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Towards feasible and credible building modelling reflecting the operational energy use and indoor environment – Nordic climate case study

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ABSTRACT

Credible building modelling is essential to the building energy certification and building renovation towards better energy performance and indoor climate. The primary objective of this work is to assess the consequences related to the level of effort necessary to simulate the building geometry and its facilities and to guide practitioners in building modelling by providing insights about the model simplification consequences both for the energy performance and comfort. This work focuses on the sensitivity of model geometry simplification and heating system and the influence of these on the energy and thermal comfort KPIs in standard simulation conditions. Moreover, the study presents models verification towards operational performance, investigates the complexity of adapted simulation conditions, e.g., heating setpoint, actual people load on the model credibility comparing to monitored data. The sensitivity study main conclusion is that there are relatively small differences in heating demand among models with different zoning methods of geometries, while the implementation of detailed heating systems in the simulation has a more noticeable effect on the results of all output KPIs. The Model verification activity main conclusion is that adapted people's load can improve the model accuracy. Models with detailed geometry, lead to more accurate results when the heating set-point in the model is defined as monitored data per apartment. For dwellings with a limited number of IAQ measured points, use of the standard set-point is advised instead of monitored. For the apartments with sufficient IAQ sensors, adapted heating setpoint and people load can significantly improve the model predictions.

1. Introduction

For the last 2–3 decades, energy use in buildings has become the focus of attention worldwide. The urbanization growth and increase in population together with expectations for higher Indoor Environment Quality (IEQ) is expected to result in an energy use increase in buildings. However, according to the report [1], buildings will be decarbonized by more than 98 % in the nearly zero energy building (NZEB) scenario by 2050 year and this shall be achieved by the deployment of energy efficiency measures, fuel switch (electrification), and behavioral changes. In that vision, 50 % of emission reduction comes from the heating of buildings. Contrary to that vision, until present emission from buildings has risen 0.5 % each year since 2010. The outlook for 2030 and 2050 and the decarbonization of buildings is highly based on political decisions that are reflected through regulations and directives that define NZEB targets and compliance schemes.

The reality shows that there are many buildings that do not meet the energy efficiency goals and this tendency is most evident for NZEBs [2–5], but also considers renovated buildings. Common for [2–5] is that energy-efficient buildings, labeled A and that fall into NZEB strategy, use more energy and energy-inefficient buildings use less energy than expected. The difference between actual/measured and predicted/simulated energy use is called building energy performance gap (BEPG) and as stated in the review on BEPG by [6] the subject was reported in more than 100 publications between 2013 and 2018 year. The reasons for the bursting number of BEPG cases should be searched in the last two decades of (1) tightening policies and building regulations towards decreasing energy, (2) unrealistic compliance calculations, and (3) multiple operational causes. For the first, for example, in Denmark, between 2005–2023 year, the building regulations were updated 5 times

Abbreviations: ACM, Adaptive Comfort Model; AHU, Air Handling Unit; BEPG, Building Energy Performance Gap; EPC, Energy Performance Certificate; EPB(D), Energy Performance of Building (Directive); HVAC, Heating Ventilation Air Conditioning; IEQ, Indoor Environment Quality; KPI, Key Performance Indicator; NTU, Number of Transfer Units; NZEB, Nearly Zero Energy Building; PMV, Predicted Mean Vote.

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and brought primary theoretical energy use for building operation from approximately 110 to 25 [kWh/m^{2}year]. The minimum requirements for the energy performance of new and existing buildings and national effort towards NZEBs is enforced by Energy Performance of Building Directive (EPBD) [7] and its revision [8] from European Member States. Therefore, tendencies that are observed in the Danish Building Regulations can be observed in all Member States. For the second, regarding the compliance calculations, for example, in Denmark, these are based on monthly and quasi-stationary building models [9]. The heating and cooling demand is based on EN ISO 52016–1 [10]. Heat production and losses from installations are based on relevant European standards. In the monthly calculations, the entire building is modeled as one zone with the same average indoor climate and distribution of solar gains from south to north-facing rooms. The heat capacity of internal walls and floors is treated as a single node with a heat capacity equal to that of the internal walls and floors also considering the utilization factor of thermal mass that takes into account the ratio of heat gains and losses. Moreover, static and quasi-stationary and monthly compliance calculations are rather common for the Member States as indicated for Italy, Denmark and Switzerland in [11]. For the third, in the operational stage, user behavior together with technical issues are repeatedly reported to be the dominant factor for the building energy performance. The behavioral aspect is well researched and acknowledged in the literature [12–14] which is not only limited to building's occupants but also as highlighted in [6] concerns all energy-related stakeholders, such as designers and energy managers. Nevertheless, occupants have a great impact on building energy performance as they control heating set points, ventilation, lighting, and the use of electrical appliances [15]. As stated in [5], understanding how inhabitants use energy is required to improve energy conservation actions and to support policymakers in setting realistic energy performance targets. On the other hand, the collection of all occupant behavior data is resource-demanding, costly, and intrusive. Therefore, one needs to be strategic about which parameters should be known and can support the understanding of the actual energy and indoor climate performance of the building. This information together with suitable modelling tools that can accommodate these inputs is also essential to set proper assumptions for modelling and computation of credible energy renovation roadmaps, which often are missing [16,17] and lead to mistrust in energy performance assessment and faulty expectations from renovations. The study presented in this paper is about finding a compromise of effort and a credible outcome of modelling that can be achieved by shifting from the use of standard assumptions for modelling towards the use of more realistic, namely "adapted" conditions, that were in more detail elaborated in [18], that can be gathered from monitoring and inspections and that can help to reflect the actual use of the particular building. The authors of this paper wish to highlight that this activity should not be mistaken with the sensitivity-based calibration of the model in which input parameters are varied within ranges and do not necessarily reflect the actual state of the building and its use.

For the last 20 years, energy performance certificates (EPCs) have proven their place for labelling the energy performance of buildings and all EU Member States have adopted to the Energy Performance of Building Directive (EPBD). Consequently, calculation tools for EPCs have been developed and begun to be applied to rate buildings. Even though there is significant scepticism about the reliability of the results which is often questioned in numerous publications [19–21], it can be seen that these relatively simple and fast computing modelling tools and calculation schemes have infiltrated to the extent where the practitioners begun to use them not only as energy certification tools for buildings, but as well as design tools and support tools to determine energy renovation actions. One of the major shortcomings of labelling calculation tools is their simplicity and therefore limited ability to capture the dynamic conditions of building operation, mainly because those tools are based on quasi steady-state, often monthly, calculations. One could claim that labelling's purpose is primarily to compare energy performance between buildings and therefore boundary conditions and simulations could be simplified. On the other hand, even if labelling is about the comparison of buildings, it is still valid whether comparison should be based on more realistic assumptions and by using methods that in a better manner could capture the dynamic building nature or not. Moreover, the responsibility of labelling is also to provide energy renovation recommendations and here credible energy predictions are of key importance. Currently, the EPBD revision is under preparation and the draft version includes an indication that future EPC calculations are expected to be required on hourly or sub-hourly frequency. This new requirement has substantial importance and indicates that a shift from steady-state monthly calculations to hourly (possibly dynamic) calculations is highly possible soon. This shift opens new possibilities for modelling while at the same time creates challenges that need to be researched and consequences that need to be better understood.

The ground for the shifting from steady-state to dynamic modelling is already laid in the set of EN ISO 52000 standard family that received a mandate M/480 [22] from the European Commission to support the updated Energy Performance of Building Directive (EPBD) EPBD:2018 [8]. The family of EPB standards is well described in [12] in which authors explained EN ISO 52000 holistic approach that addresses all types of energy use in buildings, outdoor boundary conditions, indoor climate requirements, and the dynamic interplay and complexity of all these aspects. What is more, [23] highlights the need for dynamic calculations to be able to properly quantify the energy performance of buildings and building systems (solar blinds, thermostats, needs, occupation, accumulation, mechanical ventilation, night-time free-cooling-ventilation, weekend operation, heat pump, solar panels) which all dynamically interplay with the outdoor condition. Among five primary EPB standards, special attention and relevance to the work presented in this paper should be paid to EN ISO 52016–1 [10]. In EN ISO 52016–1 can be found, among others, a general description of the hourly calculation method, input lists for geometry, thermal properties of building and elements, condition of use of technical building systems, climatic input data, and internal gains. Still, experiences towards dynamic modelling concerning energy performance assessment/certification are missing.

Shift from steady-state calculation to dynamic modelling (hourly calculation) is correlated with the increase of the modelling complexity. Consequently, modelling effort increases in time use and costs. As stated in [24] the modelling of the geometry requires almost 50 % of the total time spent on energy analysis. Therefore, a simplification of the building's geometry is required, otherwise, the simulation will have many unnecessary inputs requiring both modelling and computational time. Hence, to secure the adoption of dynamic/hourly calculation, an effort needs to be done to balance models' credibility and model simplification.

This topic has been studied and presented in several publications already. As stated in [25], three common simplifications can be identified: i) modelling a typical floor and multiplying the calculated load by the number of floors, ii) simplification of fenestration (many windows into one), iii) reduction of thermal zones and building internal thermal mass. For instance, in [26] predictions based on detailed models (every room as a zone) were compared to those from simplified models (each floor as a single zone) for five types of UK residential buildings. This study showed a mean absolute average error of 10.6 % for annual heating demand and 8.6 % for CO2 total emission while simulation computing cost was reduced by 30 % on average. The authors concluded that the impact of model simplification was low on heating demand and CO2 emission outcomes. On one hand, the error in range of 10 % is often acceptable for simulations, while on the other hand, it is often forgotten that the error compounds over the lifetime of the building operation and can result in significant BEPG. As a result, even very significant savings on the one-time simulation effort become insignificant in this context. What is more, the overheating issue was discovered to be more complicated, and the issue was highlighted for further research. Authors of [27] assessed different simplifications of model constructions, among others zoning and building obstructions. It found that strong simplifications did not significantly influence the results. Another study presented in [28] for residential buildings in the UK considered the simplification of thermal zones reduction to one per floor and one per entire house. The annual heating demand was underestimated by 17 % and 26 % respectively. In [29] authors studied the consequences of model simplification, such as the reduction of thermal zones, internal walls, and shading removal. Results showed that shading exclusion in south-facing zones must not be carried out due to significant output influence. There exist more studies focusing on the model geometry simplification, however, the shortcoming is that there is a research gap and not sufficient studies on different approaches to model building facilities, such as ventilation and/or heating and not in connection with the different thermal zoning detail levels. Moreover, as stated in [24] impact of modelling simplification on thermal comfort and indoor environment is usually not investigated.

To conclude, there is an urgent need to become better at realizing the promised energy efficiency in buildings. The building's actual energy and comfort performance can be directly determined from the operational data when this is available. However, to provide improvement solutions, e.g., reliable renovation and operational plans and to better understand the consequences of these, credible modelling is required. This paper's activities and objectives are split into two studies. In the first study, "Study 1 – Model simplification", the objective is to contribute with the knowledge and better understanding in general of possibilities and consequences of modelling simplifications both concerning building facilities (heating system) and thermal zoning of geometries under standard simulation conditions. This work adopted three methods to simulate the heating system in combination with a mechanical ventilation system that is present in the case building and 5 levels of complexity of thermal zoning of the geometry, from room level as a thermal zone (most detailed) up to the whole staircase as one thermal zone (most simple). The outcome of building modelling of energy, thermal comfort and indoor air quality are defined and compared by KPIs for the heating and non-heating period. This work holds particular significance if an update of EPBD will require dynamic modelling for building performance and certification and for feasible and credible modelling in general.

The objective of the second study that is presented in the paper, "Study 2 – Model verification towards operational performance", is to identify the potential and limits of the use of adapted conditions, rather than standard conditions of use in the building model. The criteria to select or not select input type for adapted condition was dictated by the ease of availability of the input and uncertainty. In the proposed approach standard weather conditions were substituted with actual measured weather conditions, standard heating set points with the ones determined from thermal indoor environment monitoring, standard people load with the actual ones determined from a simple site inspection. Adapted conditions are more in detailed elaborated in section 2.3. in this paper. The expected outcome is the recommendation to achieve the credible simulation model under moderate effort for monitoring and collection of actual conditions of use and operation. The adapted conditions are applied to the building models with 5 levels of geometry complexity and 3 levels of building facility complexity. The BEPG is analyzed for all three levels compared to available monitored data for IEQ and energy, e.g. space heating energy and/or CO2 at the staircase level, apartment level, and room level respectively.

It should be noted that the ventilation system in the case building is balanced ventilation with heat recovery. The ventilation system is so specific that it cannot be simplified by ideal loads HVAC system and zone ventilation or design outdoor air because neither of them includes the heat recovery system. For this reason, the complexity of the ventilation system is not studied in this work.

This paper consists of a methodology section that presents the monitoring of the case study building, a modelling approach with an overview of the complexity levels and model names, an assessment methodology for "Study 1″ and "Study 2″ together with the assessment domain addressed by different KPIs. The paper continues with the results section, including sections for "Study 1″ and "Study 2," with subconclusions for each study respectively. The manuscript is summarized with a discussion and conclusion for the work presented and carried out, and it concludes with acknowledgment.

2. Method

2.1. Monitored site

The case building used in this study is a residential multi-apartment building that was built in 1972 and renovated in 2011. The total heated area is 4756 m^2. The major orientation of the building is north/south. The building is far away from other buildings from the south, east and west orientations, and not influenced by the shadow of other buildings. The building has 4 floors, 3 staircases, 24 apartments in total, 8 apartments on each staircase and 2 apartments per floor. There are two types of apartments in the whole staircase that are very similar to each other but slightly different in size. All apartments on the one side are each 136 m^2 and has 1 living room, 3 bedrooms, a kitchen, 2 bathrooms, a balcony, and an entrance; each apartment on the other side is 110 m2 and has 1 living room, 2 bedrooms, a kitchen, a bathroom, a balcony, and an entrance. The overview of the monitored apartments and sensors is shown in Fig. 1.

The geometry of the monitored building is shown in Fig. 3(a). The west, north, and south façades of the staircase are external walls and are exposed to the sun and wind. The east and west façade of the model are made of internal walls adjacent to a staircase of the same kind. The balcony and corridor are not conditioned, thus are separated from the building zones. The details of the envelope elements construction, materials composition and thermal properties are shown in Table 6 in Appendix.

The ventilation system is a balanced ventilation with heat recovery. The constant air volume meets the requirements of the building regulations with 15 l / s from the bath and 20 l / s from the kitchen. The building's heating system is composed of water-based radiators and is connected to district heating. Solar curtains are installed by individual residents in each apartment.

The overview of the coverage of the monitoring in the staircase is shown in Fig. 1. In the figure, the 8 cells represent the 8 apartments in the case staircase. In total, tenants of 4 apartments agreed to participate on the voluntary basis in the monitoring campaign. Each apartment is equipped with a heat meter for space heating, as shown in Fig. 1(a). The number of rooms and occupants in each apartment is shown in Fig. 1(b). The monitored rooms for CO2 and temperature in each apartment are shown in Fig. 1(c) and Fig. 1(d).

The measurement campaign consisted of a set of measurements that were for all measured parameters aggregated to hourly values. At the apartment level space heating (SH) was measured by already installed heat meters from Kamstrup. At the room level, sensors were installed to measure indoor climate conditions. For that two types of sensors were used from Lansen, sensor LAN-WMBUS-E2-CO2 that can measure temperature humidity and CO2 and sensor LAN-WMBBUS-CX-T that can measure temperature. To be accepted by the tenants, all sensors that were used are wireless and battery driven. Fig. 2 illustrates the layout of the apartments with the locations of the sensors and meters. After installations were carried out, it was evaluated that the tenants have accepted the new monitoring equipment in their apartments as there were no measurement incidents observed over the course of the monitoring campaign that spans from September 23, 2021, to June 18, 2023.

Individual interviews were conducted with tenants residing in the monitored apartments in November 2021. During these interviews, tenants were asked to provide detailed information about several aspects of their occupancy. This included the number and age of

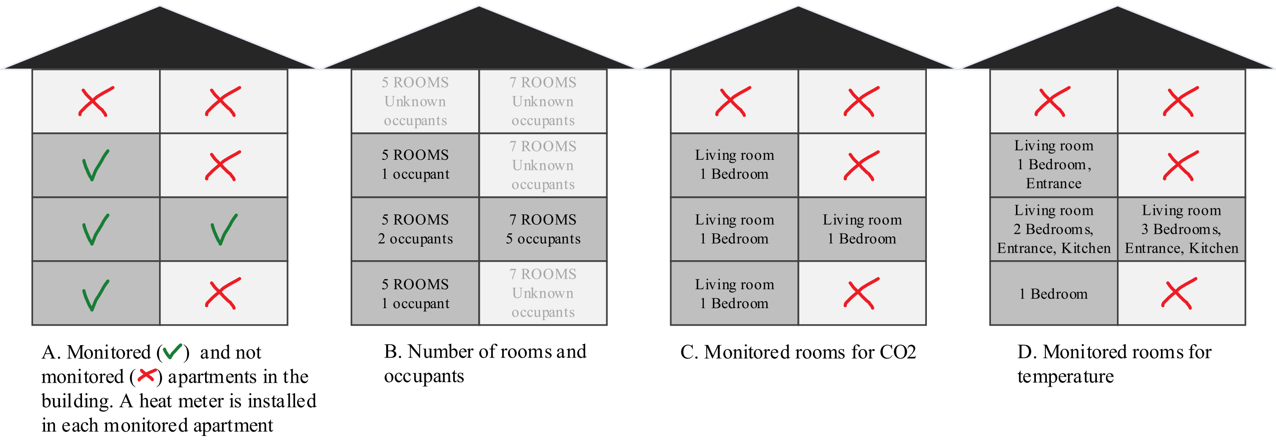


Fig. 1. The overview of the monitoring availability in the analyzed staircase.

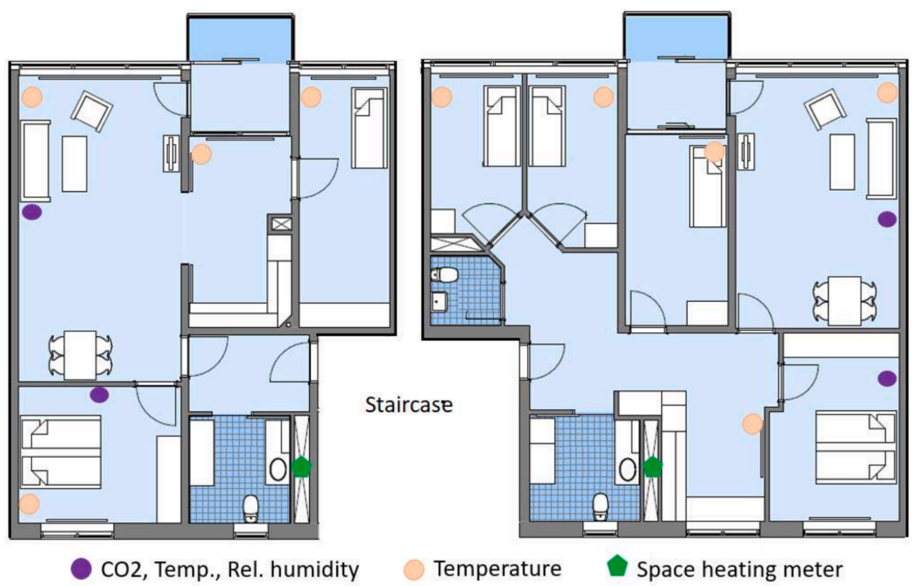


Fig. 2. The overview of the sensors and meters location in the apartments.

occupants, employment status, daily routines such as remote work or studies, weekly schedules for being at home, ventilation and shading practices, preferred room temperatures, and factors influencing their interaction with the thermostat, window opening and curtains. The response in terms of shading operation and occupancy schedule was ambiguous and therefore was not considered in this study. The interviews were facilitated by an engineer able to ask tenants to elaborate answers if needed. All tenants actively participated in the interviews, which lasted approximately 30 min each and were conducted over the phone. It's worth noting that the tenants were familiar with the interviewer and the questions were standardized beforehand.

2.2. Building models

The building simulation software EnergyPlus is used to build the models with different levels of complexity in terms of building geometry, building heating system and adapted running conditions. The U values of the constructions of the geometry are shown in Table 6 in Appendixes. The models consider detailed composition of all envelope elements that was determined based on available technical documentation and building inspections.

In total 15 models have been built, with 3 levels of heating system complexity and 5 levels of zoning complexity of the building geometry, which are shown in Table 1. It must be mentioned that the building described in this study comprises of several staircases with 8 apartments associated to each staircase (2 apartment per each floor). In this work, monitoring was confined to a restricted number of apartments (as illustrated in Fig. 1), representing only a section of the building. Consequently, the modelling and simulation efforts pertain solely to this

Table 1
The model complexity levels of the simulated staircase.

	Complexity level	
Heating	1	Electric convector
	2	Electric radiator
	3	Water-based radiator (district heating)
Thermal zoning	z1	One zone per staircase showing in Fig. 3(b)
	z2	Two zones per staircase (divide the staircase by south zone and north zone) showing in Fig. 3(c)
	z3	One zone per apartment showing in Fig. 3(d)
	z4	Two zones per apartment (south rooms as one zone, north rooms as another zone) showing in Fig. 3(e)
	z5	One room as a zone showing in Fig. 3(f)

specific section, encompassing one staircase and comprising eight apartments. Therefore, when we mention a "staircase" in this publication, it refers to a section of the building under analysis. This section includes both monitored and unmonitored apartments.

The ventilation system in the building is balanced ventilation with heat recovery. The air loop AHU is used for the whole staircase, which consists of an outdoor air mixer, a supply fan, a return fan, and a heat recovery unit. The fans are constant air volume fans. The heat recovery unit is an air-to-air heat exchanger using effectiveness relationships. The sensible effectiveness is assumed to be 0.75, and the latent effectiveness is 0.

The actual heating system in the building is from the district heating, using water-based radiators. The modelling of heating system considers three modelling approaches, see Table 1. Electric convector provides heating to the zone by convection; while electric radiator provides heating to the zone by convection and radiation, taking account of the radiation factor to different surfaces of the zone. The radiation fraction is 0.3. The efficiency of both the electric convector and electric radiator are set as 1. The water-based radiator system provides heating to the zone by water radiator with the same radiation factor of 0.3 to the internal surfaces. In addition, it accounts for the pipe model with transport delay. The heat transfer to the indoor, outdoor and underground environment is not included in the calculations, as in this simulation, the pipes are set as adiabatic. Moreover, a hot water loop supply pump is used to pump the hot water in the hot water loop of the space heating distribution system. Its energy and efficiency are not included in the energy calculation. The main difference of the electric radiator and the water-based radiator is that for electric radiator, the convective gains from the unit are evenly spread throughout the space thus having an immediate impact on the zone air heat balance; while for water-based radiator, the model employs an effectiveness-NTU heat exchanger method during simulation to determine the heat transfer between the water and zone air [30]. There is no active cooling system used in the case building.

The geometry complexity of 5 zoning approaches are shown in Fig. 3. Level 1 is the simple model, with the whole building case as a thermal zone (except the staircase and balcony which are simulated as non-heated space) and all the internal partitions are added as additional thermal mass; level 5 is the most detailed model, with each room as a separate thermal zone (except the staircase and balcony which are simulated as non-heated space). Levels 2–4 are between the simple and detailed models. The names of the models are defined in Table 2.

The computing speed is different for models with different levels of complexity. A computer with Intel® Core™ i7-10610U processor and 32 GB RAM was used for the simulation. At the timestep of 6 (calculating every 10 min), the simple model 1-z1 takes 0.23 min to run; while the most complicated model 3-z5 takes 12.6 min to run, which is 54 times more time compared to the simple model.

2.3. *The assessment methodology*

The objective of this paper is to investigate the decrease of modelling effort while securing the feasible model development and credible modelling in terms of results of energy and indoor air quality. To support the good transparency of this study, the investigation and assessment procedure including the presentation of results and conclusions were divided into two studies, "Study 1" and "Study 2", as shown in Fig. 4. "Study 1" focuses on the sensitivity of model geometry simplification and heating system and the influence of these on the energy and thermal comfort KPIs considering standard simulation conditions; while study 2 investigates the complexity of adapted simulation conditions, e.g., heating setpoint, people load on the model credibility comparing to monitored data. Results for both studies are separately presented and evaluated in sections "Results: Study–1 – Model simplification" and "Results: Study 2 – Model verification towards operational

Table 2
Definition of model names.

Model name: A-zB	Example of model name: 1–z3
A- Heating complexity level (Table 1) B- Zoning complexity level (Table 1)	1-Electric convector (Table 1) 3-One zone per apartment (Table 1)

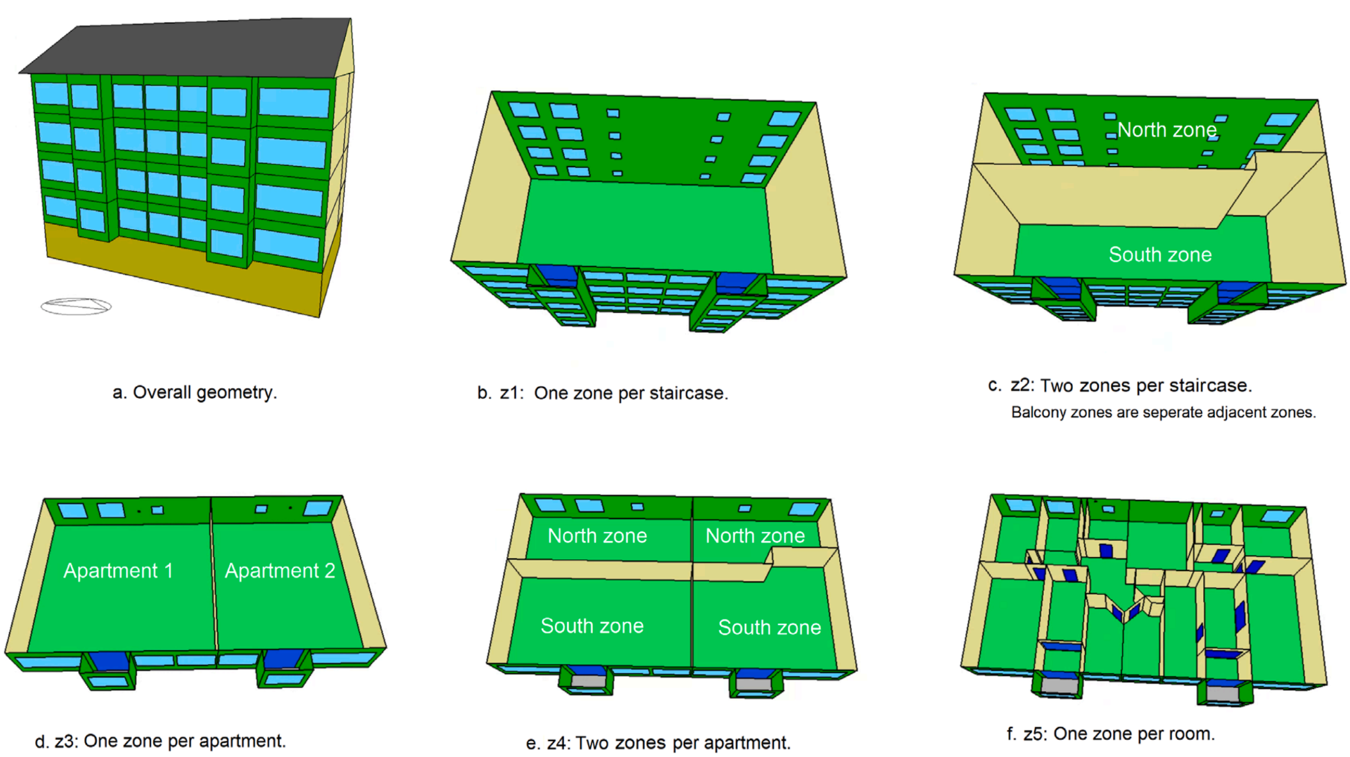


Fig. 3. The building geometry (a) and model simplification of geometry: 5 zoning methods (b-f).

Table 3
The people load based on the interview of tenants in 4 apartments in the staircase.

	People load based on the interview
Apartment 1	136 m^2/5 person = 27.2 m^2/person
Apartment 2	110 m^2/2 person = 55 m^2/person
Apartment 3	110 m^2/person
Apartment 4	110 m^2/person
All other 4 apartments	Average of above 4 apartments, 75.55 m^2/person

performance" and followed by individual conclusions. Fig. 4 check-boxes, show that the evaluation of results in Study 1 is conducted solely at the staircase level. This implies that even for models with high detail (e.g., model 3z5), all assessment parameters were aggregated to the staircase level. In Study 2, however, the assessment is more nuanced, and it is performed at both room and apartment level for those models that have a sufficient geometry resolution.

The influence of thermal zoning complexity and building system simplification is evaluated by comparing all the KPIs that are elaborated in section 2.4 of this paper.

2.3.1. Assessment approach – "Study 1": Model simplification

In "Study 1", in total 15 models that cover 5 levels of complexity of thermal zoning and 3 levels of complexity of heating system modelling is investigated with standard simulation conditions (Simulation_ID A0 in Table 4). The internal loads and schedules are taken from DS EN 16798–1 standard for dwellings [31], including the occupants, appliances, and lighting.

Results analysis is carried out only at staircase level and results are aggregated over heated and non-heated season. Analysis of the results exploit KPIs that were elaborated in Table 5. The results evaluation is carried out in the relative manner by comparing only results of modelling-to-modelling touching upon qualitative and quantitative evaluation of obtained results. Comparison of modelling results with respect to operational measured performance is not carried out.

2.3.2. Assessment approach – Study 2: "Modelling towards operational performance"

The procedure for "Study 2" is graphically presented in Fig. 4. The procedure in "Study 2" is very similar to "Study 1" with two major differences. The first major difference is that standard simulation conditions are gradually replaced by identified adapted conditions of use that reflect more actual use of the building, its loads, setpoints and boundary condition, as presented in Table 4. The second major difference is that results are analyzed at the different spatial levels, namely staircase, apartment and room level, as presented in Fig. 3.

The research study places significant emphasis on the utilization of adapted input conditions rather than standard ones, with the primary objective of quantitatively evaluating their significance and determining the optimal priority for their consideration. This approach is crucial in the context of minimizing the (BEPG) most effectively and in turn, achieving models that accurately mirror the real-world operational performance of the building. This study addresses the following adapted conditions of use that were incorporated in the modelling: i)

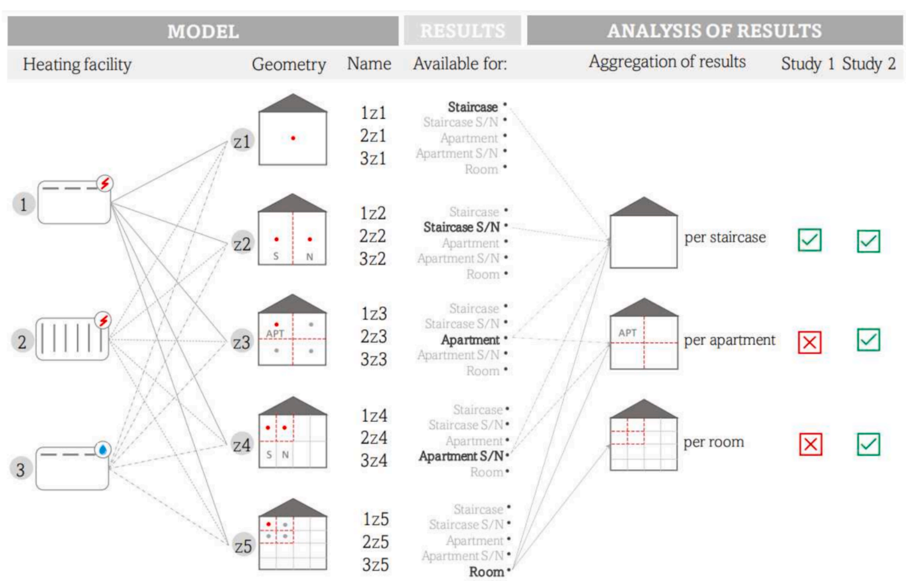


Fig. 4. The assessment methodology. Heating facility and model geometry are numbered in accordance with Table 1.

Table 4
The simulation conditions of different simulation scenarios.

	Simulation_ID	Weather	Occupant loads	Occupant schedules	Heating setpoint
Standard	A0	Typical Meteorological Year Data	Standard people loads	Standard schedules	Standard setpoint
Adapted	A	Weather station: real weather data	Standard people loads	Standard schedules	Staircase average
	B	Weather station: real weather data	Adapted people load per apartment (number of people per apartment/apartment area)	Standard schedules	apartment average
	C	Weather station: real weather data	Adapted people load per apartment (number of people per apartment/apartment area)	Standard schedules	Room average
	D	Weather station: real weather data	Adapted people load per apartment	Bedroom: 22–7; living room: 7–22	Apartment average

*Standard people load, standard schedules and standard setpoint can be found in [31].

Table 5
The KPIs used to assess the energy performance, comfort and IAQ of each model.

KPI domain	KPI name	Explanation
Heating season		
Energy	Heating	Heating demand of the building, yearly/ weekly/daily values, calculated only for the heating season. The non-heating season is defined to start when the heating load of the staircase is less than 10 % of the maximum heating load for not less than 3 consecutive days. When the non-heating season is identified, then the rest of the year is accounted for as the heating season.
	Free_running_h (free-running hours)	Calculated as 1-hour intervals, when the heating system does not call for heat in the heating season. It is calculated for the whole building, thus in multizone models, it is expected that none of the zones call for heating. Note that this parameter is not representative of the actual free-running potential in a mechanically heated building.
Thermal comfort	H_26_heating	Hours of zone operative temperature out of range ($T_{avg} < 20$ °C or $T_{avg} > 26$ °C, where T_{avg} is the volume average temperature of the zone.
	PMV cat1_heating	Hours of zone thermal comfort in the category I according to Fanger model ((−0.2) <= PMV <= 0.2) [31]
	PMV cat2_heating	Hours of zone thermal comfort in the category II according to Fanger model ((−0.5) <= PMV <= 0.5) [31]
	PMV cat3_heating	Hours of zone thermal comfort in the category III according to Fanger model ((−0.7) <= PMV <= 0.7) [31]
	PMV out_heating	Hours of PMV out of range (PMV >= 0.7 or PMV <= (−0.7)) [31]
IAQ	CO2 > 900_heating	Hours of CO2 concentration above 900 ppm. For multizone models, CO2 concentration for the whole building is defined as a volume-averaged value for all zones.
	CO2 < 600_heating	Hours of CO2 concentration below 600 ppm. For multizone models, CO2 concentration for the whole building is defined as a volume-averaged value for all zones.
Non-heating season		
Thermal comfort	H_26	Hours of zone operative temperature out of range (Tavg < 20 °C or Tavg > 26 °C, where Tavg is the volume average temperature of the zone)).
	ACM cat1	Hours of zone thermal comfort in category I according to adaptive thermal comfort model, which is defined by Tavg >= 0.33To + 18.8–3 and Tavg <= 0.33To + 18.8 + 2, where Tavg is the volume average temperature of the zone, and To is the running mean outdoor air temperature [31]
	ACM cat2	Hours of zone thermal comfort in category II, which is defined by Tavg >= 0.33To + 18.8–4 and Tavg <= 0.33To + 18.8 + 3 [31]
	ACM cat3	Hours of zone thermal comfort in category III, which is defined by Tavg >= 0.33To + 18.8–5 and Tavg <= 0.33To + 18.8 + 4 [31]
	ACM cat_out	Hours of zone thermal comfort out of the category III, which is defined by Tavg < 0.33To + 18.8–5 or Tavg > 0.33To + 18.8 + 4 [31]
IAQ	CO2 > 900	Hours of CO2 concentration above 900 ppm.
	CO2 < 600	Hours of CO2 concentration below 600 ppm.

temperatures for heating setpoints derived from monitoring of the case study building, ii) real weather data from nearby meteorological station, iii) real occupants loads.

(i) Heating setpoints derived from monitoring: the monitored indoor temperatures for all measured rooms in the case study building are shown in Figure 15 in Appendix. For models with zoning level 5 (each room as a thermal zone, e.g. z5), 15 rooms have been monitored for the whole year, and those data is used as heating setpoint for the individual room; while for the rest of the rooms without temperature sensors, the average of the 15 measurements is used as the heating setpoint. For models with zoning level 4 (each apartment is divided into 2 thermal zones: south zone and north zone, e.g. z4), the heating setpoint of the south zone is the average of the monitored rooms located in the south side of the apartment, which are living room, bedroom2 and bedroom3; while the heating setpoint of the north zone is the average of the monitored rooms located in the north side of the apartment, which are bedroom1 and entrance. For models with zoning level 3 (each apartment as a thermal zone, e.g. z3), the average monitored temperature in each apartment is used for the 4 apartments, while the rest apartments without measuring sensors use the average of the 15 measurements as heating setpoint. For models with zoning level 2 (the staircase is divided into 2 thermal zones, e.g. z2), the heating setpoint of the south zone is the average of the monitored rooms located in the south side of the entire staircase, which are all the living rooms, bedroom2 and bedroom3; while the heating setpoint of the north zone is the average of the monitored rooms located in the north side of the entire staircase, which are bedroom1 and entrance. For models with zoning level 1 (each apartment as a thermal zone, e.g. z1), the average of the 15 measurements is set as heating setpoint for the staircase zone.

(ii) Real weather data from meteorological station: A weather station is located 11 km away from the building site and measures the weather data, which is used for the building simulation with adapted conditions. The parameters used in the simulation are: dry bulb temperature [^{o}C], relative humidity [%], atmospheric pressure [Pa], total sky cover [-], wind speed [m/s], wind direction [deg], and global horizontal radiation [W/m^2].

(iii) Real occupants loads: Quick site inspection and tenants interview allowed to collect information about number of occupants per apartment that allowed to determine actual people load. The estimate of presence, occupied/non-occupied was also collected but did not allow to derive credible occupation schedules and therefore standard occupant schedules from DS EN 16798–1 [31] were used. Still, one simulation case (Simulation_ID: D in Table 4) was developed making assumption that there is day occupancy of living room and night occupancy of bedrooms.

For models with geometry level z3 to z5, the people loads are set as in Table 3. For models z4 and z5 people load is calcualed as uniformly distrubuted over floor area and then assigned to each thermal zone respecting its floor area. For models with geometry level z1 and z2, the people load is set as the average of the 4 apartments, which is 75.55 m^2/person.

Solar shading: although inspection identified presence of manual shading systems these were decided not to be included in the modelling studies because of unknown operation routines.

2.4. Assessment domains

A number of suitable KPIs have been identified to fully exploit a wide range of outcomes from the dynamic models. The domains of interest are energy performance, thermal comfort and IAQ. The model results are evaluated and compared using different KPIs for heating season and non-heating season respectively. The KPIs are listed in Table 5.

3. Results: "Study 1": Model simplification

In this chapter, in comparative manner, are presented annually aggregated results of the model simplification. The model simplification study considers variation of 5 levels of complexity of thermal zoning and 3 levels of complexity of heating system modelling using standard assumption for weather, internal loads and set points. The evaluation of thermal zoning complexity and building system simplification is evaluated by comparing all the KPIs that are elaborated in section 2.4 of this paper, for both heating season and non-heating season.

3.1. Heating season

The annual results from models for the heating season are shown in Fig. 5. It shows a deviation in heating demand among the models. The group of lowest heating demand, approximately 34 ($\pm$1) kWh/m^2, belongs to models simulated with district heating water radiator system (models 3-z1 to 3-z5). Then after the middle results belong to models simulated with electric radiator (models 2-z1 to 2-z5) and slightly higher results belong to models simulated with electric convector (models 1-z1 to 1-z5). Within the same heating system, the influence of thermal zoning simplification has limited impact on the results. Moreover, for the models with the same facility, the 5-zone models have slightly higher heating demand, while other zoning approaches have better agreement with each other. When comparing different facility modelling methods, detailed heating system (water-based radiator system, 3-z1 – 3-z5) modelling methods have the lowest heating demand compared to two other heating system modelling methods. The thermal comfort for PMV cat1 and PMV cat2 are in good agreement among all models, while PMV cat3 and PMV_out indicate more significant differences. Overventilation (CO_2 <600) and free-running hours have big deviations among the models, while underventilation hours (CO_2 > 900) are at zero for all the models.

3.2. Non-heating season

Fig. 6 shows the yearly modelling results of all the models in the non-heating season. Since there is no heating used in the summer and the ventilation system is modelled the same for all cases and no cooling is present in the building, the only reason for the differences in the results between the models is the zoning complexity. It shows that thermal comfort (CEN-values and H_26) vary among the models, as well as the overventilation (CO_2 <600). Zoning 1 (one zone per staircase) and zoning 5 (one zone per room) seem to have a bigger influence on the air quality (CO_2 <600) than other zoning methods.

3.3. Conclusions of "Study 1–" – model simplification

The presented analysis is valid for the building with balanced mechanical ventilation with heat recovery. However, exploring model design choices related to ventilation is not possible due to limitations in modelling approaches for this specific system in the simulation tool that was selected to carry out the study, namely EnergyPlus. Hence, this work primarily focuses on considerations related to the heating system set-up and thermal zone simplification. As illustrated in Fig. 5, it becomes evident that the building's space heating energy demand displays a relatively low sensitivity to variations in the model's geometry with different zoning methods. The relative differences between the outcomes of simpler (one zone) and more complex (multizone) models are relatively small, with an average deviation of only 3 % across five zoning approaches. However, it is important to note that the sensitivity lies in how the heating system is defined within the geometric model. It is worth noting that detailed heating and ventilation models can still influence the evaluation of heating demand.

Nonetheless, the findings indicate that the thermal zoning plays a

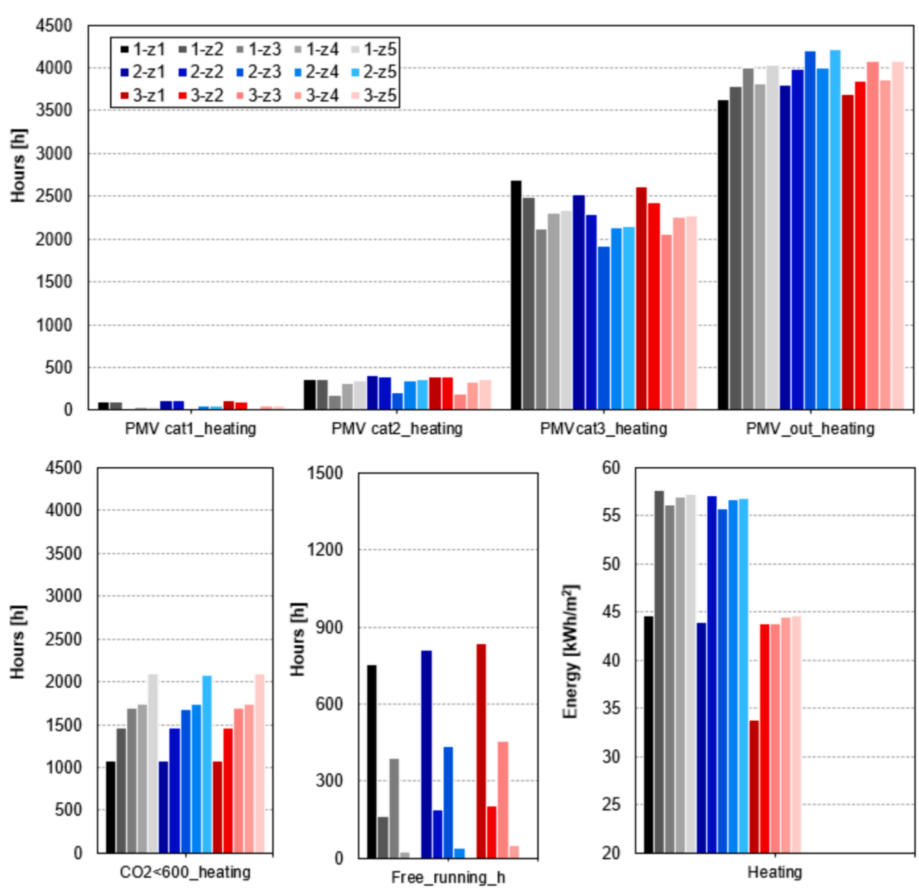


Fig. 5. Annual calculated KPIs for heating season for all the models. Note: CO_2 > 900_heating and H_26_heating is not included in the figure, having a value of zero.

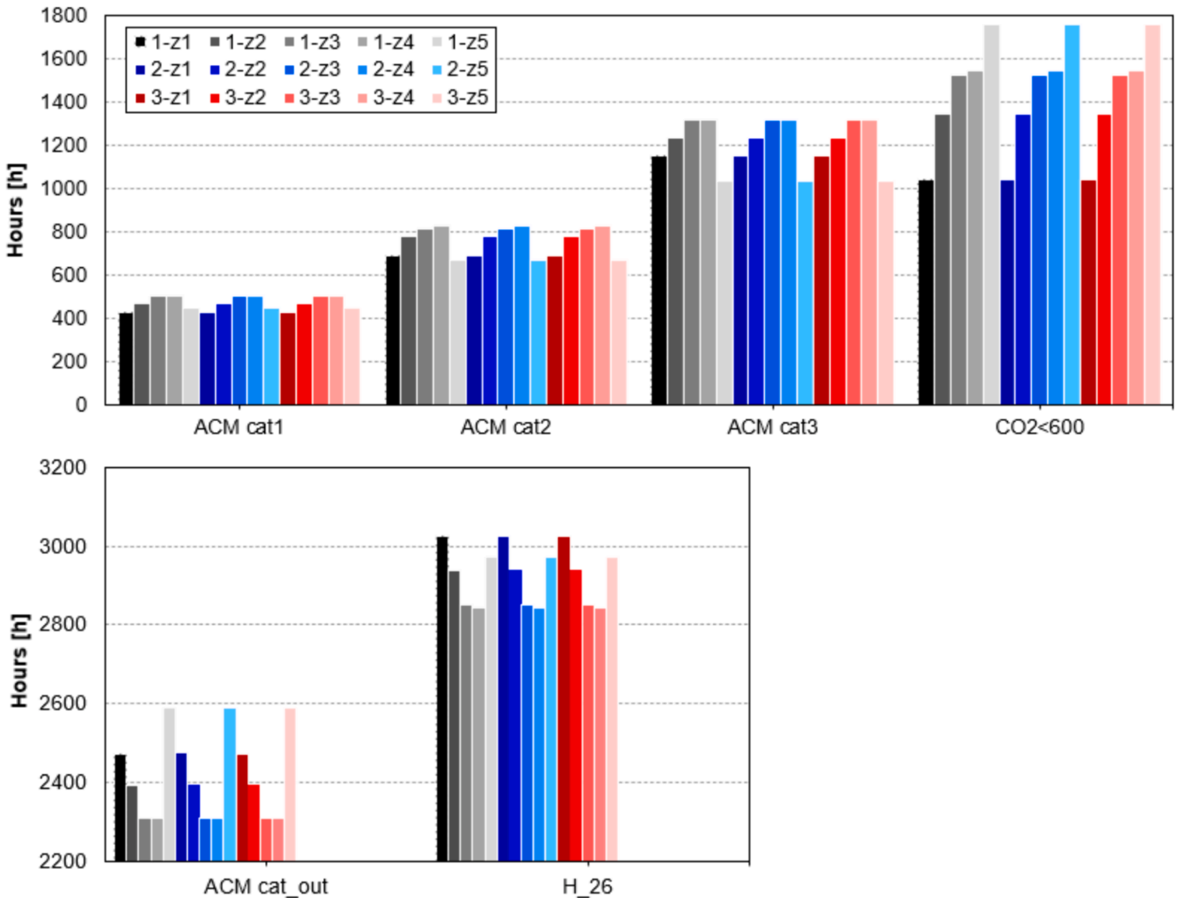


Fig. 6. Annual calculated KPIs for non-heating season for all the models. Note: CO2 > 900 with zero-value is not included in the figure.

substantial role in simulating non-energy related KPIs. For non-energy related KPIs, in both heating and non-heating seasons they are all sensitive to the thermal zoning method, while in heating season facility modelling demonstrates certain importance, but less pronounced compared to zoning of the models. In non-heating season no facility simplification has been studied, because the heating system is not operating. In heating season, the thermal comfort KPIs results in the maximum difference of 23.7 % for PMV cat3 for zoning level 1 to 5, while CO2 remains unaffected as no simplifications to the ventilation system were applied. In non-heating season, the highest maximum deviation (σ_{max}) is found for ACM cat3, which is 24 %.

A notable feature of this study is its adherence to the "standard" approach of defining loads, schedules, and set-point temperatures in the thermal zones of the models, in accordance with ISO16798-1 guidelines [31]. Consequently, these modelling assumptions restrict the impact of model geometry on heating demand outcomes. Specifically, the use of spatially and temporally uniform schedules, loads and set points for all zones in a multizone models, results in the suppression of dynamics imposed by occupants This leads to a lack of spatial and temporal variation between zones in a model. Consequently, the dynamics of building performance is not fully evaluated in this study, resulting in good agreement between one zone and multizone models, when comparing the estimated heating demand. The integration of some dynamics into the thermal zones of the models (i.e., different heating set points) could potentially yield different outcomes that are not considered in the Study 1 analysis of this paper.

The statistical evaluation approach was not applied since it does not allow for explicitly linkage between model result and the model itself. Of that reason, the conclusions address the data qualitatively with the integration of the quantitative characteristics when it is meaningful. The comparative model simplification analysis is of qualitative character, pointing out what KPIs are affected when zoning or facility are simplified. In Fig. 6, all non-energy KPIs are presented as a number of hours when the KPI falls within a certain threshold range although there are not yet guidelines on what number of hours within the range is actually acceptable.

"Study 1" neither provides the discussion on closing the performance gap nor provide recommendation for moving away from traditional "standard" boundary conditions commonly employed in the energy performance certification (EPC) towards implementing practical and realistic operational conditions as indicated in EN 52016. This step is particularly crucial to draw conclusions regarding the suitability of both simple and detailed models for energy certification/evaluation of buildings. Furthermore, outcomes of Study 1 allow to provide guidance on which aspects of the models are particularly significant when the decisions about model simplification must be made. To address this issue even further, an empirical study is performed and presented in chapter 4 of this paper and indicated as "Study 2".

4. Results: "Study 2" – Model verification towards operational performance

This section focuses on the model verification by comparing selected KPIs to the monitored data. To understand which of the key parameters for building simulation are essential to achieve reliable results and decrease the gap between the simulation and real operation of the building, the set of four simulations with adapted condition are conducted. The setup of the simulation parameters of the 4 set of simulations are shown in Table 4. The weather station close to the building site measures the outdoor air dry-bulb temperature, wind speed, wind direction and solar radiation. Those data are used for Simulation_IDs A-D. In this section only KPIs related to heating demand and CO2 are compared, because all other KPIs are not monitored. The model verification is carried out in three spatial levels: staircase level, apartment level and room level as presented in Fig. 4, including the comparison of modelling and monitored results of space heating and CO2 concentration.

4.1. Staircase aggregation

Fig. 7 and Fig. 8 include results for all models (1Z1-3Z5) simulated upon two different scenarios: Simulation_ID A (average monitored set-point and standard people load) and Simulation_ID B (average monitored set-point and adapted people load to real occupancy) defined according to Table 4. In general, Fig. 7 illustrates that models result in lower errors, when internal load in the models is adapted according to actual conditions (Simulation_ID B). Furthermore, models with the most complex heating facility settings (3z1-3z5) perform worst and underestimate heating demand up to 40 %, while simple ideal load models have an error down to 20 %. The highest performance gap is observed for the spring season (week 9–14), as in Fig. 8. Looking upon models with the same facility complexity, but varying geometry of the models (e.g., models 1z1-1z5), it appears that model geometry shows no significant impact on the model accuracy. This statement is supported by annual results, Fig. 7, where 1z1-1z5 models results show similar level of error.

The comparison of IAQ in the models against the experimental data for the corresponding simulations (Simulation_IDs A and B) in Fig. 9 indicate that the models significantly underestimate the CO2 levels when the occupancy load is adapted to actual loads. It is important to acknowledge that the placement of CO2 sensors and the habits of occupants regarding the opening and closing of doors within the dwelling can greatly impact the aforementioned conclusion. The models assume even distribution of occupants across zones (rooms), with minimal air exchange between zones, while in real-life scenarios, the occupants move between the spaces and, they may keep the door open/closed between those spaces. Hence, when comparing a multizone model to monitoring data obtained from sensors placed in a densely occupied room during the day but unoccupied during the night (e.g., living room), it is important to consider that the model may underestimate CO2 concentrations during the day and overestimate them during the night if the occupants keep the doors between the rooms closed. This error is then propagating in the calculation of an average CO2 concentration for the whole staircase. As illustrated in Fig. 9 the advantage of use of adapted condition with respect to CO2 predictions is questionable when only total people load is known but neither detailed knowledge of their spatial nor temporal presence is available and their behavior with respect to venting and activity levels remain unknown.

4.2. Apartment aggregation

In the present study, the average heating set-point of the entire building in one-zone model has shown its potential, however, it remains uncertain what number of spaces and which spaces must be monitored to establish the heating set-point for the entire building or whether it can have negative consequences for the model accuracy. To some degree this uncertainty can be assessed through inspection of the results from models, where the apartment-scale data resolution can be obtained. Furthermore, the set of models that can calculate the energy need for heating at the apartment level can provide an added value for the energy optimization and fault-detection in the building.

In this study, only the models that can provide data at apartment level are analyzed. The space heating, observed at apartment level for Simulation_IDs A-C in Fig. 10, clearly illustrates the reduction of the deviation between simulation and the monitoring as more adapted inputs are integrated in the models. The improvement is apparent for all apartments, except for the Apartment 4, which is due to the limited measured indoor temperature data, which is shown Figure 15. In this apartment only data for bedroom temperature was available, in which occupants maintained lower temperatures comparing to other occupied spaces. As a result, monitored temperature is not fully representative (underestimated) for entire apartment and consequently the heating demand for this apartment is also underestimated.

The model simplification process revealed slight deviations among all models, with an error range of approx. 5–15 % among the models for the same apartment, for all simulations considered. The most significant errors in calculating heating demand were found to be associated with inaccurately defined set-point temperatures, as observed in transition from Simulation_IDs B to C, and the internal people load, when moving from Simulation_IDs A to B. This suggests that these factors have a greater impact on the accuracy of heating demand calculations compared to the facility definition (whether detailed or not) in the model, observed in "Study 1". Therefore, when analyzing the results for Simulation C, which represents the case with the most accurate definition of heating set-points and internal loads, it can be concluded that all models perform comparably well.

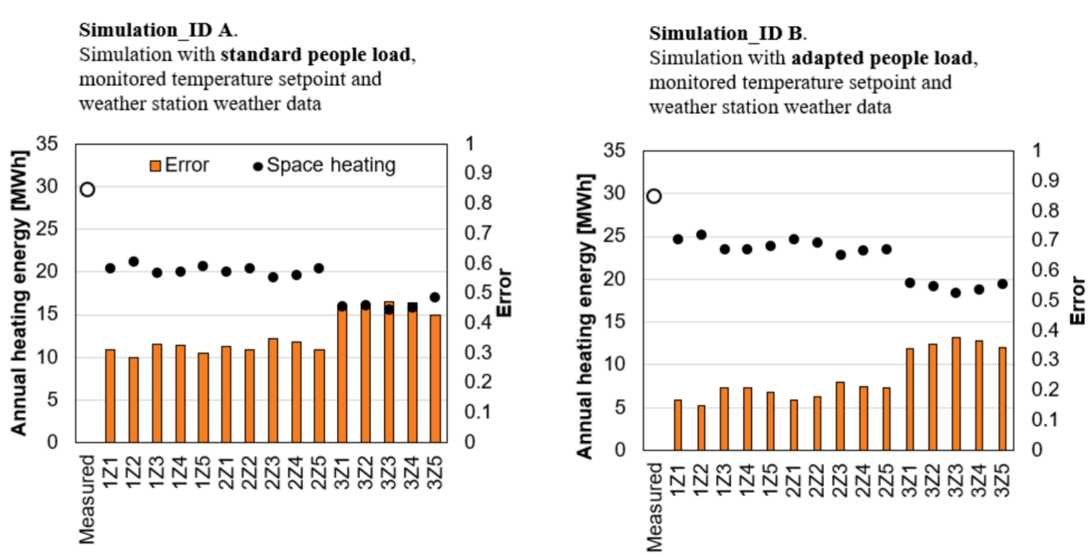


Fig. 7. Annual heating demand of a staircase for two types of simulation runs: Simulation_ID A (left) and Simulation_ID B (right). Simulation results are shown for all models against the monitored data, with error calculated for comparison.

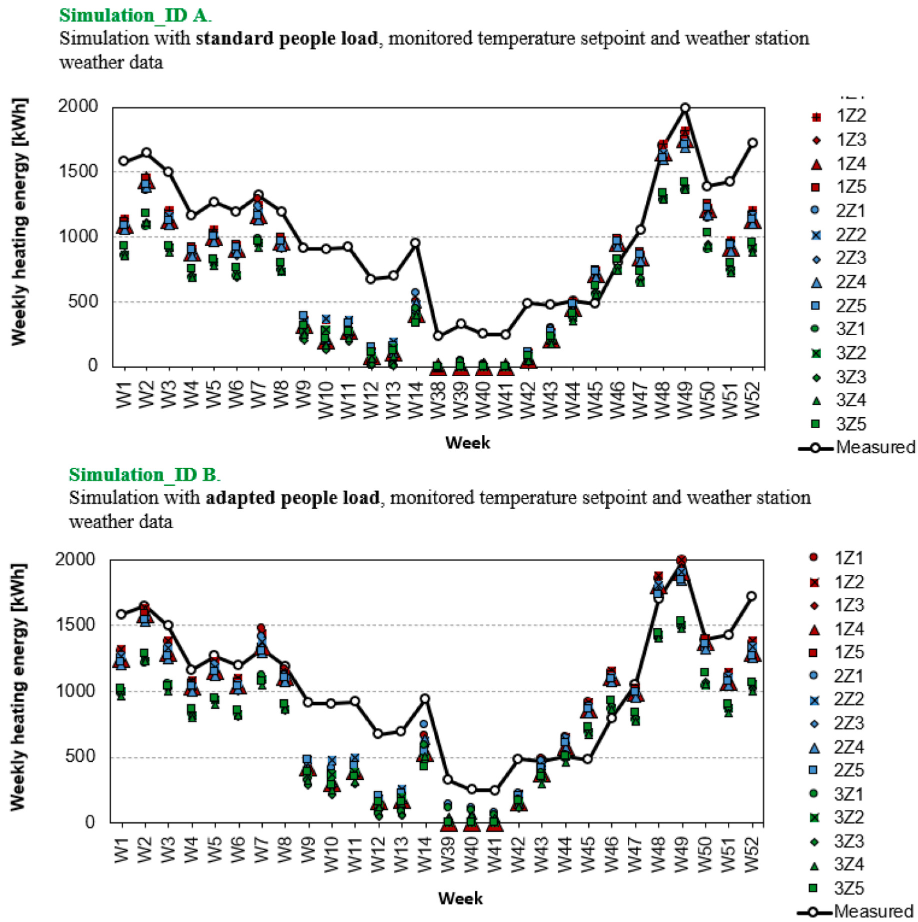


Fig. 8. Weekly heating demand of a staircase for two types of simulation runs: Simulation_ID A (top) and Simulation_ID B (bottom). Simulation results are shown for all models against the monitored data.

Apartment 1 and Apartment 2 stand out as the extensively monitored apartments in terms of thermal comfort and CO2 levels. As a result, the heating set-points in these apartments are defined with greater accuracy, leading to notably low errors in Simulation_ID C. Interestingly, this observation implies, albeit indirectly, that the best-performing models for Apartments 1 and 2 are 1z5 and 3z5, which are the models with the most detailed geometry, defined at a room level.

Another conclusion from the results is that the models with the geometry at apartment or even room-level are able to predict the heating demand with very good accuracy (an average daily error is down to 5 %), upon good information availability about the set-point temperature and occupant loads.

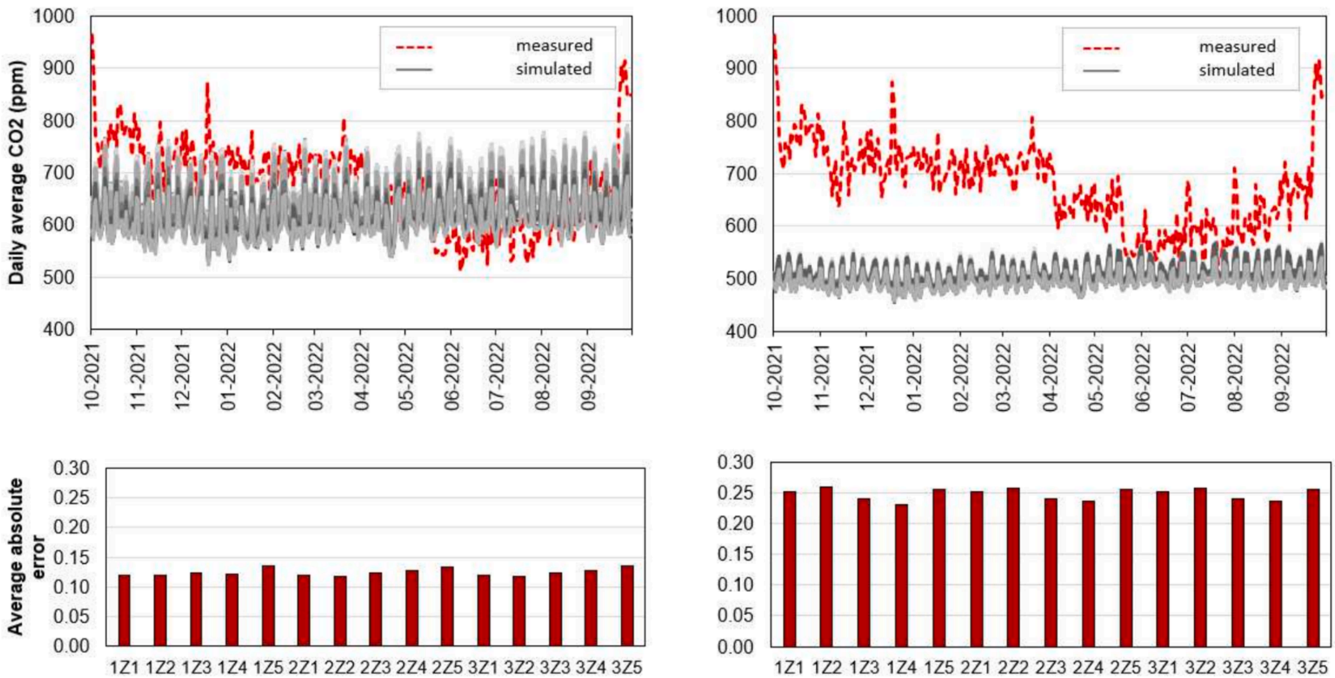
Fig. 11 displays the average error in predicting CO2 concentration for each apartment for Simulation_IDs A and B. For Simulation_ID A, which is based on the standard occupancy load, the IEQ performance of the 1z3 model is equivalent to the 3z3 model, and the same applies to the 1z5 and 3z5 models. These models only differ in the setup of the heating system, which does not impact IEQ. For Simulation_ID B, which is based on actual occupancy load, their overall performance worsens. However, when comparing the models to each other, there are only minor differences of up to 4 % for both Simulation_IDs A and B. These differences, in contrast to the significant total errors (ranging from 14 % to 32 %), are therefore not significant. For Simulation_ID C, which is based on the same people load as Simulation_ID B, the CO2 concentration is the same as Simulation_ID B, thus is not showed in Fig. 11.

4.3. Room aggregation

From Fig. 12 it is seen that the standard occupancy loads and schedules work well for some apartments if the average error is considered. If inspecting the results as the timeseries, the range of CO2 variation in models is predicted poorly for most of the time, an example is shown for Apartment 2 in Fig. 13(a).

Next moving to Simulation_ID B and C, when the occupancy loads are adapted to actual situation, surprisingly minor improvement was observed in the models, as shown in Fig. 12. It is explained by a combination of the sensor positioning and the occupant behavior. In practice in the daytime the occupants spend most of their time in the living room, then the concentration of CO2 in the bedrooms will remain largely unaffected by the occupants, while the concentration in the living room would be affected the most. Similarly reversed situation is valid for the night-time, when the living room is empty of occupants and instead bedrooms receive all CO2 load. In the models, though an assumption of CO2 load equally distributed to all rooms, as formulated in ISO 16798 [31] has been made, which can be the main reason for significant disagreement between the models and monitoring.

To test the above hypothesis, the internal people load was assigned to bedrooms during the night (22:00–8:00) and to living spaces during the day (8:00–22:00), while maintaining the standard schedule from ISO 16798 [31], which is referred as Simulation_ID D. Fig. 14 includes simulation results for two monitored rooms of Apartment 2 and demonstrate a significant improvement in model predictions during night-time for Simulation_ID D in bedroom. However, deviations still persist during daytime periods even for Simulation D and can be attributed to less predictable occupant behaviour during the day. The simulations for Simulation_ID D are carried out for all apartments and deliver similar results (Fig. 13(b)), with the deviations mainly related to the daytime periods and the assumptions made when distribute people



Simulation_ID A. Simulation with **standard people load**, monitored temperature setpoint and weather station

Simulation_ID B. Simulation with **adapted people load**, monitored temperature setpoint and weather station weather data.

Fig. 9. Hourly concentration of CO2 for models set-up according to Simulation A(left column) and Simulation_ID B (right column). The error is the absolute daily error between monitored and simulated values. The CO2 concentration is calculated as an average for the entire staircase.

between living rooms and bedrooms. Based on these findings, the following conclusions can be drawn. The multizone models exhibit high potential for predicting indoor air quality (IAQ) and thereby for the accurate computation of CO2-related KPIs. For residential buildings simulations it is recommended to adapt model inputs by assigning all people loads to bedrooms during the night and to common living spaces during the day. By adopting this approach, simulation results can support the identification of comfort issues specific to the actual dwelling, rather than relying on a standard, uniform scenario. Furthermore, this method can assist in identifying malfunctions in the ventilation system or unsuitable user behaviour, offering valuable insights for improving indoor air quality.

4.4. Conclusions of "Study 2" – Model verification towards operational performance

The empirical assessment of model simplification was conducted on the mechanically ventilated building, which features a heat recovery system. In this study, no simplification was applied to the ventilation system due to limitations in Energy Plus in simplifying this type of a system. However, three different models were used to simulate the heating system.

For heating demand evaluation at *staircase level*, it is found out that geometry complexity does not have an impact on the model accuracy although neglected thermal mass du tot this simplification need to be represented by included in the remaining construction elements. With adapted people load (Simulation_ID B) it improves the model accuracy of the heating demand compared to standard people load (Simulation_ID A). Furthermore, examining heating demand *at the apartment level* demonstrates that models with detailed geometry (both Z3 one apartment per thermal zone and Z5 one room per thermal zone) can generate accurate results (with errors as low as 1 %) when the heating set-point in the model is defined as monitored data per apartment and there is good coverage of temperature monitoring in the rooms composing the apartment. For the dwellings with the limited number of measurement points (or potentially inappropriate positioning of the sensors), use of the standard set-point is advised, like the case of Apartment 4. For instance, measurements by one sensor in the bed room if used as set point for modelling entire apartment heating demand can be misleading and result in error increase. The evaluation of models from the perspective of IAQ reveals that the calculated CO2 concentration for the *staircase level* (Fig. 9) and for the *apartment level* (Fig. 11) does not have a higher accuracy with the adapted people load. Noticed that the CO2 concentration is similar across all considered models, which is explained by the same assumptions made for people load in all zones, which is calculated as number of occupants per m^2 of the building. These results appear to have limited applicability in identifying performance gaps, poor system performance, or inappropriate user behaviors.

Meanwhile, the analysis of CO2 results conducted *at the room level* (Fig. 12-Fig. 14) are showing more interesting results. For Simulation_IDs A-C, the evolution of results is observed from standard to adapted conditions, presented as a timeseries. It highlights the challenges faced by the models with adapted occupancy in accurately capturing the range of CO2 fluctuations, including the minimum and maximum values, as shown in Fig. 13(a). These challenges arise from the uniform distribution of the people load to thermal zones, which suppresses the natural fluctuation of CO2 in the models. To address this issue, detailed geometry models are necessary, incorporating a non-uniform distribution of occupants in both time (schedule for people load) and space (assuming occupants move between thermal zones), studied in Simulation_IDs D and demonstrate a significant improvement in model predictions for all modelled apartments.

5. Conclusions/discussions

The primary objective of this work is to assess the level of effort necessary for building simulation to accurately quantify the influence of dynamic services and technologies in building energy certification.

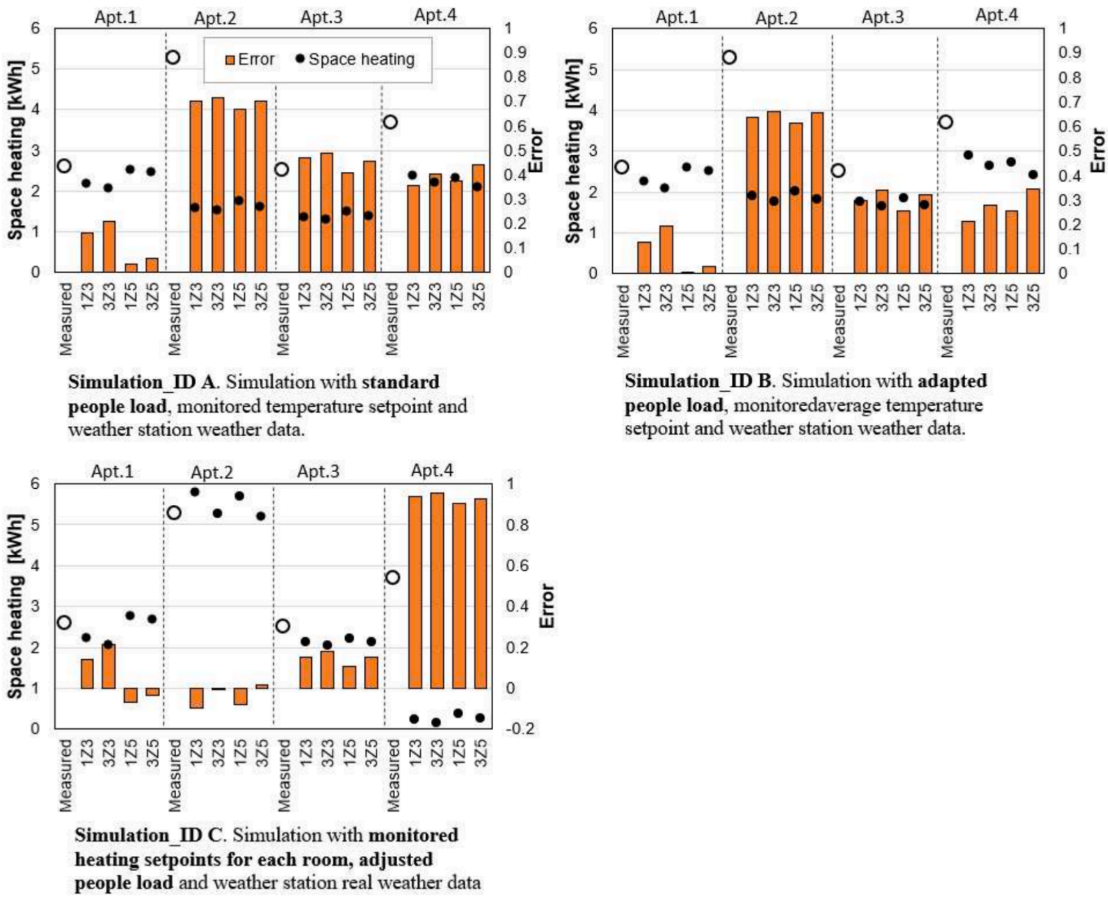


Fig. 10. Heating demand for models set-up according to Simulation_IDs A-C indicated in Table 4. The error is between monitored and simulated values. The heating demand is calculated per apartment.

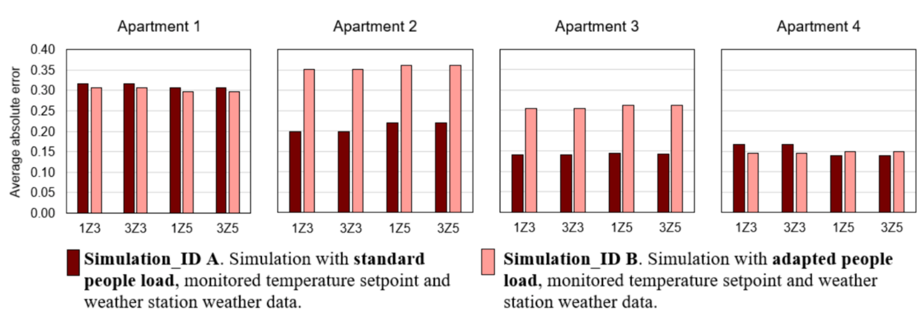


Fig. 11. A daily average absolute error in prediction of CO2 compared against the monitored data for Simulation_IDs A and Simulation_ID B.

Traditional approaches, such as sensitivity and uncertainty studies, are commonly utilized to address these inquiries, while model calibration against monitoring data is typically employed to improve reliability. However, implementing these procedures in routine energy certification practices and in more specific building assessment in general can be complex and challenging. Therefore, this work follows a different methodology to be able to support practitioners in modelling by providing insights about the model simplification consequences both for the energy performance, comfort and applicability of the results. In this work, "Study 1" primarily focuses on the impact of model simplification, while "Study 2" delves into the effects of adapted conditions and specific scenarios for heating demand, and IEQ. The overlap between the two studies serves to reinforce the importance of these common themes in different contexts, while also developing initial recommendations to use the modelling efforts efficiently.

In Section 3, an initial comparative "Study 1" on model simplification was performed. The comparative study demonstrates that there are relatively small differences in heating demand among models with different zoning methods of geometries. This suggests that there is potential for simplifying the geometry of the models without significantly impacting the accuracy of the heating demand calculations. Contrary, the implementation of detailed heating and ventilation systems in the simulation(3Z1-3Z5), has a more noticeable effect on the results of all output KPIs. It is important to note that the comparative study was conducted under the assumption of uniform standard occupant loads, schedules and heating set-point temperatures, thus damping the dynamic effects in the model, which would take place in practice due to varying user behavior. This aspect is partially addressed in the second study by implementation of different levels of adapted conditions in Simulation_IDs A-D in Section 4.

In "Study 2", for the staircase level, the analysis reveals that by accounting for the zoning complexity of geometry, energy demand can be

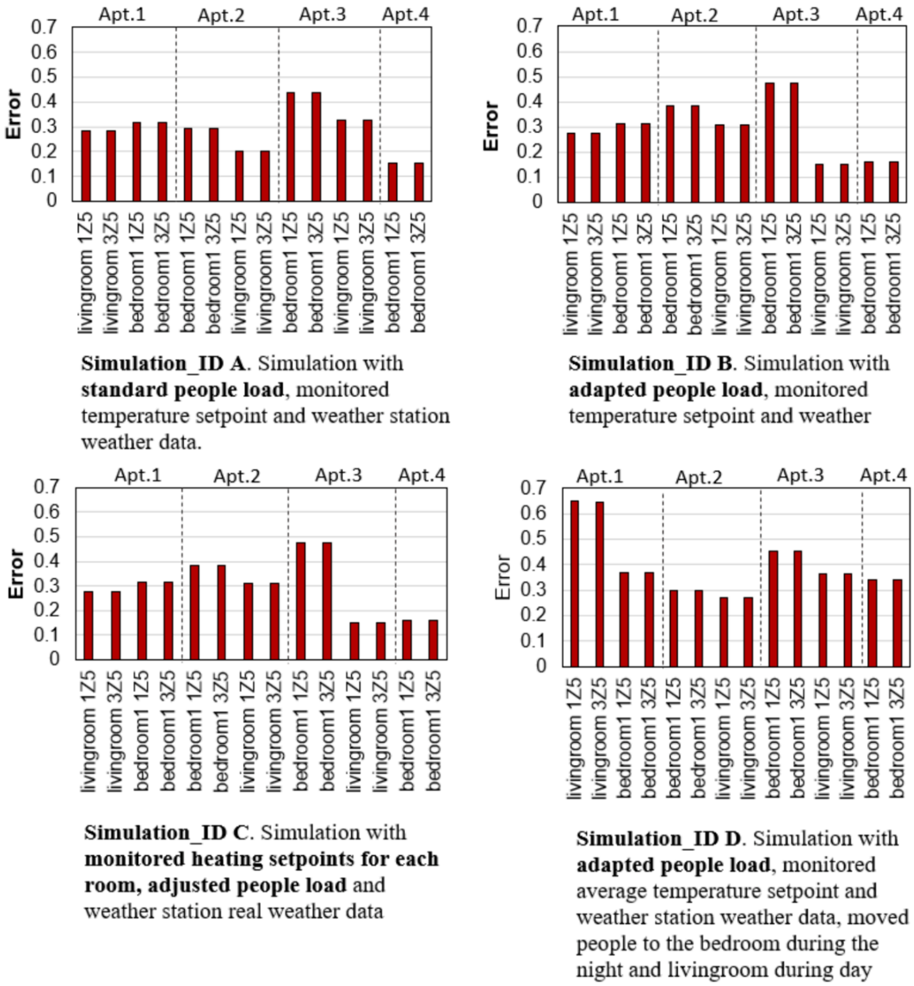
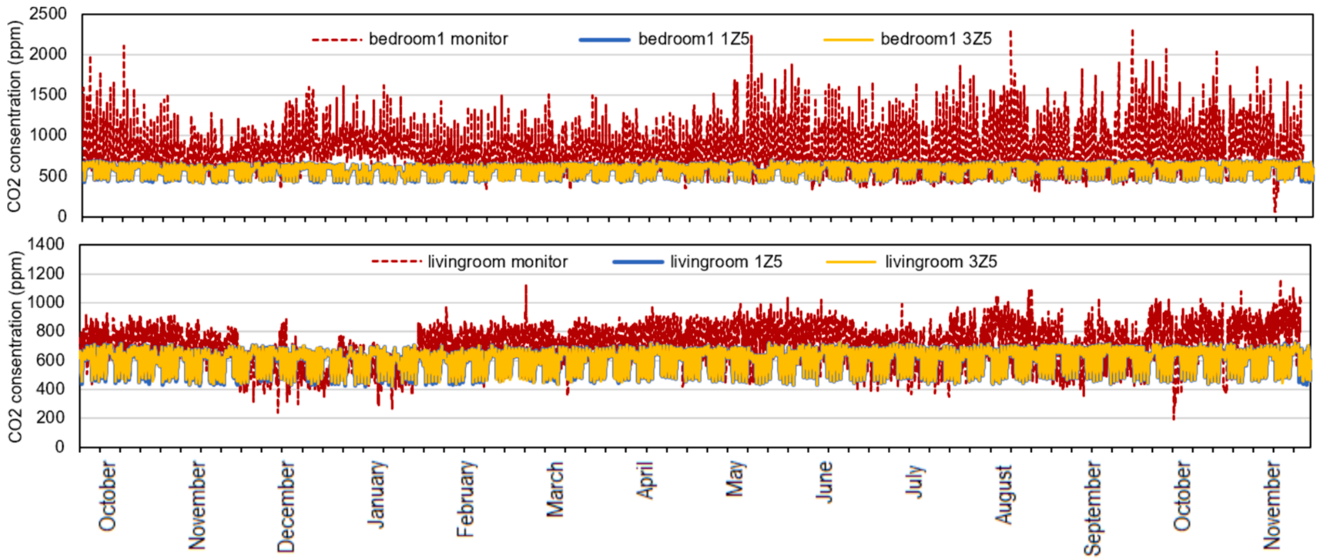


Fig. 12. The daily average absolute errors of the CO2 concentration in Simulation_IDs A-D compared to the monitored data.

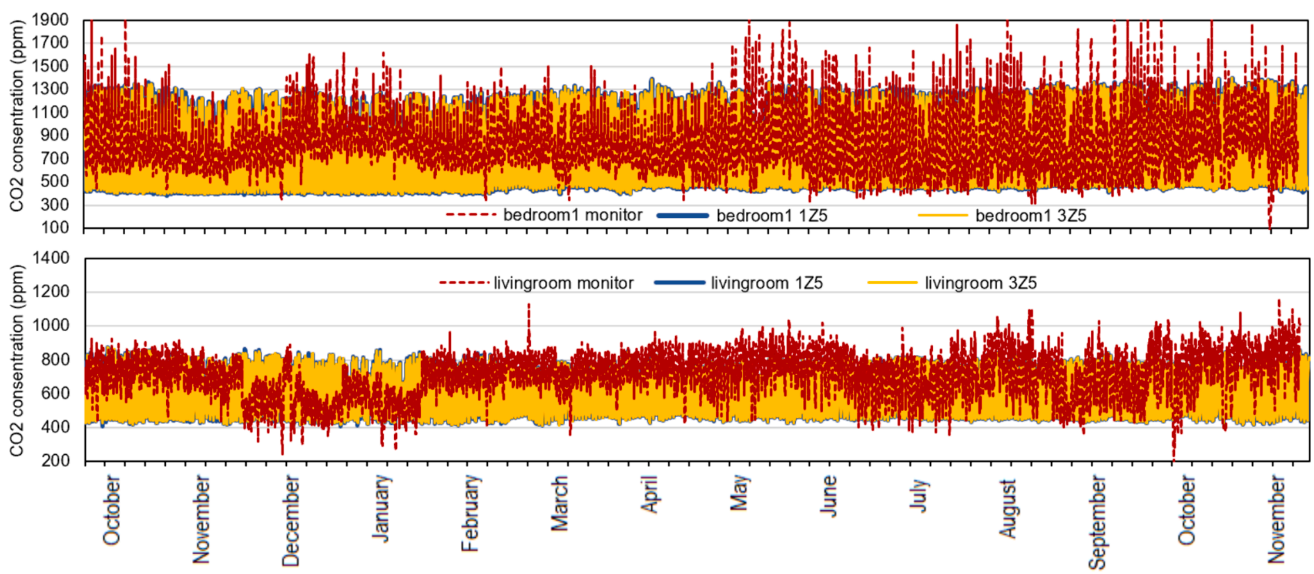
accurately estimated during the primary heating season when an average monitored set-point temperature is employed in the model (Simulation_ID A). These results can be improved even further if the people load in dwellings is known (Simulation_ID B). For both Simulation_IDs A and B, it is in particular spring and fall seasons appear challenging to match with monitored data. At the same time, these are the periods that are particularly important when evaluate the expected end of the heating season or account for the free running operation hours.

Furthermore, examining heating demand at the apartment level demonstrates that models with detailed geometry (both Z3 one apartment per thermal zone and Z5 one room per thermal zone) leads to more accurate results (with errors as low as 1 %) when the heating set-point in the model is defined as monitored data per apartment under the condition that monitored data is sufficient. This is because that the detailed validation of the model on apartment level and room level decreases the impact of unreasonable data collected in the typical apartment on the validation accuracy of the whole staircase. For the dwellings with the limited number of measurement points (or potentially inappropriate positioning of the sensors), use of the standard set-point is advised, like the case of Apartment 4. For the apartments with sufficient monitored sensors, adapted heating setpoint and people load can greatly improve the model accuracy.

The evaluation of IAQ calculations reveals that the results for the models at staircase level (represented by a one-zone model) have limited practical applicability, as they are challenging to interpret and cannot facilitate the identification of poor ventilation performance or inappropriate occupant behavior. On the other hand, analyzing CO2 results at the apartment level proves to be more meaningful and relevant. However, achieving satisfactory results requires detailed geometry models at room level that incorporate a non-uniform distribution of occupants in terms of both time (considering day/night occupancy patterns) and space (assigning occupants to thermal zones that represent common areas and sleeping spaces). Such an approach requires the implementation of detailed model geometry at room level as well as a high-quality inspection of the building, potentially including interviews with the occupants, prior to modelling. Having a building model with room-level geometry can offer significant advantages to users, such as professionals and tenants, by providing comprehensive insights into building operation (for professionals) and facilitating relatability with the monitored operation. This enables a deeper understanding of how the building functions and how it aligns with the actual observed performance. Considering the findings presented in this paper, it becomes evident why many studies often conclude that model geometry has minor importance in estimating heating demand, a conclusion consistent with our findings in Study 1. However, a critical question arises: Is it prudent to employ dynamic simulations while damping the dynamics of building behavior through the application of standard conditions, as illustrated in “Study 1”, even when utilizing simple geometry models that yield credible results for the given input? In “Study 2”, we demonstrate that by transitioning to more realistic assumptions, we not only significantly improve the estimation of heating energy use but also gain the ability to address indoor environmental quality (IEQ), which is unattainable using simplified models. Therefore, the recommendation to



a. Hourly CO2 concentration of apartment 2 in Simulation A.



b. Hourly CO2 concentration of apartment 2 in Simulation D.

Fig. 13. The hourly CO2 concentration of apartment 2 in Simulation_IDs A and D.

achieve a credible simulation model, as confirmed in these studies, is to move away from traditional "standard" assumptions when employing dynamic building simulation models. This shift not only enhances result credibility but also explores the potential of dynamic tools and, when necessary, supports a credible evaluation of IEQ. Moving towards efforts needed for the facility modelling, and the heating system in the case building, it is possible to observe that the deviation between modelling results and monitoring data is notably more sensitive to set-point temperatures and internal loads in the zones, rather than the level of detail in modelling the facility. This once again supports shifting the effort towards acquiring the data for implementation of adapted conditions, i. e. heating set-points and people load rather than modelling of complex heating system.

CRediT authorship contribution statement

Olena Kalyanova Larsen: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Data curation, Conceptualization. **Yue Hu:** Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation. **Michal Zbigniew Pomianowski:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Olena Kalyanova Larsen reports financial support was provided by European Commission. Yue Hu reports financial support was provided by European Commission. Michal Zbigniew Pomianowski reports was provided by European Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

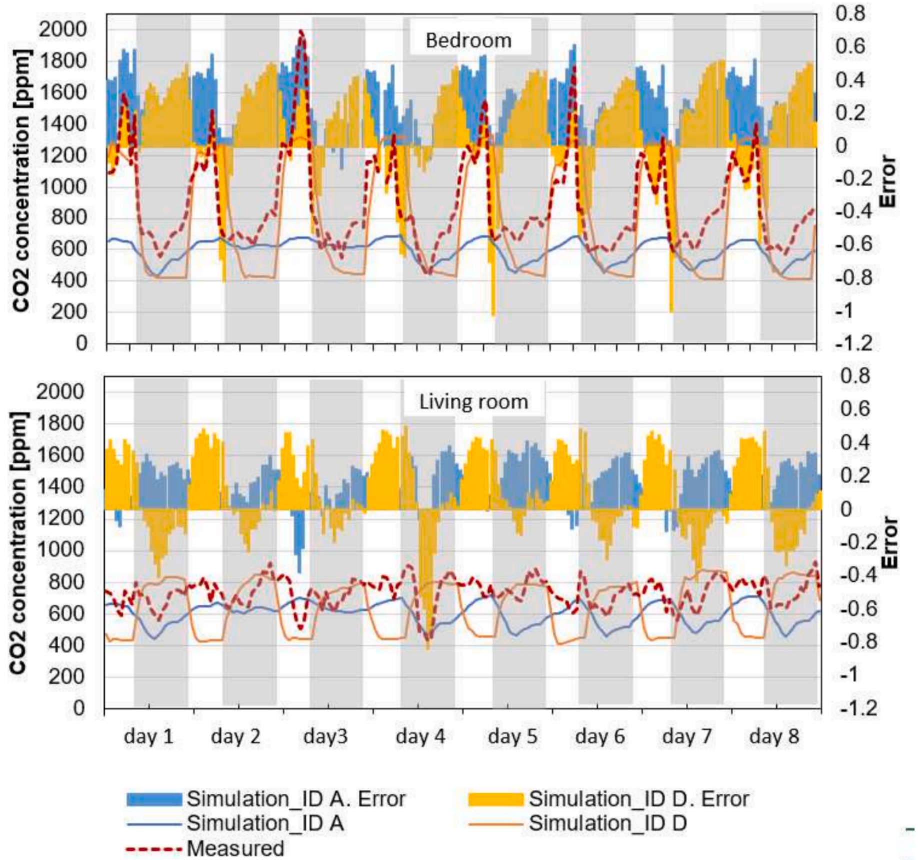


Fig. 14. Hourly CO2 concentration and error in prediction of CO2 compared against the monitored data for Simulation_ID A and Simulation_ID D for Apartment 2, bedroom1 and living room. Simulation_ID D uses actual occupancy load, but the occupants are assigned only to bedrooms during night and only to living spaces during day. Shaded area is the time without occupants assigned in the bedroom. All simulations performed by model 1Z5.

Data availability

The authors do not have permission to share data.

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Declaration

During the preparation of this work the authors used GPT-3.5 developed by OpenAI, to assist in proofreading, and to improve language and readability. After using this tool the authors reviewed and edited the content as needed and take responsibility for the content of the publication.

Appendixes

Table 6
The U values of the different constructions.

Constructions	U value (W/m^{2}K)	Material	Thickness (m)	Thermal conductivity (W/m·K)
Roof	0.12	Insulation	0.12	0.037
		Insulation / rafter footing	0.15	0.042
		Vapor barrier	0.0002	0.25
		Insulation	0.045	0.045
		Formwork	0.022	
		Ceiling panel	0.02	0.15
Gable	0.22	Brick/plaster	0.11	0.55
		Insulation	0.15	0.037
		Concrete	0.19	2
External wall	0.35	Brick/plaster	0.11	0.55
		Insulation	0.09	0.037
		Concrete	0.19	2
Window	1.5			

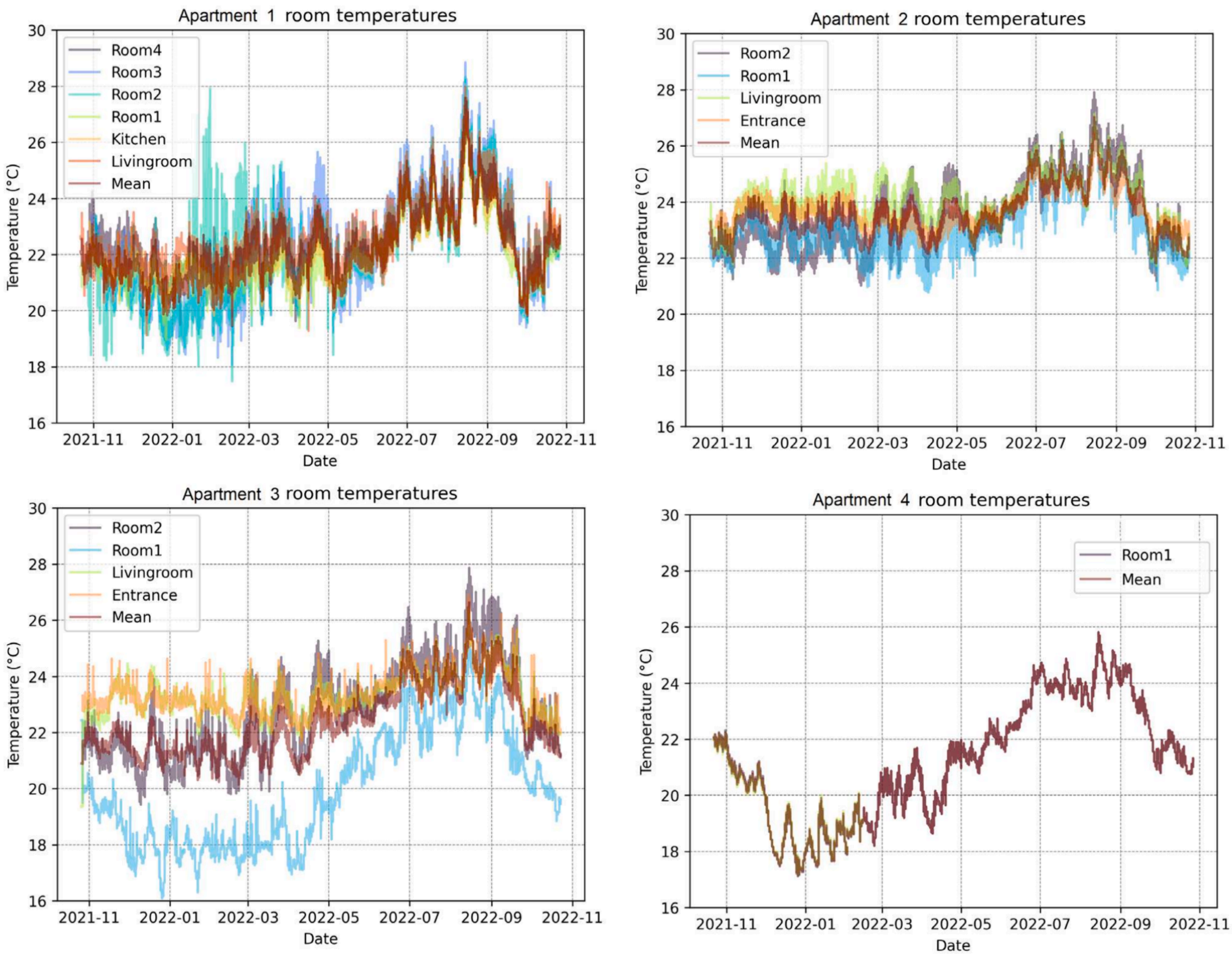

Fig. 15. The monitored indoor temperature. For apartment 4 only living room delivers reasonable data.

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