Room (continued)	Height (cm) (continued)
CS8	iButton	Air	Living room north (RTD check)	160
CS10			Bedroom upstairs	60
CS11		Surface	Door bedroom west, towards living room north	160
CS12			Door bedroom west, towards living room north	150
CS15		Air	Entrance	165
CS16		Surface	Living room door towards bedroom east	150
CS21			Living room door towards bedroom west	160
CS23		Air	Living room south (RTD check)	160
CS28			Bathroom (RTD check)	160
CS41			Kitchen	160
CS42		Surface	Radiator 1	50
CS48			Radiator 3	47
CS49			Radiator 2	47

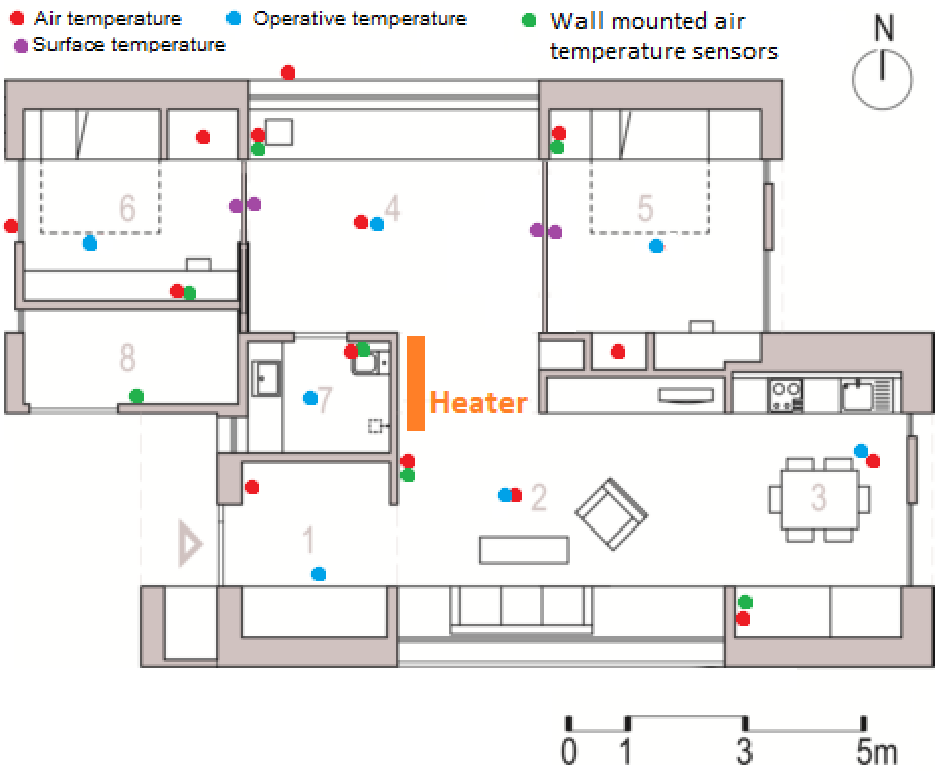

Figure 15: Placement of sensors and heater for experiment 3. (Picture from [1]*, adapted and reused with permission)*

Excitation sequence

Initially, the heating was operated using a thermostatic control to stabilise the indoor temperature (a ventilation experiment had been made between experiment 2 and experiment 3, which had led to a significant cooling of the building). Then, it was operated according to a pre-computed PRBS sequence for rest of the experiment. The PRBS was generated using a sample time of 15 minutes and a succession of long time-constants: 2h, 6h, 12h, and 48h. The resulting heating sequence and indoor air temperature are shown in Figure 16.

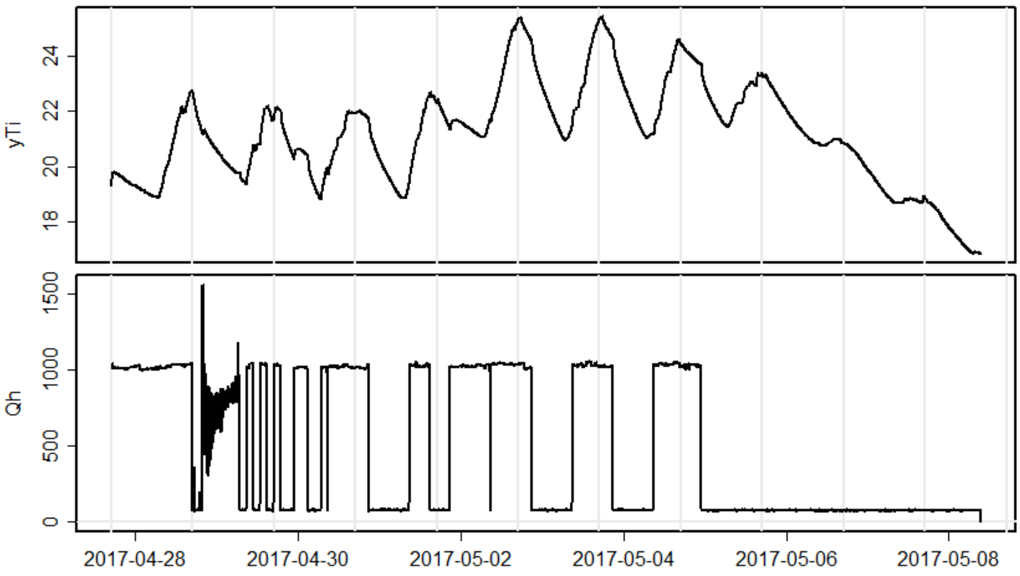

Figure 16: Power to the radiator (lower graph) in experiment 3, and its effect on building-averaged indoor temperature (upper graph).

Access to the building

The lab was accessed in several occasions:

- 28/04/2017 – 17:00-17:20: 2 people accessed the building to add radiators 1 and 2
- 28/04/2017 – 18:45-18:53: one person accessed the building to stick sensors on radiators
- 04/05/2017 – 12:05-12:15: the door of the air handling unit (AHU) in the technical room has been opened
- 04/05/2017 – 13:33-13:44: 3 people entered the building for a visit
- 05/05/2017 – 11:50-11:52: the door of the AHU in the technical room has been opened

Experiment 4

The second experiment started on 08/05/2017 – 11:00 and ended on 15/05/2017 – 07:45. The building was unoccupied during the experiment, the door to the bathroom was closed and doors to the bedrooms opened. No shading from blinds was used.

This time the ventilation was initially activated (the supply air was regulated to a temperature of 18 °C) until 12/05/2017 – 09:54, and disabled after that (additional sealing was made on the ventilation inlets and outlets was installed between 09:54 and 10:12 on that day).

Sensor layout

The sensor layout of experiment 4 is summarised in Table 6 and Figure 17 below.

Table 6: Sensor placement for the fourth experiment

Sensor name	Type	Temperature	Room	Height (cm)
PT100-V2-41	Pt100	Operative	Bedroom East	65
PT100-V2-42			Entrance	80
PT100-V2-43			Bathroom	65
PT100-V2-44			Bedroom upstairs	70
PT100-V2-45			Living room south	75
PT100-V2-46			Kitchen	70
PT100-V2-47			Living room north	75
PT100-V2-48			Bedroom west	80
PT100-V2-51		Air	Living room north	110
PT100-V2-52			Living room north	170
PT100-V2-53			Living room north	230
PT100-V2-54			Living room north	290
PT100-V2-55			Living room north	350
PT100-V2-57			Living room south (RTD check)	160
PT100-V2-58			Ambient temperature north facade	
PT100-V2-59			Ambient temperature west facade	
PT100-V2-60			Ventilation outlet, bedroom west	
PT100-V2-61			Ventilation outlet, living room south	
PT100-V2-56-BaR			Bathroom (RTD check)	160
PT100-01_LRS			Living room south	18
PT100-02_LRS			Living room south	95
PT100-03_LRS			Living room south	170
PT100-04			Kitchen	18
PT100-05_K			Kitchen	120
PT100-06_K			Kitchen	215
PT100-07_BR			Bedroom west	170
PT100-08_BR			Bedroom west (RTD check)	175
PT100-09			Living room south	230
PT100-10_BR			Bedroom east (RTD check)	160
PT100-11			Living room south	340
PT100-17_BR			Bedroom east	175
PT100-18			Kitchen	345
PT100-19			Living room north	10
PT100-20			Living room north	70
PT100-ENTR			Entrance	145
PT100-KIT			Kitchen (RTD check)	160
PT100-LRN			Living room north	160
PT100-LRUP			Bedroom upstairs	60
PT100-RAD			Radiator 1 *(fell during the experiment)*	50
PT100-RAD2			Radiator 2 *(fell during the experiment)*	50
Multi Sensor 6	Multi sensor 6		Living room south	150

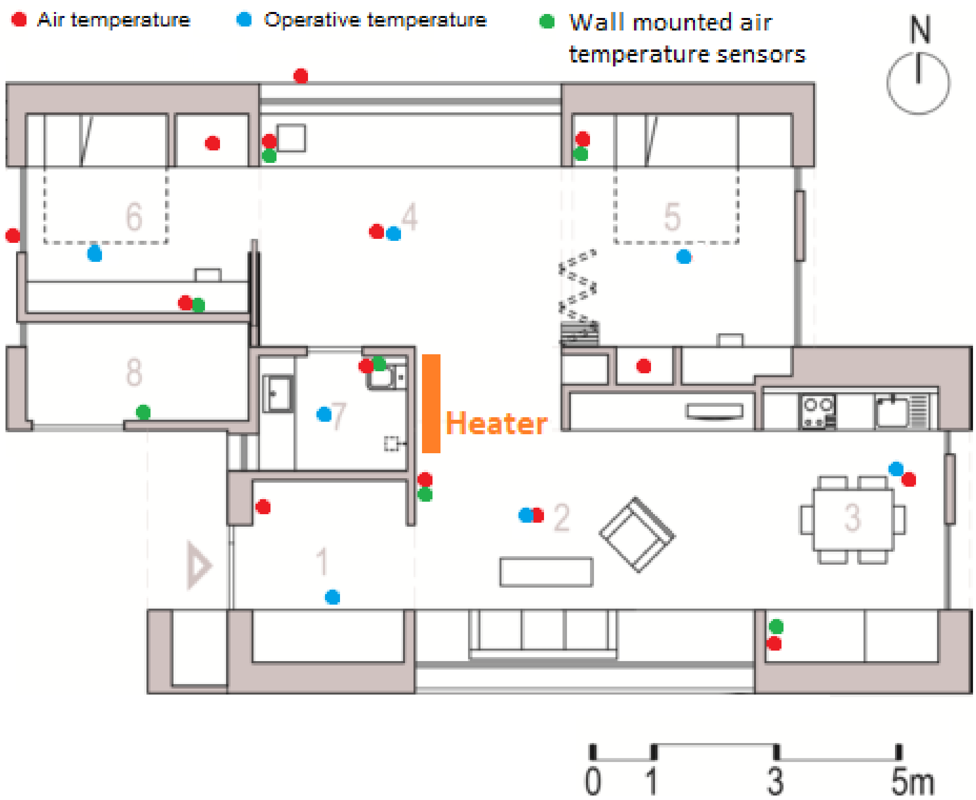

Figure 17: Placement of sensors and heater for experiment 4. (Picture from [1]*, adapted and reused with permission)*

Moreover, Pt100 sensors were now put on all the main RTD sensors of each room of the building to evaluate their bias. Correspondence is found in Table 7.

Table 7: Correspondence between installed sensors (RTD) and added verification sensors (Pt100)

RTD sensor (at 1.4–1.6m)	Added Pt-100 sensor name
Living room south	Pt100-V2-57
Living room north	Pt100-LRN
Kitchen	Pt100-KIT
Bedroom west	Pt100-10
Bedroom east	PT100-08BR
sBathroom	Pt100-V2-56

Excitation sequence

The heating was operated according to a pre-computed PRBS sequence for the full duration of the experiment, with an extra 800W radiator activated full time in the first 2 days in order to increase the temperature to the typical usage range (as the temperature had been dropping as a result of the long stop of the heating at the end of experiment 3). The PRBS was generated using a sample time of 60 minutes and a succession of long time-constants: 2, 4, 8, and 30 h. This heating schedule and resulting variations in indoor air temperature are shown in Figure 18.

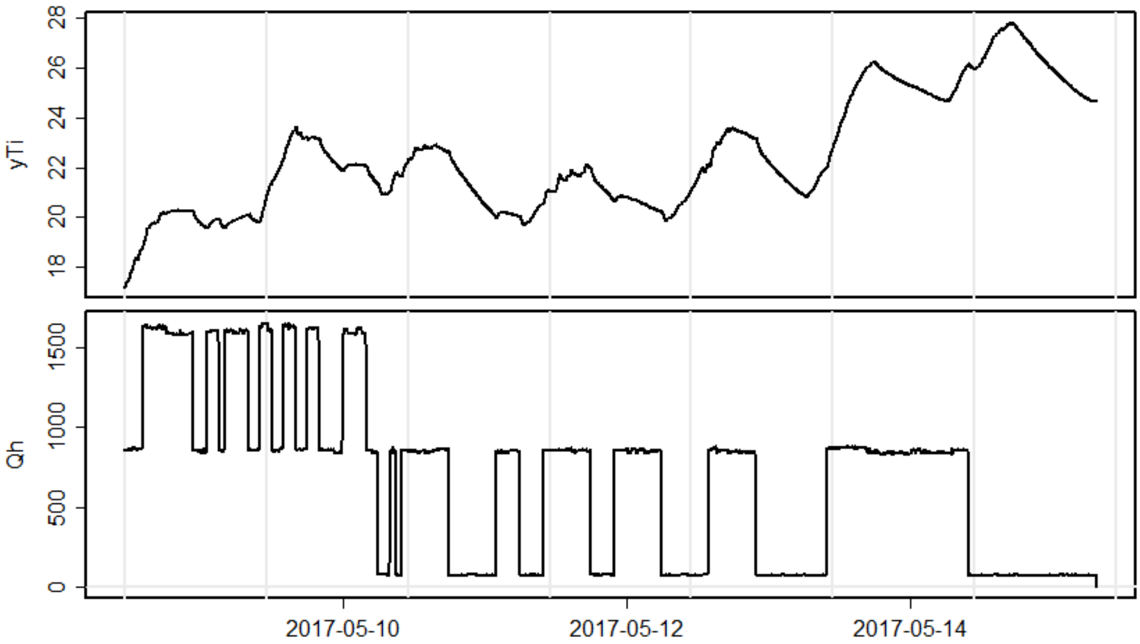

Figure 18: Power to the radiator (lower graph, where the 800W offset in the first 2 days originates from the full-time use of an extra heater) in experiment 4, and its effect on building-averaged indoor temperature (upper graph).

Access to the building

The lab was accessed in several occasions:

- 08/05/2017 – 13:57 - 13:59: 1 person accessed the building to close the door to the bathroom.
- 12/05/2017 – 09:54 - 10:17: 1 person entered the building to switch off the ventilation and seal the air ducts.

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Appendix 1: Building-averaging of indoor temperatures

For single thermal zone modelling, a single value representing the temperature of the zone needs to be computed from available measurements. Different methods can be employed for this purpose, including: area-weighted average, volume-weighted average, or first principal component of room temperatures (either operative or air temperatures) constituting the zone.

Strong disparities of temperatures were observed between rooms during the 3 experiments. Therefore, the averaging method is a sensitive parameter when computing a building-averaged temperature out of these.

Additionally, the temperature of each of these rooms can be estimated in different manners: average of sensor measurements, height-weighted[22], 'layer volume'-weighted average of the measurements at different heights (see Figure 19), or even quality-weighted[23] . Several possibilities were considered for averaging, as presented in Table 8 below.

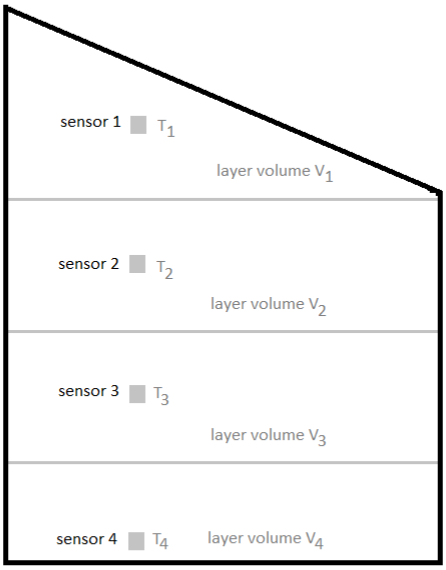

Figure 19: Principle of 'layer volume'-weighted average for room temperatures. Layer separation is made at equal vertical distance between sensors. In this case, the aggregated temperature would be $T = (V_1 T_1 + V_2 T_2 + V_3 T_3 + V_4 T_4) / (V_1 + V_2 + V_3 + V_4)$.

In the dataset, the 'Pt100 (avg)' was used for building-averaged air temperature, and 'Operative' for building-averaged operative temperature. Zone-averaging was conveyed in a similar way than building-averaging, replacing total floor area by zone floor area.

Table 8: Different possibilities of averaging temperatures

Name	Sensors	Temperature	Room weight in building-averaging	Sensor weight in room-averaging	Bedroom upstairs
Pt100 (avg)	iButton & Pt100	Air	Fraction of room floor area to total floor area	'layer volume' averaged	Neglected
Pt100 (PCA)			Coefficients of the first principal component		Considered
RTD	Wall-mounted RTD sensors		Fraction of room floor area to total floor area		Neglected
Operative	Pt100 in black globe	Operative		(single measurement per room)	Neglected

[22] By using e.g. larger weights at human level.

[23] In the sense of 'sensor quality', e.g. distinguishing RTD and Pt100 sensor data.

Regarding the first principal component, the *score* of the different components was computed according to the following equation:

$$T_{PCA} = \frac{\sum_j w_j \times T_j}{\sum_j |w_i|} + \frac{1}{N} \sum_j T_j \quad (1)$$

where N is the number of signals to aggregate, and w_j is the *score* (in the first principal component sense) of the signal T_j.

Differences between the 4 approaches and a single measurement point (in the living room south) using a commercial temperature sensor from a smart home kit[24] are shown in Figure 20, Figure 21 and Figure 22 below.

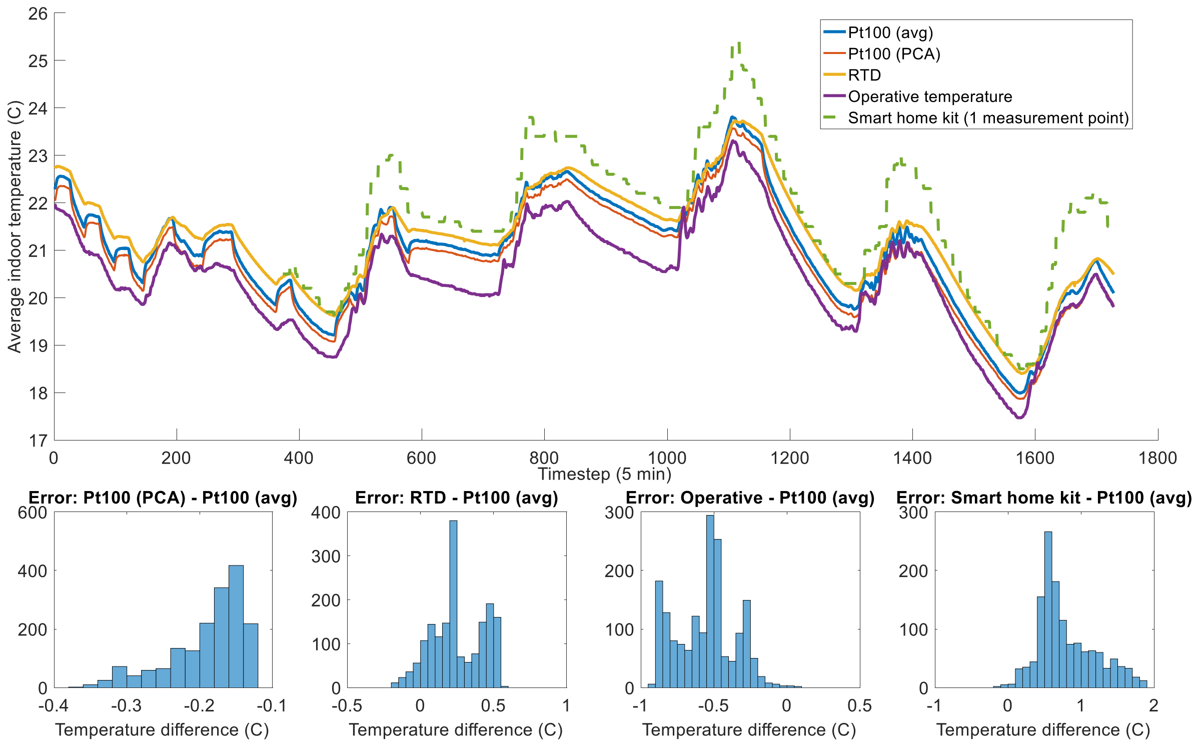

Figure 20: Comparison of estimated building-averaged temperatures in experiment 2.

[24] See the 'Multi-sensor 6' presented in Figure 10.

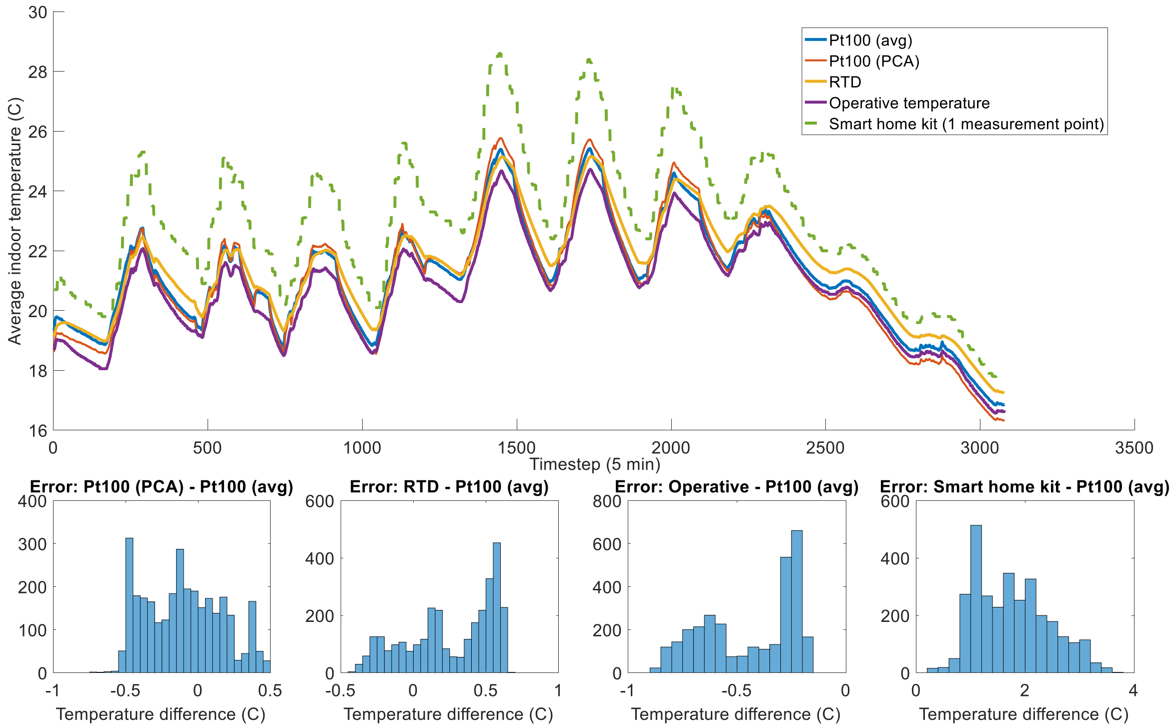

Figure 21: Comparison of estimated building-averaged temperatures in experiment 3.

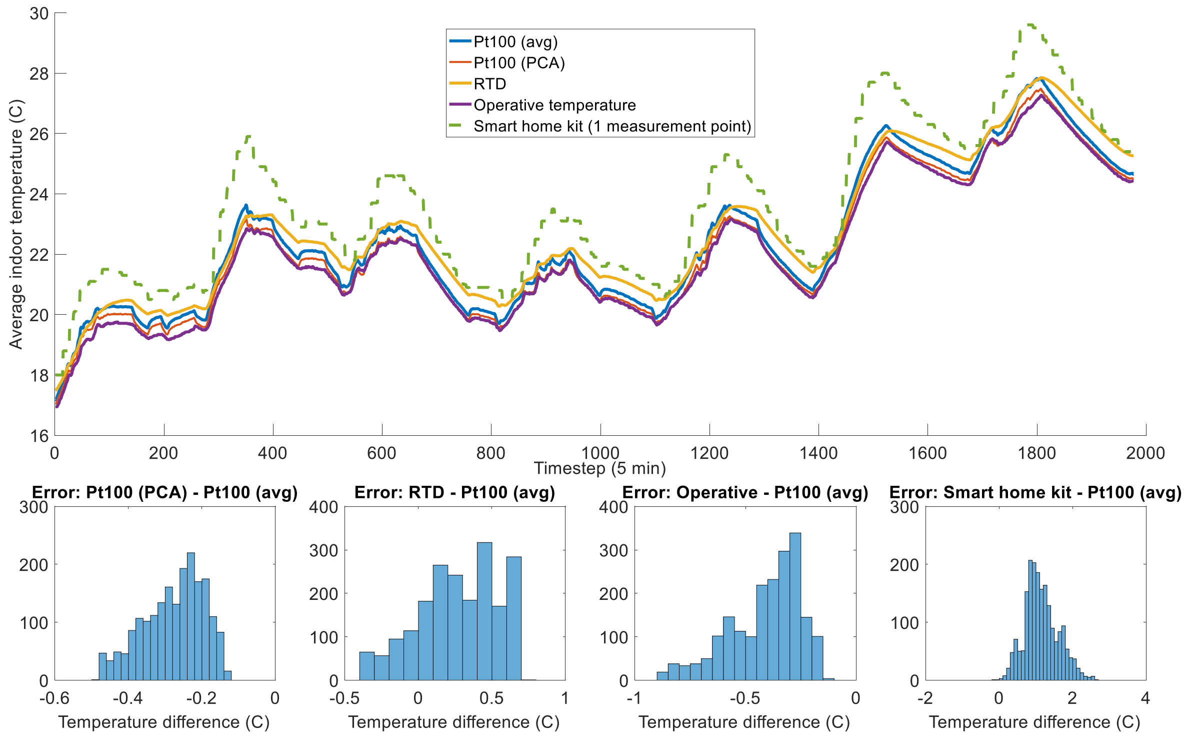

Figure 22: Comparison of estimated building-averaged temperatures in experiment 4.

Appendix 2: Estimation of heat gains from ventilation

The heat gain from ventilation $Q_{ventilation}$ were estimated using the following approximation:

$$Q_{ventilation}(t) = C_{p,air}\, M_{air}\, \rho(t)\, \left(T_{supply}(t) - T_{extract}(t) \right) \quad (3)$$

where $C_{p,air}$ the specific heat of air, M_{air} is the volume mass of air, ρ the air flow rate, T_{supply} the supply air temperature and $T_{extract}$ the extract air temperature.

Supply and extract temperatures were part of the measurements collected on the building. Unfortunately, the air flow sensors of the building were delivering erroneous values during the experiment, so that these air flows needed to be estimated. This was made using measurements from previous experiments in similar conditions. The air flow of the air handling unit in the *normal mode* used here is regulated to a constant flow of 130 m^3/h (supplying 52 m^3/h to each bedroom and 26 m^3/h to the living room, while extracting 52 m^3/h from the kitchen and 78 m^3/h from the bathroom).

This value of 130 m^3/h was used for ρ when computing ventilation heat gains of the reduced dataset. A value of 0 was however used at the times when the ventilation was disabled (at the end of experiment 4, with extracts and supplies manually sealed).

Appendix 3: Frequency content of the input-output data

The information content of input and output data is an essential consideration in system identification. Ideally, data should be *persistently exciting,* which means having a non-zero spectrum for almost all frequencies (see chapter 13 of [5]). As shown in Figure 23, this was the case of the input sequences in the experiment, thanks to the PRBS type of excitation used.

As seen in Figure 24, the output data has a similar characteristic, although it must be highlighted that higher frequencies have significantly less power than in the case of inputs.

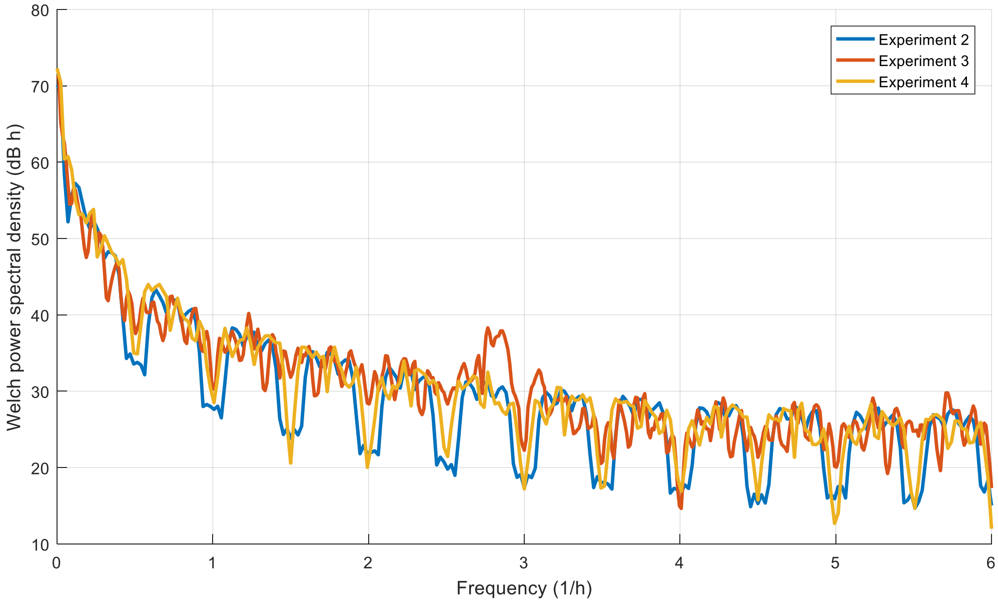

Figure 23: Spectrum of the power of excitation (power to heating) sequences in the 3 experiments (computed using the 5 minutes samples of the excitation sequence, hence the Nyquist frequency at 6 /h).

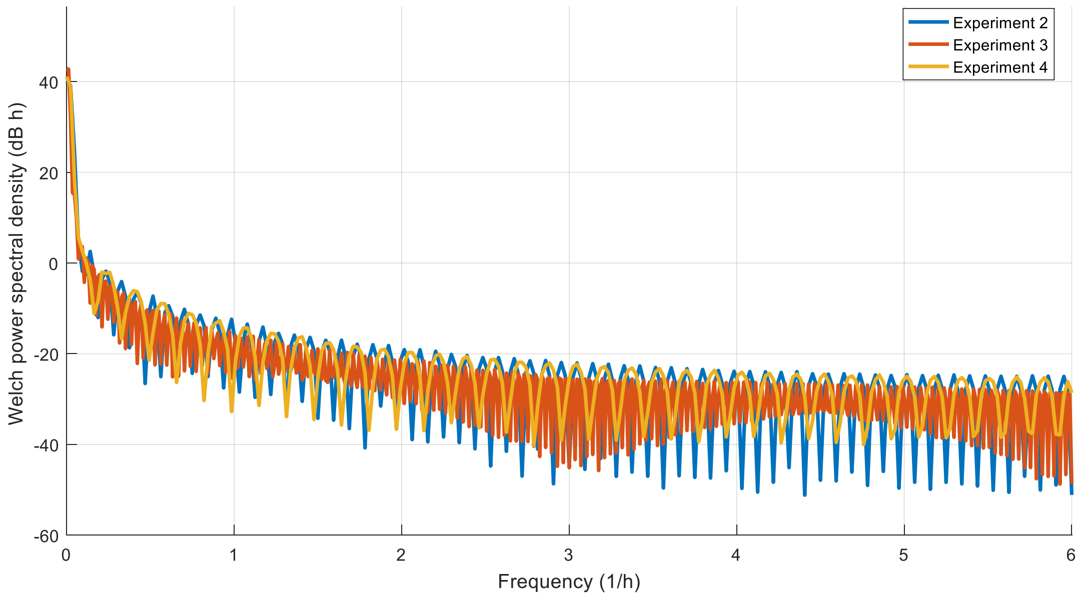

Figure 24: Spectrum of the power of output (average indoor temperature) sequences in the 3 experiments (computed using the 5 minutes samples of the excitation sequence, hence the Nyquist frequency at 6 /h).

Further information on information content of input-output data from buildings may be found in [6] (referring to [7] for the choice of time constants of excitation sequences).

Appendix 4: Statistical summary of the dataset

A statistical summary of the data of experiments 2, 3 and 4 is presented in Table 9 below.

Table 9: Statistical summary of reduced datasets.

		Experiment		
Parameter	**Property**	**2**	**3**	**4**
Mean indoor air temperature (°C)	Min	18.0	16.8	17.2
	Mean	21.0	21.2	22.5
	Median	21.1	21.2	21.9
	Max	23.8	25.4	27.8
Mean indoor operative temperature (°C)	Min	17.5	16.6	16.9
	Mean	20.4	20.7	22.1
	Median	20.5	20.8	21.5
	Max	23.3	24.7	27.3
Ambient temperature (°C)	Min	-3.5	-2.9	-2.3
	Mean	2.7	6.3	6.8
	Median	2.9	6.5	6.3
	Max	8.8	17.2	18.4
Global solar radiation (W/m^2)	Min	0	0	0
	Mean	131	174	212
	Median	31	72	108
	Max	892	834	922
Power to heating (W)[25]	Min	71	71	71
	Mean	539	493	680
	Median	84	120	850
	Max	1056	1560	1656
Heat from ventilation (W)	Min	321	-202	-88
	Mean	385	-41	-27
	Median	379	-78	-19
	Max	464	467	57
Power to appliances (W)	Min	150	152	152
	Mean	195	197	197
	Median	174	176	177
	Max	282	284	290

[25] Here the non-zero minimum is due to a control computer connected to the same power line as the heating. Strictly speaking, these 71 W should be part of the appliances heat gains and these values should be decreased by the same amount.

Appendix 5: A priori knowledge of the building

A first investigation of model identification has been made on the dataset resulting in the paper [8]. This work compared the results using the MATLAB System Identification toolbox [9] and CTSM [10].

The model considered was a simple first order model of the building-averaged thermal dynamics, modelled using the equation below:

$$\mathrm{dT_i} = \frac{1}{C_i}\Big(UA_i\,[\,T_a(t) - T_i(t)\,] + \,\mathrm{A_W}\,\Phi_G(t) + P_{app}(t) + Q_{vent}(t) + P_{rad}(t)\Big)\,dt + d\epsilon_p(t) \qquad (2)$$

where T_a is the ambient temperature (using '*Ta*' from the dataset), T_i the indoor temperature (using '*Ti*' from the dataset[26]), Φ_G the global solar radiation (using '*I_sol_G*' from the dataset), P_{rad} the power to the radiator (using '*Q_heating*'), P_{app} the power to the appliances (using '*Q_appliances*'), and Q_{vent} the estimated heat gain from ventilation (using '*Q_ventilation*'). $d\epsilon_p$ is a stochastic noise (typically a Wiener process).

The values of the parameters estimated by the model are given in Table 10 below (using a 5 minutes sample time and data from all 3 experiments). These values suggest a long time-constant ($C_i/\,UA_i$) in the range of 40–55h.

Table 10: Value of first order model parameters identified in a first study (uncertainty corresponding to 2 standard deviations is given under brackets).

Parameter (unit)	**MATLAB System Identification toolbox**	**CTSM**
UA_i (kW/K)	0.100 (+/- 0.005)	0.097 (+/- 0.004)
C_i (kWh/K)	4.91 (+/- 0.41)	4.67 (+/- 0.30)
$\mathrm{A_W}$ (m^2)	4.89 (+/- 0.48)	4.48 (+/- 0.36)

It was observed that, for this model structure, sample times of 5 and 15 minutes resulted in better prediction performance on validation data, compared to sample times of 30 and 60 minutes.

In case further study is of interest (e.g. over longer periods), a detailed dynamical model of the building in the software package IDA ICE[27] is available at NTNU. This model was calibrated with respect to indoor and operative temperature in heating conditions. For further information on this matter, please contact John Clauß (john.clauss@ntnu.no).

[26] In fact, the operative temperature '*To*' would be more appropriate to represent such a lumped temperature. Its usage is therefore recommended in further investigations.

[27] More information on the software package is available on http://equa.se/en/ida-ice .