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Using data-driven indoor temperature setpoints in energy simulations of existing buildings: a Swedish case study

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Abstract. Building energy analyses of large samples or building stocks commonly use National building stock temperature averages in their calculations. However, such averages may not be representative of the conditions in a specific building type and may mask meaningful information found at building or dwelling level. Analysis of indoor temperature data from the Swedish housing stock showed that 25% out of approximately 1000 dwellings were heated at a temperature ≥23°C in wintertime. If indoor temperature management is considered as a potential energy saving measure for the building stock it may be more effective to explore implementation in these specific dwellings, than considering average temperature reduction across the entire building stock. This however would require more detailed input data on indoor temperatures. Would such an approach be worthwhile? To answer this question, two types of Swedish multifamily buildings were simulated with i) business-as-usual scenarios and ii) setpoints based on indoor temperature data from the last Swedish National Survey. The study shows that using data-driven, dwelling-specific indoor temperatures could lead to more effective decision making on indoor temperature management, targeting buildings and dwellings where temperature reduction would most likely cause the least compromise on comfort. Such a strategy however should be complementary to a wider plan of improved energy efficiency measures across the building stock.

1. Introduction

Building energy analyses, certification schemes and building stock modelling typically use in their calculations standard setpoint indoor temperatures. This often leads to differences between calculated and actual energy use, the so-called performance gap [1], or aggregated results which may not be valid on a case-by-case basis. This is also evident in the great variability in indoor temperatures that has been found in real everyday home environments [2-6], especially during the heating season. Using standard values or averages may therefore mask the role of indoor temperature in specific dwelling and building types or under special socioeconomic conditions.

In Sweden, it is common to estimate energy savings from reducing the indoor temperature from baseline values of 21.2°C for single-family houses and 22.3°C for multi-family buildings [7-9], which are averages from measurements in Swedish dwellings from the National building stock survey BETSI in 2007/08 [10]. Using these averages however has limitations: i) different characteristics of the buildings, spanning across 5 age groups, or the dwellings, being located at different floors, are not considered and ii) the averages are based on measurements in dwellings at different periods and locations in Sweden, hence at different outdoor weather conditions. A few of them were even taken at the borderline of the heating season (end of April/beginning of May). In a follow-up analysis of the above-mentioned indoor air temperature data, we found a considerable range in average dwelling temperatures of 9 K, highlighting a substantial variability between homes in maintained indoor temperature [4].

Using data-driven input parameters in building simulations reduces uncertainties and allows for a more realistic evaluation of building energy use [11]. Such practice however is time- and resource-demanding and would be rather impractical when dealing with large numbers of buildings, e.g. building stocks. A way to overcome this challenge is to produce dwelling groups based on the measured data with representative thermal climates (maintained temperatures) as input in the building models. The study aims to quantify the impact of using such more realistic, yet still aggregated, dwelling-specific indoor temperatures on the buildings' modelled energy use and on the potential energy savings from temperature management measures, e.g. radiator balancing.

2. Methods

The methods include indoor temperature data analysis and energy simulations. This study is a continuation of a detailed analysis on dwelling indoor temperatures in Sweden which used the BETSI dataset [12]. The aim of this additional data analysis is to extract the information required for the energy simulations and scenario testing, i.e. dwelling-specific maintained temperatures for use as setpoint temperatures in the models.

2.1. Data

The BETSI study (Buildings, Energy consumption, Technical Status and Indoor environment) was conducted in the heating season 2007/08 and included, among others, inspection of 1400 residential buildings. The collected information included building and dwelling characteristics, energy systems and energy use, measurements of indoor climate parameters and occupants' perception, satisfaction levels, health symptoms, occupancy and behavioural aspects regarding the indoor climate. In this paper, the measured indoor temperatures, building age group and dwelling floor level are used in the development of dwelling-specific temperature setpoints.

In the previous detailed analysis [12], 795 dwellings in single-family and multifamily buildings were categorised based on indoor temperature level. To achieve this, standardised temperatures at an outdoor temperature of 5°C were generated for each dwelling from the 2-week measurements to enable comparison between dwellings, since the measurements were taken at different periods, outdoor conditions and in different locations across Sweden (the process is described in detail in [12]). This was applied in a reduced sample size compared to the initial sample of the BETSI study, due to extensive data cleaning and exclusion of inappropriate records. The standardised indoor temperatures were then grouped based on the quartiles of their distribution, as outlined in Table 1. These temperatures will be referred to in this paper as 'maintained indoor temperatures' and will be used in setpoint development for the models.

Table 1. Standardised indoor temperatures (T') grouped in quartiles of their distribution.

Group	Condition	Description
Q1	T'< 21.2 ºC	Low indoor temperature group- conservative heating pattern
Q2	21.2 < T' < 22 ºC	Lower range of typical temperature group
Q3	22 < T' < 22.8 ºC	Upper range of typical temperature group
Q4	22.8 < T'ºC	High temperature group- potentially wasteful heating pattern

The most likely cause of the rather high winter indoor temperatures in Q4 was identified to be a combination of lack of heating system balancing, which results in higher temperatures especially in newer buildings and middle-placed apartments, increased overall heat supply to address complaints from colder apartments and occupants' limited use of heating controls. Unfortunately, no relevant data were collected to explain this with certainty.

The building age groups in the dataset are: Before 1960, 1961-1975, 1976-1985, 1986-1995 and 1996-2005. The dwelling floor level groups are: basement/semi-underground, ground floor, middle floor, top floor. The analysis in this paper includes only dwellings in multifamily apartments with corresponding standardised indoor temperatures, which further reduces the sample to 352 dwellings.

2.2. Building models

Two building age groups were selected for the simulations, the '1961-1975' and '1996-2005', which have high % of buildings in the high temperature group Q4 [12], while also being reasonably spread between them to ensure differences in building characteristics and construction standards. The models were built and simulated in IDA ICE 4.8.

The period 1961-1975 was one of unprecedented growth for the Swedish housing stock and the most common type of building that was constructed was a three-storey building block ('lamellhus'). This type also represents 50% of dwellings at this age category in the BETSI dataset. Next most predominant type (30% in age category) is the 'skivhus', which is the tall version of Lamellhus. Lamellhus is therefore selected for the simulations. In the other age category for investigation (1996-2005) there is larger variety in building types, with high rise blocks of the type 'punkthus' being the majority in the age category (36%) and were therefore selected for the simulations. The building models were generated using relevant literature sources: form, construction and characteristics of the buildings from [13], thermal properties of materials from [14] and [15]. Both buildings have concrete structural system and mineral wool insulation. The 60s building has 2-pane windows while the 90s building 3-pane windows. The U-values of building components are summarised in Table 2.

Table 2. U-value (W/m^2K) of building components for both multifamily buildings.

Component	Lamellhus	Punkthus
External wall- long side	0.41	0.21
External wall- short side	0.40	0.21
Windows and balcony doors	2.40	1.90
Roof slab	0.22	0.14
Ground slab	(0.17 effective)	0.36 (0.13 effective)
Building average	0.62	0.52

Standard input values for occupancy, electricity use, hygienic ventilation air flow and airing were based on the Swedish Standard Sveby for residential buildings [16] and are summarised in Table 3.

Table 3. Standard model input values and schedules.

Parameter	Input value
Occupancy	1.4 persons/1-room apartment and 2.2 persons/3-room apartment, away weekdays 8-17, 80 W pp
Electricity use from appliances and lights	30 kWh/m^2 (A_{temp}), of which 70% becomes useful heat gains
Hygienic ventilation air flow	0.35 $l/s*m^2$ (A_{temp})
Airing	+ 0.5 $l/s*m^2$ (A_{env}) at 50 Pa on average (added to infiltration)

Heat is supplied to the buildings by district heating and distributed to the apartments through water radiators. Both building types are modelled with exhaust-air ventilation, which is the predominant system of buildings in their age categories [15]. The minimum required hygienic air flow of 0.35 l/s m^2 is applied to all apartments. Each apartment is modelled as one zone, since the same setpoint temperature is prescribed for all rooms. The area of the heated stairwells is distributed to the apartments for simplicity.

Thermal bridges were set in the models so as to constitute 20% of the envelope transmission losses, as applied in BETSI and in agreement with recommendations by the National Board of Housing, Building and Planning [17]. The buildings' infiltration rate in the models combines the envelope's air leakage with an added value to account for airing through window opening (Table 3). The envelope's air leakage is set to 0.8 l/s*m^2 at 50 Pa pressure difference. This value was the required maximum according to the 1995 building regulations [18]. Although there were no regulatory requirements for envelope air leakage before 1975, a study of apartments from the period 1965-1975 found an average air leakage of 0.66 l/s*m^2 at 50 Pa [19]. As all investigated apartments were either on the ground or top floor, a higher average can be assumed including middle-placed apartments, which was done in [14] by using an average value of 0.8 l/s*m^2 at 50 Pa. This approach is followed here, leading to a common air leakage- hence infiltration value- in both building types.

Location for both buildings is taken to be Gothenburg (57.7089° N, 11.9746° E), which is located in the Swedish climate zone III. The ASHRAE IWEC2 Weather File for Gothenburg airport is used for the simulations (SWE_GOTEBORG-LANDVETTER) [20].

2.3. *Model calibration and validation*

The developed models are based on typical buildings of their respective age categories and therefore cannot be directly validated with empirical data from specific existing buildings. For the purpose of this work, which is to generate representative results for the selected building types, peer model validation is considered sufficient [21]. Model calibration and validation were therefore based on 2 sources: a) the BETSI reports on the building stock's technical characteristics [15] and envelope heat losses (per component and total) [22], b) the thermal properties and energy demand of Generic Building Types for Sweden in the European TABULA project [23]. In the validation process, focus is placed on the envelope and the building systems, while occupancy and associated use (e.g. DHW, internal gains, occupancy schedules) are set to normal. This approach is chosen in order to isolate the impact of indoor temperatures on energy demand, which is the interest of this work.

All component U-values were compared with the building age-group averages in BETSI and were calibrated accordingly. For validation of the final models as representative for their age-group, the average building U-value and total UA-value per m^2 heated area were compared (Table 4). The 1960s lamellhus is well within the BETSI values, as is the average building U-value of the 1990s punkthus. The total UA-value per m^2 A_{temp} of the 1990s building is slightly below the BETSI sample's SD range, which is most likely related to the increased number of floors in the selected building. Given the good agreement of component and building U-values, this difference is considered acceptable.

Table 4. Comparison of modelled parameters with BETSI averages and TABULA results.

	1961-1975		1996-2005	
Parameter	BETSI	modelled	BETSI	modelled
Average building U-value (W/m^{2}K)	0.56 ± 0.1	0.62	0.43 ± 0.1	0.52
Total UA-value per m^2 A_{temp} (W/K)	0.70 ± 0.1	0.78	0.80 ± 0.2	0.57
	TABULA	Modelled	TABULA	Modelled
Space heating demand (kWh/m^2 a)	76.2	65.5	52.1	53.8

For comparison with the TABULA results, we use the theoretical setpoint temperature of 20ºC used in TABULA. Climate zone III is selected in the TABULA webtool to align with the model. The differences in space heating demand seen in Table 4 between the TABULA and this study's models are reasonable considering the differences between the form of modelled buildings (e.g. the TABULA buildings include basement, the modelled punkthus form has large envelope area).

Based on the above, the models are considered adequately representative of their respective age-groups and appropriate for the intended parametric study.

3. Results

3.1. Analysis and grouping of standardised temperatures

The share of dwellings from the investigated sample in each temperature group (Q1-Q4) per building age group is summarised in Table 5. It can be seen that 34% of dwellings in the age group 1961-1975 and 55% of dwellings in the age group 1996-2005 belong to the high temperature group Q4, with potential for reduction (maintained temperature above 22.8°C).

Table 5. Distribution of apartments in the 4 temperature groups (Q1-Q4) by building age group.

Building age group		Quartile				Total
		Q1	Q2	Q3	Q4	
<=1960	Count	11	18	24	18	71
	% within group	15.5	25.4	33.8	25.4	100
1961-1975	Count	15	20	21	29	85
	% within group	17.6	23.5	24.7	34.1	100
1976-1985	Count	5	18	15	16	54
	% within group	9.3	33.3	27.8	29.6	100
1986-1995	Count	6	11	23	26	66
	% within group	9.1	16.7	34.8	39.4	100
1996-2005	Count	3	11	20	42	76
	% within group	3.9	14.5	26.3	55.3	100
Total	Count	40	78	103	131	352
	% of Total	11.4	22.2	29.3	37.2	100

Table 6 presents the mean maintained indoor temperature per temperature group for the two selected building age groups, that can be used as corresponding setpoint temperatures for apartments in the models. For the building age group 1961-1975, the mean maintained temperature ranges from T_{st}=20.6ºC in Q1 to T_{st}=23.5ºC in Q4, while for the age group 1996-2005, from T_{st}=20.9ºC in Q1 to T_{st}=23.7ºC in Q4.

Table 6. Average maintained temperatures per temperature group for the two investigated age groups.

B age group		Mean T_{st}	N	Std. Deviation
1961-1975	Q1	20.6	15	0.5
	Q2	21.6	20	0.3
	Q3	22.5	21	0.2
	Q4	23.5	29	0.6
Age group		22.3	85	1.2
1996-2005	Q1	20.9	3	0.1
	Q2	21.7	11	0.2
	Q3	22.6	20	0.1
	Q4	23.7	42	0.6
Age group		23.0	76	1.0

Distribution of apartments in floor level by temperature group can be seen in Table 7. Q1 dwellings (low temperature) are almost shared between the ground, middle and top levels, though with higher percentage at the top floor, Q2 between middle and top levels and Q3 and Q4 are mostly found in middle-placed apartments, followed by the ground floor.

There is unfortunately no data on dwelling location within the building layout, i.e. if it is in the middle of the floor or at the side, which also influences its exposure to the outside weather conditions. Furthermore, direct mirroring of the floor distribution by age category from the dataset to the modelled buildings cannot be made, due to different apartment distributions per floor, e.g. for the 1961-75 building: in the dataset 2%, 21%, 45%, 32% inspected dwellings were located in basement, ground, middle and top floors respectively, while the modelled building has an equal dwelling distribution to ground, middle and top floors. Therefore, the information on floor level can be used only indicatively for more representative modelling and in combination with tables 5 and 6.

Table 7. Distribution of dwellings in floor levels by temperature group Q1-Q4.

Quartile		Basement	Ground	Middle	Top	Total
Q1	Count	1	11	13	15	40
	% within Quartile	2.5%	27.5%	32.5%	37.5%	100.0%
Q2	Count	2	18	32	25	77
	% within Quartile	2.6%	23.4%	41.6%	32.5%	100.0%
Q3	Count	0	29	54	20	103
	% within Quartile	0.0%	28.2%	52.4%	19.4%	100.0%
Q4	Count	1	37	69	23	130
	% within Quartile	0.8%	28.5%	53.1%	17.7%	100.0%
	Count	4	95	168	83	350
	% of Total	1.1%	27.1%	48.0%	23.7%	100.0%

3.2. Setpoint temperature allocation to apartments

To allocate the models' apartments to representative temperature groups (Q1-Q4), three aspects were considered: i) the share of each temperature group in the respective building age category (Table 5) for representativeness within the sample, ii) the average maintained temperature for each temperature group in the respective building age category (Table 6) and iii) the distribution of floor levels within the temperature groups (Table 7), for representativeness across buildings.

With the above considered, the 12 apartments of the 1961-75 building and 20 apartments of the 1996-2005 building were allocated to temperature groups as in Table 8. Location on floor level (middle vs side) was based on the premise that more exposed side dwellings would have lower temperatures. Remaining cases were randomly placed, as long as the above main criteria are generally met.

The final temperature group shares correspond to those in Table 5 for the corresponding building categories and the weighted average setpoint temperatures are:

- T_m= 22.3 °C for the 1961-75 building, which equals the age group average (Table 6) and, coincidentally, the average of multi-family buildings derived from the BETSI survey [10], often used in building stock modelling [7-9].
- T_m= 23.0 °C for the 1996-05 building, which equals the age group average (Table 6).

Table 8. Allocation of apartments to temperature groups for the two buildings (average Q group maintained temperature °C in brackets to be used as apartment/zone setpoint, as per Table 6).

Model	Floor level	Apartment			
		1	2	3	4
Lamellhus	3	Q1 (20.6)	Q2 (21.6)	Q2 (21.6)	Q1 (20.6)
	2	Q2 (21.6)	Q4 (23.5)	Q4 (23.5)	Q3 (22.5)
	1	Q3 (22.5)	Q4 (23.5)	Q4 (23.5)	Q3 (22.5)
Punkthus	5	Q1 (20.9)	Q2 (21.7)	Q3 (22.6)	Q2 (21.7)
	4	Q3 (22.6)	Q4 (23.7)	Q4 (23.7)	Q2 (21.7)
	3	Q4 (23.7)	Q4 (23.7)	Q4 (23.7)	Q4 (23.7)
	2	Q3 (22.6)	Q4 (23.7)	Q4 (23.7)	Q3 (22.6)
	1	Q4 (23.7)	Q4 (23.7)	Q4 (23.7)	Q3 (22.6)

It is sensible to presume that such temperature distribution in a building would lead to issues such as: a) increased average temperature of the building (hence of the building stock too, if scaled up) and b) complaints from the apartments with the lowest temperatures (<21°C), which however constitute the smallest percentage within the building. It is highly likely that the increased temperatures in middle-placed apartments are the result of a quick-fix solution to address low temperatures in few apartments which have larger areas exposed to the outside weather conditions.

3.3. Parametric study

Based on the previous analysis, the scenarios as depicted in Figure 1 were modelled. Scenario A is split in 3 sub-scenarios. These sub-scenarios include the application of a single setpoint temperature to all apartments within the buildings, i.e. 21°C, 22.3°C and the age-group average maintained temperature (included in Table 6). Scenario B includes the application of different setpoint temperatures to apartments, based on the allocation in Table 8. The following analysis focuses on the modelled space heating demand and compares the energy savings from reducing indoor temperature to the standard design value of 21°C (scenario A.1).

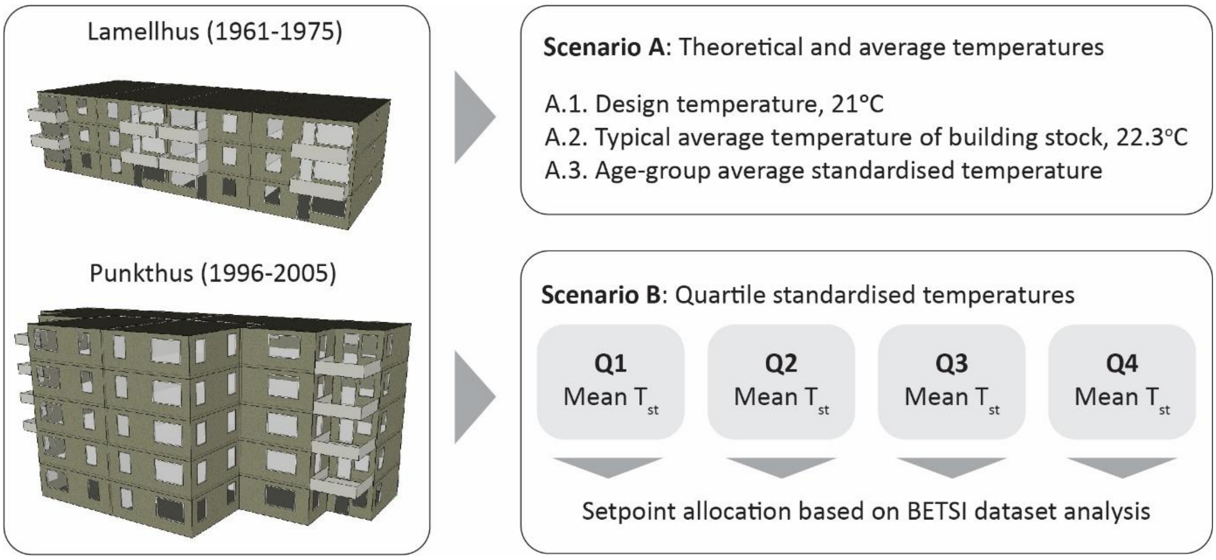

Figure 1. Modelling process for the two representative buildings.

As can be seen in Figure 2(a), in the case of the 60s building there is no difference in space heating demand between using the building stock temperature average or the age-group average, as they were coincidentally the same value. Similarly, the difference between using the average values in all apartments and using allocated Q-specific temperatures is very small. The latter is influenced by the specific building form of Lamellhus, with an equal 1/3 share of ground-middle-top placed apartments. The difference would likely be larger for the high-rise buildings of that period, as high temperatures are more evident in middle-placed apartments. Either way, based on the 3-storey Lamellhus, the use of more detailed temperature input values would not affect the estimation of total energy savings from temperature reduction to the design value of 21°C, being 12% in all scenarios. However, looking at the temperature allocation in Table 8, temperature management on dwelling level would be very beneficial.

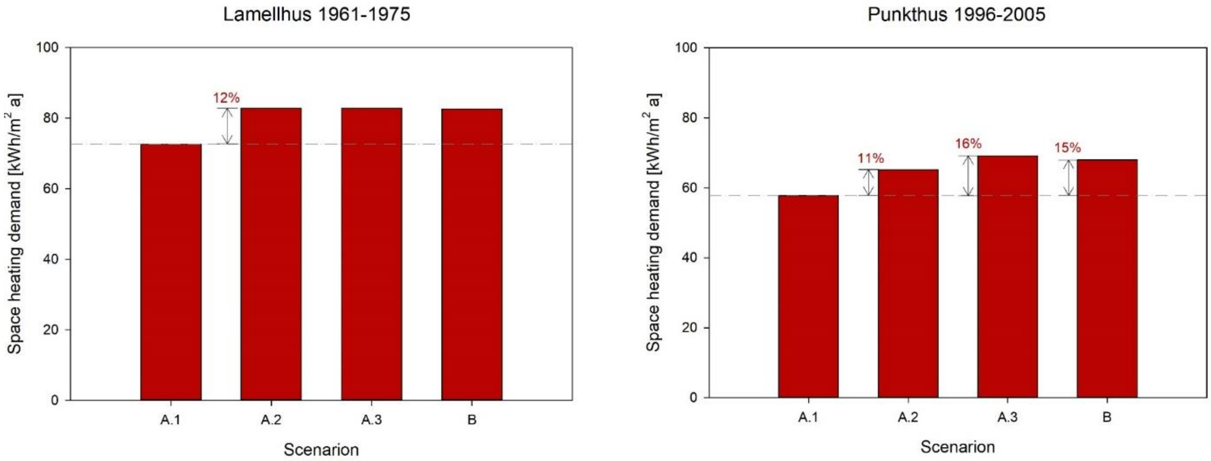

Figure 2. Modelled space heating demand for a) the 60s building and b) the 90s building by scenario: A.1. Design indoor temperature 21ºC, A.2. Building stock average 22.3ºC, A.3. Age group average of standardized temperature (22.3ºC for Lamellhus, 23.0ºC for Punkthus), B. Quartile averages of standardized temperature distributed in apartments as per Table 8.

Figure 2(b) shows the results for the 90s building. There is a 5% difference in energy savings between using building stock temperature average or the respective building age-group average maintained temperature, with the building stock average underestimating the energy savings. Therefore, in this building age group, using a more representative average makes a difference in the results.

As can be seen in the absolute savings in kWh/m^2 a of Table 9, using the building stock average temperature (scenario A.2) leads to higher energy savings from the 60s building, while using the dwelling-specific temperatures based on the temperature data analysis (scenario B), the savings from the two age-groups are equal. From the perspective of strategic planning for energy savings, this result is important. The 1996-2005 age-group category buildings appear to be a better target for indoor temperature management as an energy and cost savings measure, e.g. through radiator balancing. Given the better envelope and mainly high-rise buildings with large share of middle-placed apartments, temperature reduction would likely be a lot easier to implement and with less impact on occupants' thermal comfort. However, it should be highlighted that on a building stock level there are fewer, though also taller, newer buildings. For this reason, such a strategy should be part of a wider plan where other energy saving solutions would target the less efficient older building stock (e.g. envelope improvement, building systems upgrade, etc). Such a plan allocates different energy savings measures to different building groups according to specific characteristics and needs of the groups.

Finally, for the 1996-2005 age-group, using the age-group average standardised temperature (scenario A.3) instead of allocated dwelling-specific temperatures (scenario B) leads to a slight overestimation of savings. This result is due to the equal distribution of a rather high age-group average to all apartments on top-middle-ground floors. Therefore, dwelling-specific allocation appears to be important for more accurate results, although the difference may be seen as too small to make the detailed allocation worthwhile.

Table 9. Space heating savings in kWh/m^2 a from scenarios A.2, A.3 and B to scenario A.1.

	From A.2	From A.3	From B
1961-1975	10.2	10.2	10.0
1996-2005	7.3	11.3	10.2

4. Conclusions

In this paper we compared different scenarios of input temperature setpoints of existing multi-family buildings based on level of detail, including standard/normative values, building stock averages and data-driven, dwelling-specific temperatures based on measurements. The increased level of detail did not make a big difference for the 60s building, but in the case of the 90s building it led to higher heating energy use and therefore higher potential for energy savings/m^2 from indoor temperature reduction compared to business-as-usual input values. However, the results may not be representative of the situation across the entire building stock due to the extensive data cleaning that led to a much smaller sample (352 dwellings). It is intended as an example of the potential of using more detailed temperature input data instead of building stock averages. In future building stock evaluation studies, such as BETSI, this could be taken into account in the study design to ensure the collected indoor climate data is appropriate to be used in the way described in this paper.

In Mata et al. (2013) it is stated that "…decreasing the indoor temperature, despite its great potential for energy savings, is difficult to implement in less energy-efficient houses in which the increased air temperature compensates for other factors in the operative temperature (i.e., high air velocity due to infiltrations or low radiation temperatures from the envelope surfaces)" [9]. Although overall reasonable, the statement is not always valid based on our analysis. While some indoor temperature levels in exposed apartments may partly compensate for the building's poor envelope, the rather high temperatures in middle-placed apartments do not support this hypothesis and show potential for energy savings without considerable compromise on thermal comfort. 34 % of the dwellings in the 1961-1975 building age group of this sample belonged to the high temperature group with an average of 23.5°C, which are most likely in middle-placed apartments. Without a more detailed analysis of the indoor temperature data, this temperature distribution would not have been so evident, although balancing issues are generally well known and common.

The high temperatures are also more evident in the newer buildings, which have better insulated envelope compared to pre-1975 buildings. It would therefore be easier to implement this measure if the dwellings with excess warmth in better insulated buildings are targeted first, such as the 1996-2005 building in our analysis. However, on a building stock level, such a strategy should be complementary to a wider plan of improved energy efficiency measures.

The aim of this paper was to investigate whether it is feasible and meaningful to use measured indoor temperatures of a sample of buildings to develop input setpoint temperatures in energy simulations of existing buildings. The results show that more realistic, yet still aggregated, temperature values lead to findings and possible recommendations that may not be considered when using building stock averages. Increased level of detail in building stock analysis requires however resources and therefore this approach would need to become more efficient through automatization processes. Alternatively, even building age-group averages make enough of a difference, as shown in this analysis.

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References

[1] Mahdavi A, Berger C, Amin H, Ampatzi E, Andersen RK, Azar E, et al. The Role of Occupants in Buildings' Energy Performance Gap: Myth or Reality? *Sustainability*. 2021;13:3146.
[2] Nicol F. Temperature and adaptive comfort in heated, cooled and free-running dwellings. *Building Research & Information*. 2017:1-15.
[3] Nicol F, Bahadur Rijal H, Imagawa H, Thapa R. The range and shape of thermal comfort and resilience. *Energy and Buildings*. 2020;224:110277.
[4] Teli D, Langer S, Ekberg L, Dalenbäck J-O. Indoor temperature variations in Swedish households: implications for thermal comfort. *Cold Climate HVAC*. 2018.
[5] Huebner GM, McMichael M, Shipworth D, Shipworth M, Durand-Daubin M, Summerfield A. The reality of English living rooms – A comparison of internal temperatures against common model assumptions. *Energy and Buildings*. 2013;66:688-96.
[6] Firth SK, Lomas KJ, Wright AJ. Targeting household energy-efficiency measures using sensitivity analysis. *Building Research & Information*. 2010;38:25-41.
[7] Nik VM, Mata E, Sasic Kalagasidis A, Scartezzini J-L. Effective and robust energy retrofitting measures for future climatic conditions—Reduced heating demand of Swedish households. *Energy and Buildings*. 2016;121:176-87.
[8] Mata É, Sasic Kalagasidis A, Johnsson F. Cost-effective retrofitting of Swedish residential buildings: effects of energy price developments and discount rates. *Energy Efficiency*. 2015;8:223-37.
[9] Mata É, Sasic Kalagasidis A, Johnsson F. Energy usage and technical potential for energy saving measures in the Swedish residential building stock. *Energy Policy*. 2013;55:404-14.
[10] Boverket. *The status of our houses. Så mår Våra Hus. Redovisning av Regeringsuppdrag Beträffande Byggnaders Tekniska Utformning m.m. (in Swedish)*. Karlskrona, Sweden2009.
[11] Cuerda E, Guerra-Santin O, Sendra JJ, Neila FJ. Understanding the performance gap in energy retrofitting: Measured input data for adjusting building simulation models. *Energy and Buildings*. 2020;209:109688.
[12] Teli D, Psomas T, Langer S, Trüschel A, Dalenbäck J-O. Drivers of winter indoor temperatures in Swedish dwellings: Investigating the tails of the distribution. *Building and Environment*. 2021;202:108018.
[13] Cecilia Björk, Per Kallstenius, Reppen L. *Så byggdes husen 1880-2000 : arkitektur, konstruktion och material i våra flerbostadshus under 120 [in Swedish]*: Svensk Byggtjänst; 2013.
[14] Olsson D. Model-based control of heating system based on forecasted weather, Licentiate thesis [in Swedish]. Göteborg, Sverige: Chalmers University of Technology; 2014.
[15] Boverket. *Technical status of the building stock. Teknisk status i den svenska bebyggelsen – resultat från projektet BETSI (in Swedish)*. Karlskrona, Sweden2010.
[16] SVEBY. Brukarindata bostäder (User data for Residential buildings, in Swedish). Stockholm2012.
[17] Boverket. Handbook for energy management according to the National Board of Housing, Building and Planning's building regulations [In Swedish]. Karlskrona2012.
[18] Boverket. Swedish Building Code, Boverkets byggregler, BBR 94:3 BFS 1995:17. Karlskrona, Sweden1995.
[19] Mjörnell K. Teknikupphandling: Rationell isolering av klimatskärmen på befintliga flerbostadshus Rapport från etapp 1. SP, Borås2011.

IOP Conf. Series: Earth and Environmental Science 1196 (2023) 012017 doi:10.1088/1755-1315/1196/1/012017

[20] ASHRAE. ASHRAE IWEC2 Weather Files for International Locations [in collaboration with White Box Technologies (WBT)]. ASHRAE; 2013.
[21] Ryan EM, Sanquist TF. Validation of building energy modeling tools under idealized and realistic conditions. *Energy and Buildings*. 2012;47:375-82.
[22] Boverket. *Energy in the building stock – technical characteristics and caluculations. Energi i bebyggelsen – tekniska egenskaper och beräkningar – resultat från projektet BETSI (in Swedish)*. Karlskrona, Sweden2010.
[23] TABULA. Tabula Webtool (Typology Approach for Building Stock Energy Assessment). 2012.