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A Novel Method for Calculating Heat Emitter and Controller Configuration Setpoint Variations with EN15316-2

Karl-Villem Võsa^a, Andrea Ferrantelli^a, Jarek Kurnitski^{a,b}

^aTallinn University of Technology, Department of Civil Engineering and Architecture, Ehitajate tee 5, 19086 Tallinn, Estonia

^bAalto University, Department of Civil Engineering, P.O.Box 12100, 00076 Aalto, Finland

Abstract

Estimating heat emission losses of heating systems is an important task of energy efficiency assessments in buildings. However, the present international standards do not specify how emission losses should be calculated or measured for different emitter and control system configurations. Aiming to fill this gap, here we propose a method for computing the temperature setpoint variations by addressing the heat distribution throughout a room with space heat emitters. This general and exact procedure enables the calculation of product category-specific setpoint variations for different types of heat emitters, accounting for the overall heat balance in the enclosure and including the cross-correlations of each component. Our method complements the procedure presented in the Standard EN15316-2, making it possible to compute emission losses as product-specific values of setpoint variations instead of tabulated values. As the main finding of the study, the calculation process is defined for a European Reference Room that allows an accurate and transparent evaluation of total setpoint variations. These are computed for specific products from measured vertical stratification and control parameters, by means of an annual IDA ICE simulation model of the reference enclosure. Applying the method to an annual energy performance simulation for an old and a new building in Strasbourg shows that emission losses are compensated by a total setpoint variation of respectively up to 2.00 °C and 1.20 °C, corresponding to an increase in total heating energy usage of up to 22% and 20%.

Keywords: Emission efficiency, Heat emission, Setpoint variation, Operative temperature, European Reference Room

1. Introduction

Space heating is responsible for a large portion of the total energy demand of buildings worldwide [1, 2]. As it is well known, it indeed consumes a huge amount of resources, both natural and financial [3]. Improving the energy efficiency of heating systems is therefore a priority for the actual building research.

In this context, since heating systems are obviously far from perfect, their heat emission losses need to be taken into account. These are due to non-uniform temperature distribution, heat emitter position and indoor temperature control [4]. More in specific, wall insulation, flow temperatures, heat output of radiators and dynamic effects that are caused by internal heat gains all concur to the emission losses, generating an ensemble of complex dynamical phenomena that were investigated e.g. in [5, 6, 7, 8]. In these studies, dynamic simulations allowed assessing the performance of heating energy systems, although without a specific quantification of the emission losses. A model where this could be possible was recently proposed in [9], where an analytical calculation of the operative temperature in a European reference room allowed to quantify and compare the heat emission losses of different radiator types.

On the experimental side, several studies addressing the efficiency of heat emitters do exist [10], in particular the authors of [11] compared heat transfer coefficients for radiant ceiling and radiant floor, although

*Corresponding author

Email address: andrea.ferrantelli@taltech.ee (Andrea Ferrantelli)

the emission losses were not quantified explicitly. This was instead accomplished in [12] (only for different types of radiators) and in [13] for radiators, underfloor and air heating systems with upper distribution. In Ref.[13] it was shown that the vertical temperature gradient and underfloor structural (embedded) losses are critical for the performance of the different heating systems. The crucial role of the operative temperature was also confirmed. Interestingly, even though the problem of quantifying heat emission losses is clearly important, as of today the dedicated literature remains underdeveloped.

Two methods have previously been used in the standardised assessment of space heating efficiency and emission losses. The so-called German method, based on DIN 18599-6, uses multiplicative part efficiency factors to calculate the necessary primary energy from the net heating energy [14]. To account for all system losses in the heating energy calculation, the French method that is adapted from the national Standard RT2005 ("Réglementation Thermique 2005") uses instead an equivalent increased temperature setpoint [15]. This approach is more dynamic, as the effect of increased setpoint temperature on system losses and overall heating energy use will vary depending on the ambient conditions. Both methods rely on tabulated values for different emitter and control system configurations, with the option of using product-specific values when available.

Remarkably, as of today no standardised method exists for determining these values. The standards do not introduce any procedure highlighting how to measure or calculate these setpoint variation values. Another drawback of both these methods is the underlying assumption that effects of each component in the equations are independent of other components. This is in contrast with experimental evidence, since it is well known that e.g. losses due to vertical stratification and temperature control of the system are in reality cross-dependent (see [13] and references quoted therein). Such a situation is also present in the European Standard EN15316-2:2017 [4], and the existing literature [16, 17, 18] does not fully cover this topic.

In the present paper we attempt to overcome the above limitation, by proposing a new method for the analysis of heat distribution losses throughout a room with different types of space heat emitters. Our procedure, which is general and exact, fills the existing gap by calculating product category-specific setpoint variations for different types of heat emitters, accounting for the overall heat balance in the enclosure and including the cross-correlations of each component that were not previously accounted for. In a fashion that is complementary to the Standard EN15316-2, we can compute emission losses by using product-specific values of setpoint variations instead of tabulated values.

Remarkably, our calculations allow assessing the product category specific setpoint variations for each emitter by using a specified room geometry (similar to the test chamber specified in EN 442-2 [19, 20]) and two sets of boundary conditions for old and new building types, which together define a European Reference Room.

Validated simulation models, implemented with the software IDA ICE [21], are then used to calculate the heating demand in an annual simulation. This is compared to the energy consumption of a reference configuration, and a total setpoint variation is derived for a specific emitter and controller configuration. The simulation model relies on the accurate modelling of the emitter and control system, which get their input parameters from field measurements. Remarkably, this is an *exact* model that is still absent in the present literature.

The method is applied to selected emitter configurations that were field-measured in early 2018 at the Tallinn University of Technology, to serve as a proof of concept [22, 23]. We find that the total setpoint variation which is required to offset system losses and maintain the necessary operative temperature in the enclosure is as high as 1.20 and 2.00 °C for the new and old building types, respectively. This induces up to a 20 and 22% increase in the annual heating energy consumption.

In the current revision of the European Standard EN15316-2:2017, which reports tabulated values for the emission losses as an equivalent increase in indoor air temperature, only the French method is adopted [24]. Consequently, the content of this paper applies to that method exclusively. The article is structured as follows: in Section 2 we discuss the implementation of heat emission losses in the European Standard, and define our calculation model as well as the yearly simulations setup. In Section 3 we report our results, which are then discussed in depth in Section 4, and we finally draw our conclusions in Section 5.

t_{in}	supply water temperature [°C]		
t_{out}	return water temperature [°C]		
t_{slab}	average slab temperature [°C]		
R_t	virtual resistance [m ² K/W]		
\dot{m}	mass flow rate [kg/s]		
\dot{Q}	Heat flow rate [W]	subscripts	
\dot{Q}_N	Nominal heat flow rate [W]	ctr	control
A	Surface area [m ²]	emb	embedded
c_p	isobaric specific heat [J/(kgK)]	exh	exhaust
K	gain	hydr	hydronics
T_i	integration time [s]	int,ini	internal, initial
T_t	tracking time [s]	int,inc	internal, increased
AHU	air handling unit	im	intermittent
θ	air temperature setpoint [°C]	rad	radiation
$\Delta\theta$	air temperature setpoint variation [°C]	roomaut	room automatics
t_{air}	air temperature [°C]	str	stratification
t_{op}	operative temperature [°C]	N	nominal
t_{MRT}	mean radiative temperature [°C]		
P	proportional		
PI	proportional integral		
n	power law exponent		
LMTD	logarithmic mean temperature difference [°C]		

2. Methods

2.1. Emission losses and efficiency in EN 15316-2

The European standard EN 15316-2 [4] assesses heat emission efficiency by considering the following aspects in the physical process:

- Vertical temperature variation due to air stratification
- Accuracy and control variation of the control device
- Embedded losses in the building envelope
- Thermal comfort (operative temperature)
- Hydraulic imbalance
- Possibility of intermittent heating
- Building automatics.

The effect of these components is quantified by means of an equivalent air temperature setpoint that accounts for the extra energy required to overcome system losses in the heat emission system (Figure 1). To each of these components a setpoint variation value is assigned and then added to the initial air temperature setpoint for energy calculation purposes 1 (see also [24, 13]),

$$\theta_{int,inc} = \theta_{int,ini} + \Delta\theta_{str} + \Delta\theta_{ctr} + \Delta\theta_{emb} + \Delta\theta_{rad} + \Delta\theta_{im} + \Delta\theta_{hydr} + \Delta\theta_{roomaut}. \quad (1)$$

This increased setpoint value is then used to calculate the heating energy required in a building. The standard provides tabulated default values for different space heating systems and use scenarios, while also

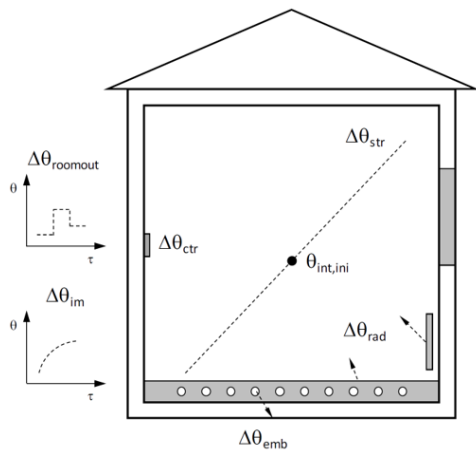


Figure 1: Heat emission losses according to ISO 52031 [25].

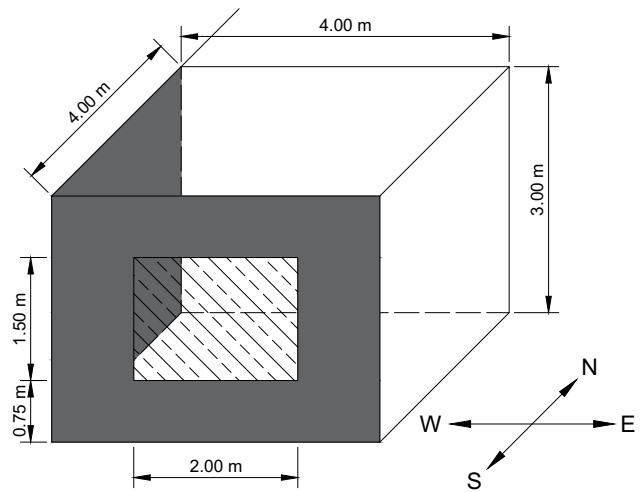


Figure 2: European Reference Room geometry. Shaded surfaces are external walls, rest of the boundary is adiabatic.

allowing product-specific and different regional default values to be applied. However, the determination of product-specific values is not regulated in the current revision of the EN 15316-2 standard. The draft version of the international standard ISO 52031, which is based on EN 15316-2, specifies a European Reference Room that defines the boundary conditions for the determination of these product values. Nevertheless, it does not provide any calculation method for the setpoint variations. Losses in the heat generation and distribution system are evaluated separately and are not included in this efficiency calculation; all the listed components consider emission in the room exclusively.

2.2. European Reference Room

The draft version of ISO 52031 provides two sets of boundary conditions - one each for a newer and an older building. The geometry of the room is shown in Figure 2. This theoretical room is located on the southern facade of a multi-storey building on an intermediate floor. There are either one or two windows with a total size of 3 m² on the south-facing external wall, while all other bounding surfaces are internal and adiabatic. In such a configuration, the heating demand is a combination of transmission losses through external wall and ventilation supply air heating. A detailed list of imposed boundary conditions is reported in Table 1.

The internal gains value shown in Table 1 represents the weekly average load as the sum of occupant, equipment and lighting loads. Usage schedules for these loads are shown in Figure 3, while the thermal properties of envelope materials can be found in [9].

2.3. Simulations

The emission performance of a selection of heat emitters was evaluated with a simulation study according to the developed method. The selection of emitters was based on an experimental study carried out at the Tallinn University of Technology in early 2018, which included the testing of panel radiators, underfloor heating, ceiling panels and air heating [22, 23].

Several experimentally obtained parameters, such as the vertical temperature gradient and control parameter values, were used as input for computer simulations performed with IDA ICE ver. 4.8. The complete list of simulated emitter and controller systems, along with the experimental values being used, is shown in Table 2. Proportional control was not adopted in the experimental study, and typical dead-band values were assumed for the simulation instead. Vertical temperature gradient values of 0.04 °C/m for underfloor heating, 0.13 °C/m for radiators, 0.36 °C/m for air heating and 0.62 °C/m for ceiling panels were used.

Boundary condition	New building	Old building
Windowed area	3 m ²	3 m ²
Window thermal transmittance	1.08 W/(m ² K)	2.34 W/(m ² K)
Window frame fraction	30%	30%
Window Frame thermal transmittance	1.20 W/(m ² K)	2.00 W/(m ² K)
Window glazing g-value	0.64	0.76
Air change rate	1.0 h ⁻¹	1.0 h ⁻¹
Supply air temperature	18 °C	outdoor temperature
Heat recovery efficiency	0.8, $t_{exh} \geq 0^\circ\text{C}$	-
Cooling setpoint (air)	25 °C	25 °C
Heating setpoint (operative)	20 °C	20 °C
Window orientation	South	South
Internal gains (weekly average)	3.8 W/m ²	3.8 W/m ²
Occupant load (Total)	2.67 W/m ²	2.67 W/m ²
Equipment load	2.87 W/m ²	2.87 W/m ²
Lighting load	2.87 W/m ²	2.87 W/m ²

Table 1: European Reference Room boundary conditions.

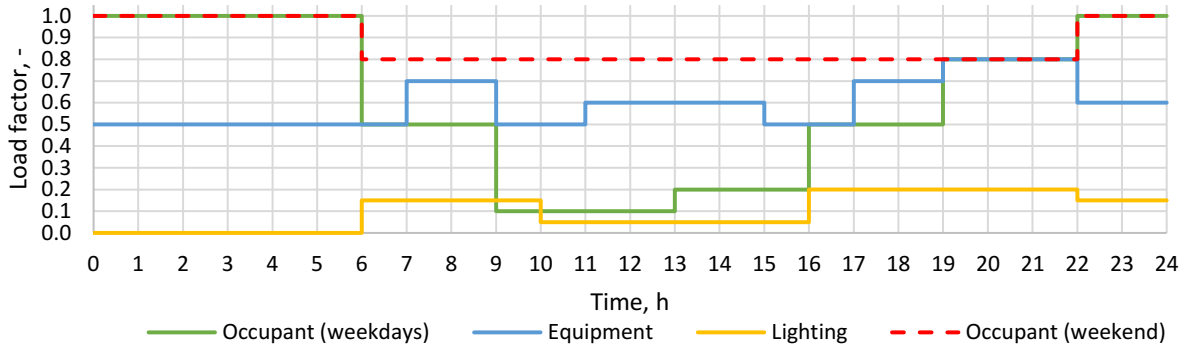


Figure 3: Usage schedules of internal loads.

The annual simulations were run with the IWEC2 climate file for Strasbourg-Entzheim at the geographic location 48.550 N, 7.633 E at an elevation of 153 metres [26]. This weather data is visualized in Figure 4. All boundary conditions listed in Table 1 were implemented into the software for the simulations.

2.4. Emitter models used in IDA ICE

In each and every simulation discussed in this section, the generation side of the heating systems is ideal, and only room emission is considered in the calculation. Specifically, the CEWATHET model was used to simulate the heat output of the panel radiators. This model uses a power law equation for calculating the heat output,

$$\dot{Q} = \dot{Q}_N \left(\frac{LMTD}{LMTD_N} \right)^n, \quad (2)$$

where \dot{Q} is the calculated heat output, \dot{Q}_N is the nominal heat output, LMTD is the logarithmic mean temperature difference at calculated supply, return and room temperatures, LMTD_N is the LMTD at nominal supply, return and room temperatures, and n is the power law exponent.

According to EN442-2[19], the nominal heat output, LMTD_N and power law exponent are performance parameters of the heat emitter. The model uses a uniform surface temperature to calculate the radiation and convection from the front panel surface, while the rest of the heat output is assumed to be a sum of

Heat emitter type	Nominal heat output	Geometry	Control
Panel radiator, new	685 W at 75/65 °C design temperatures, n = 1.2803	0.9 x 0.3 m, center-aligned under the window at installation height of h = 0.15 m	PI (K=2.78, T _i =1309 s, T _t =164s), Proportional (P-band = [0.5, 1.0, 1.5, 2.0] °C) and ON/OFF (DBW = 0.51 °C)
Underfloor heating, new	42 W/m ² _{floor} at 34/29 °C design temperatures	Covers whole floor area	PI (K=3.10, T _i =820 s, T _t =95 s), ON/OFF (DBW = 0.78 °C)
Ceiling panels, new	418 W at 55/45 °C design temperatures	0.6 x 2.4 m, placed at the centre of the ceiling	PI (K=3.15, T _i =508 s, T _t =208 s), ON/OFF (DBW = 0.78 °C)
Air heating, new	500 W duct heater	-	Proportional (P-band = 0.90 °C)
Panel radiator, old	1817 W at 75/65 °C design temperatures, n = 1.3048	2.3 x 0.45 m, center-aligned under the window at installation height of h = 0.15 m	PI (K=2.78, T _i =1309 s, T _t =164s), Proportional (P-band = [0.5, 1.0, 1.5, 2.0] °C) and ON/OFF (DBW = 0.51 °C)
Underfloor heating, old	92 W/m ² _{floor} at 43/38 °C design temperatures	Covers whole floor area	PI (K=3.10, T _i =820 s, T _t =95 s), ON/OFF (DBW = 0.78 °C)
Ceiling panels, old	1904 W at 75/65 °C design temperatures	1.2 x 3.0 m, placed at the centre of the ceiling	PI (K=3.15, T _i =508 s, T _t =208 s), ON/OFF (DBW = 0.78 °C)

Table 2: Simulated emitter system descriptions.

convective heat distributed into the room and transmission losses to the external wall behind the radiator. The ceiling panels are simulated with an identical model. In both cases, the water flow was modulated with a valve according to the control signal from controllers.

The heat emission of the underfloor heating system was simulated with the HCFLOOR model. A virtual resistance R_t characterizes the influence of pipe type, spacing, water flow rate and resistance of the conductive layers in the construction, as described in EN 15377-1 [27]. The water-side heat balance is calculated as

$$\dot{Q} = \dot{m}c_p (t_{in} - t_{out}), \quad (3)$$

where \dot{m} is the mass flow rate in the hydronic circuit, c_p is the isobaric specific heat of water and t_{in} , t_{out} are the supply and return water temperatures in the hydronic system. The return temperature is calculated as

$$t_{out} = t_{slab} + (t_{in} - t_{slab}) \exp\left(-\frac{A}{\dot{m}R_t c_p}\right), \quad (4)$$

where t_{slab} is the average temperature of the conductive slab layer at the piping depth and A is the surface area of the UFH system. Air heating was simulated with an electric heating coil in the supply air stream. The heat output of this coil was modulated according to the control signal from the P-controller. Detailed descriptions of the used emitter and controller models can be found in [28].

3. Results

In this section we review our results in their entirety, first discussing those relative to the novel energy balance method here introduced, then reporting on the yearly simulations outcome.

3.1. Developed method

Annual energy simulations are used to calculate the total setpoint variation according to the procedure outlined in Figure 5. By comparing the space heater with a baseline configuration with no emission losses,

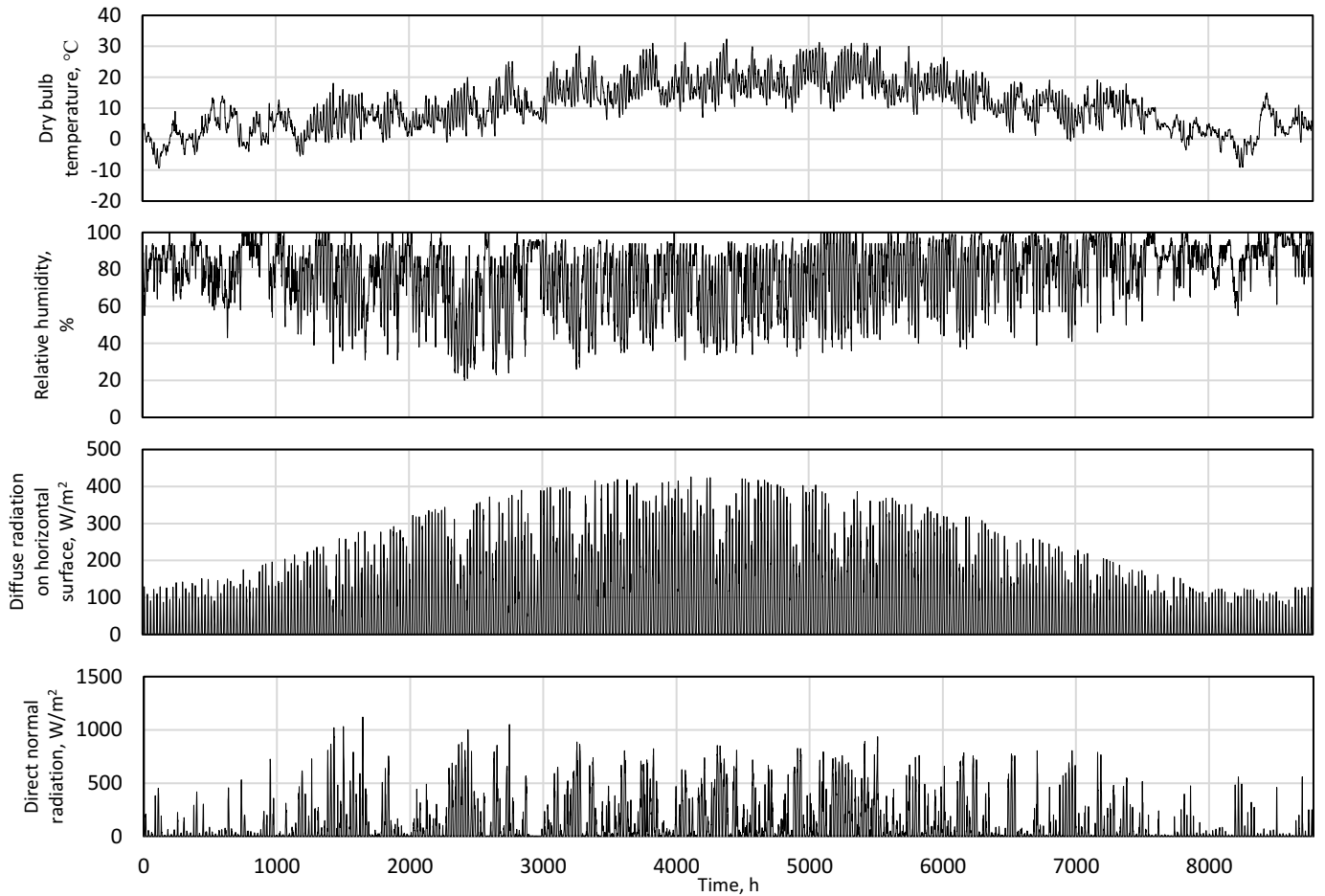


Figure 4: Strasbourg-Entzheim annual weather data. From top to bottom: dry bulb temperature, relative humidity, diffuse radiation on a horizontal surface, direct normal radiation.

we compute the difference between the according values of annual energy consumption. This represents the heat that is lost by virtue of all emission losses within the system.

Now, since the amount of heating energy that is used to obtain the setpoint temperature with a real heat emitter will be equal to the heating energy used with an idealized heater at a higher temperature setpoint, the difference in setpoint temperatures will be the total setpoint variation.

For the baseline configuration we choose a fully convective point heat source. The heat expelled by convection from this idealized heat source is instantly and uniformly distributed within the room, so that no stratification losses occur. The power output of this ideal source is unlimited and responds to the heat demand instantly.

Moreover, to achieve the best control of the system we assume the heat source to have no thermal mass; since it is a point source, embedded losses do not occur either. In other words, such a point heat source represents a case with no inherent heat emission losses. Additionally, this system should be controlled according to operative temperature instead of air temperature, as is the case with real heat emitters.

The operative temperature is defined as the uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the existing non-uniform environment [29]. In most practical cases where the relative velocity is small (<0.2 m/s), or where the difference between mean radiant and air temperature is small ($<4^{\circ}\text{C}$), the operative temperature can be

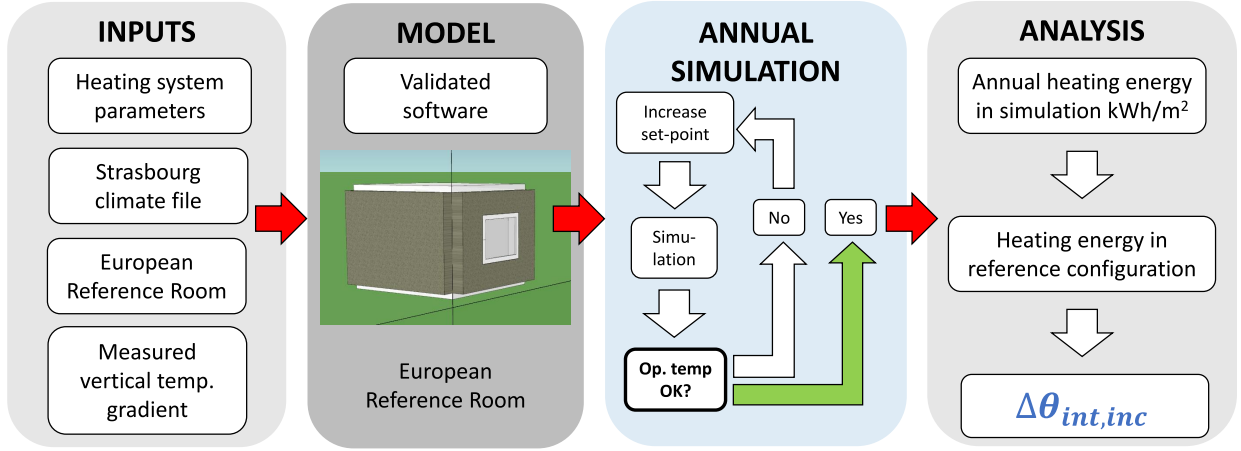


Figure 5: Flow chart of developed method.

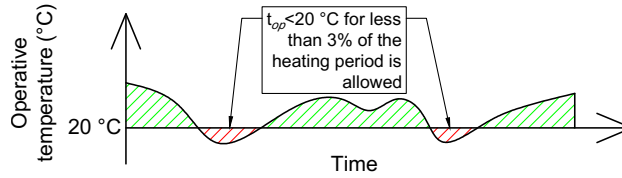


Figure 6: Operative temperature criterion

calculated with sufficient approximation as the mean value of air and mean radiant temperature (MRT),

$$t_{op} = \frac{t_a + t_{MRT}}{2}. \quad (5)$$

For 3% of the heating period, the operative temperature is allowed to deviate below the setpoint value (Figure 6) as described in [30]. This tolerance avoids unnecessary over-dimensioning of heat emitters due to short periods of unfavourable operating conditions. Such systems would otherwise be operating on a lower partial load which reduces system efficiency.

Considering Eq.(1), the effects of $\Delta\theta_{im}$, $\Delta\theta_{hydr}$ and $\Delta\theta_{roomaut}$ are undefined in the boundary conditions of the European Reference Room, therefore they should be evaluated separately. Accordingly, the total setpoint variation within the scope of this method takes the following form:

$$\Delta\theta_{int,inc} = \Delta\theta_{str} + \Delta\theta_{ctr} + \Delta\theta_{emb} + \Delta\theta_{rad}. \quad (6)$$

Since the result is achieved from the simulation software, accurate modelling of the emitters and their control systems is required. The simulation software should use input parameters from field measurements, such as nominal heat outputs, controller (valve) performance parameters and vertical air stratification. Validation and accuracy of emitter models are outside the scope of this paper.

3.2. Annual simulation results

The main results from the simulation campaign are shown in Table 3. In addition to the heating energy used by the space heaters, the energy used to heat the ventilation supply air is also listed. The sum of these two values represents the total heating energy needed in the room, which is reported in the tables both as an absolute value and as divided by the room floor area. The air temperature setpoints represent the setpoint value needed to satisfy the operative temperature constraint that is shown in Figure 6, when it is subjected to the control parameters in Table 2. Such temperature itself is not directly used in the evaluation of the

total setpoint variation, because the direct result of this setpoint is instead the amount of required heating energy. The annual heating energy was compared to the demand of the baseline configuration at different air temperature setpoints, as illustrated in Figures 7a and 7b.

Such a comparison was needed to quantify the total setpoint variation, whose values ranged from 0.14 to 1.20 °C in the new building and from 0.38 to 2.00 °C in the old building. In both cases, the PI controller outperformed the proportional controller, with the simple ON/OFF control exhibiting the worst performance. The annual heating energy demand in the new building type is an order of magnitude smaller than in the old building type. Supply air heating accounted for 8-22% of the total heating energy used in the new building. Lack of supply air heating and heat recovery in the old building means that cold outdoor air is heated up by the heat emitter directly.

Building type	Heat emitter	Air temperature setpoint °C	Annual heating energy used				$\Delta\theta_{\text{int,inc}}$ °C
			Emitter kWh	AHU kWh	Emitter+AHU kWh	kWh/m ²	
New	Ceiling ON/OFF	20.60	298.60	25.61	324.21	20.26	1.20
	UFH ON/OFF	20.40	264.10	42.55	306.65	19.17	0.85
	Air heating	20.30	0.00	303.60	303.60	18.98	0.78
	Rad 21 ON/OFF	20.47	257.30	44.25	301.55	18.85	0.74
	Ceiling PI	20.24	257.70	31.37	289.07	18.07	0.48
	Rad 21 P 2.0	19.83	243.70	44.97	288.67	18.04	0.47
	Rad 21 P 1.5	19.97	241.60	45.69	287.29	17.96	0.44
	Rad 21 P 1.0	20.11	239.50	46.45	285.95	17.87	0.41
	Rad 21 P 0.5	20.26	238.60	47.01	285.61	17.85	0.40
	Rad 21 PI	20.40	235.20	47.65	282.85	17.68	0.34
UFH PI	20.03	214.40	59.58	273.98	17.12	0.14	
Old	Ceiling ON/OFF	20.30	2697.00	0.00	2697.00	168.56	2.00
	Rad 21 ON/OFF	20.68	2436.60	0.00	2436.60	152.29	0.98
	Rad 21 P 2.0	20.55	2431.70	0.00	2431.70	151.98	0.96
	Rad 21 P 1.5	20.57	2409.90	0.00	2409.90	150.62	0.88
	UFH ON/OFF	20.04	2403.00	0.00	2403.00	150.19	0.85
	Rad 21 P 1.0	20.58	2385.60	0.00	2385.60	149.10	0.78
	Rad 21 P 0.5	20.60	2365.30	0.00	2365.30	147.83	0.69
	Ceiling PI	19.96	2345.20	0.00	2345.20	146.58	0.61
	Rad 21 PI	20.62	2341.30	0.00	2341.30	146.33	0.60
	UFH PI	19.81	2287.40	0.00	2287.40	142.96	0.38

Table 3: Detailed simulation results.

To enable further analysis, air and operative temperature duration graphs are shown in Figures 8 and 9. The effect of different control systems is clearly visible when observing the air temperatures during the heating period. Underfloor heating with PI control performed the best in the new building, the air temperature closely followed the operative temperature and thus the operative temperature setpoint. In the old building, the offset between operative and air temperature was greater for all systems.

4. Discussion

According to the current implementation, the EN15316 standard fails to account for different building specifications. Only an indirect evaluation is provided, in the sense that tabulated values provide limited selections that might correspond to a building of a certain era (e.g. older buildings generally have inferior control for space temperature regulation, but not necessarily in the case of refurbished buildings).

Furthermore, the component-wise assessment of emission efficiency presented in Eq.(1) poses a problem from both theoretical and experimental viewpoints. Cross-dependencies between most of the loss compo-

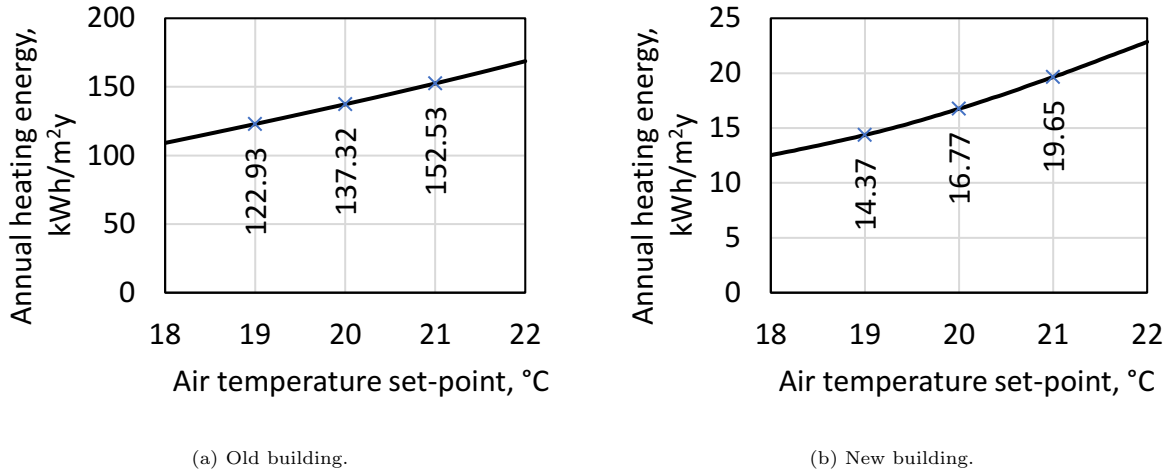


Figure 7: Annual heating energy usage of reference configuration.

nents do exist indeed, making it impossible to evaluate each individual component separately. For example, heat recovery in modern ventilation units greatly reduces the differences in emission losses between different emitter systems. Extra heat is emitted into the room as a result of non-uniform distribution of air temperature due to imperfect control, together with vertical stratification and a higher air-temperature setpoint due to thermal comfort requirements. Such free energy can be largely recovered in the heat air handling unit (a process that is limited only by the heat recovery efficiency), thus reducing the energy required to heat the supply air, which itself contributes to the total heating energy used. This explains the great differences in the annual heating energy used in the heating coil of the AHU, as seen in Table 3.

In Figures 7a and 7b, the correlation between air temperature setpoint and annual heating energy is non-linear. Each additional increase in the temperature setpoint will then have a larger effect on the energy usage. In other words, if each setpoint increment is evaluated separately and later summed up to achieve the total setpoint variation, the energy used will be over-estimated.

Based on these arguments, we recommend that the setpoint variations should be *evaluated as a single total setpoint variation* instead. Our developed method uses a common set of boundary conditions in the European Reference Room to derive this value from annual simulations. Employing two subsets of boundary conditions (for modern as well as older buildings) eliminates the ambiguity under which the emission loss components are evaluated, providing at the same time a common platform to compare emitter emission efficiency under standardised conditions.

Understandably, these boundary conditions cannot reflect the operating conditions in every geographical region in Europe, but rather constitute average European operating conditions. To this end, we also suggest that national versions of the standard may impose a different set of boundary conditions, to best represent the climate and construction materials used in the region under question.

The three components omitted in the total setpoint variation in Eq.(6) are better suited to be evaluated separately from room emission efficiency. Namely, the extra losses due to hydraulic imbalances and building automation systems are part of a system that is larger than a single space and is not uniquely defined within the European Reference Room specification.

On the other hand, intermittent heating should be implemented directly within the simulation, in order to capture its effect on the annual energy use rather than trying to evaluate it indirectly. When considering energy performance certificates of buildings, intermittent may not even be allowed, as is the case in some Nordic countries such as Finland and Estonia, where the required setpoint has to be maintained at all times.

Knowing the detailed parameters of the emitter system, one may argue that their direct implementation in the simulation would provide the most accurate result. While certainly true, this also increases the complexity of the simulation considerably, since detailed heat emitter models need to be used instead of

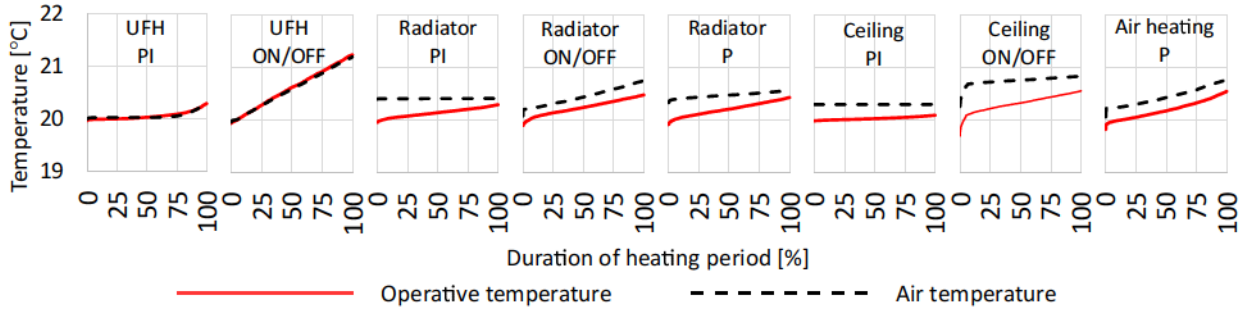


Figure 8: Air and operative temperature duration graphs - new building.

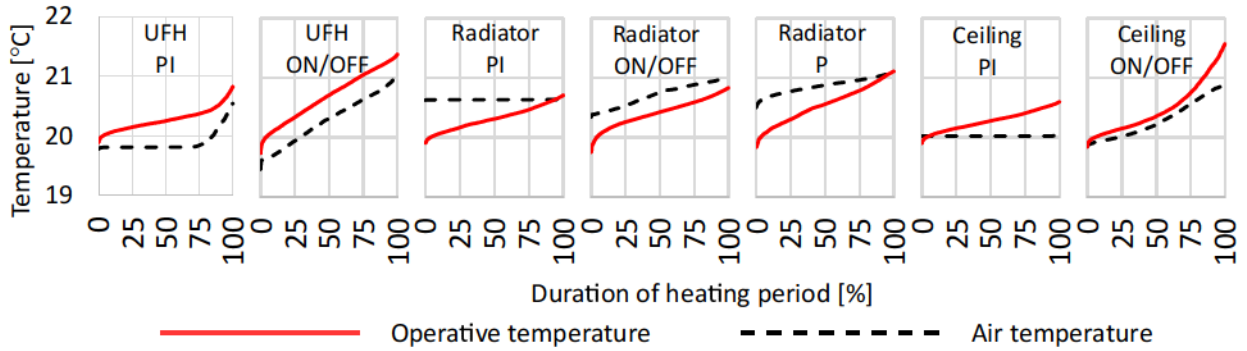


Figure 9: Air and operative temperature duration graphs - old building.

common ideal heaters. The zoning should also be on the room level, rather than on larger floor level zones. Furthermore, this would limit the choice of simulation software available for system designers, because some packages might not be capable enough to include certain parameters whilst air temperature set-points are available in all of them.

There are accordingly valid grounds for using the temperature variation method, together with dynamic simulations based on ideal heaters and flexible zoning. In essence, accuracy of the simulation, time spent modelling and even the uncertainty of the simulation boundary conditions provide by themselves some overall optimisation, where one has to consider the time and money spent against the accuracy of the results. Developing a standardized method for calculating the total set-point variation is also important from the product design viewpoint, as it incentivizes more energy-efficient solutions. Currently, the default values of the corresponding product category are to be used as provided in the standard, while more energy-efficient solutions are unclassified in the context of existing standards. Our method provides a tangible output that enables objective comparison of heat emission efficiency and emission losses among different emitter configurations.

Observing the results from the simulation study, the effect of the control system was the greatest for underfloor heating. This is the expected result, as this system has the highest thermal mass and therefore the greatest thermal inertia. This is more evident in the new building, where the deviations in the heating demand are relatively higher. On the other hand, underfloor heating systems are known to provide the same level of thermal comfort at a lower air temperature when compared to other systems, due to a higher mean radiant temperature [5, 13]. This explains why the UFH with PI control has the lowest total setpoint variation in both building types. Furthermore, the air temperature and operative temperature duration curves in Figures 8 and 9 are almost identical for the underfloor heating in the case of new building, resulting in only minimal heat losses due to the room being controlled by air temperature in relation to the operative temperature criterion.

5. Conclusions

In this study we presented a novel calculation method for assessing heat emission losses in annual heating energy calculations. This enables precise estimation of heat losses in relation to the heating demand, based on the operative temperature. Our model is exact and in line with the present standards and applies to both existing and new buildings.

As a concrete example and application, in this study we calculated product-specific total setpoint variations to be used in the EN15316-2 standard. The definition, specification and boundary conditions of a European Reference Room included in the ISO/DIS 52031 standard were used, along with specific criteria that were developed to obtain the total setpoint variation from annual simulations. The main criterion requires an operative temperature of 20°C to be maintained within the room for at least 97% of the heating period duration. The air temperature setpoint in the simulation was increased until this constraint is satisfied, and the annual heating energy use in the simulation was then compared to the consumption of a lossless reference configuration. Crucially, this comparison allowed achieving a total setpoint variation.

This method was applied to a selected set of emitter and controller configurations, which were previously measured in an experimental study including panel radiators, underfloor heating, ceiling panels and air heating with PI, Proportional and ON/OFF controls. Relevant parameters such as measured vertical stratification, controller parameters and nominal heat outputs were used as input for the model in the annual simulations. Total setpoint variations of up to 1.20 and 2.00 °C were obtained for the new and old building definitions in the Strasbourg climate. This resulted respectively in 20 and 22% increases in annual heating energy consumption due to system losses. Overall, the method provides a reliable, accurate and transparent way to calculate the total setpoint variation for specific product configurations.

We recommend this procedure to quantify the total setpoint variation since it better represents the effect of real system losses, if compared to an individual assessment of each component. The European Reference Room definition provides standardized conditions to objectively compare the heat emission efficiency over a wide variety of configurations. National versions of the standard could define a different set of boundary conditions to best characterize the emission efficiency in their local climate and building practices.

As a concluding remark, we should stress that the precise calculation method introduced in this paper has a general validity, and is not restricted to the heat emitters tested in the European reference room. Accordingly, the promising results that were obtained in this study should be confirmed with further testing on other heat emitters and room layouts.

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References

- [1] S. Serrano, D. Ürge Vorsatz, C. Barreneche, A. Palacios, L. F. Cabeza, Heating and cooling energy trends and drivers in europe, *Energy* 119 (2017) 425 – 434. doi:<https://doi.org/10.1016/j.energy.2016.12.080>.
- [2] D. D'Agostino, B. Cuniberti, P. Bertoldi, Data on european non-residential buildings, *Data in Brief* 14 (2017) 759 – 762. doi:<https://doi.org/10.1016/j.dib.2017.08.043>.
- [3] M. Lu, J. H. Lai, Building energy: a review on consumptions, policies, rating schemes and standards, *Energy Procedia* 158 (2019) 3633 – 3638, innovative Solutions for Energy Transitions. doi:<https://doi.org/10.1016/j.egypro.2019.01.899>.
- [4] Comité Européen de Normalisation, European Standard EN 15316-2:2017. Energy performance of buildings. Method for calculation of system energy requirements and system efficiencies. Space emission systems (heating and cooling), Module M3-5, M4-5., Tech. rep., CEN, Bruxelles, BE (2017).
- [5] A. Hasan, J. Kurnitski, K. Jokiranta, A combined low temperature water heating system consisting of radiators and floor heating, *Energy and Buildings* 41 (5) (2009) 470 – 479. doi:<https://doi.org/10.1016/j.enbuild.2008.11.016>.

- [6] G. Sevilgen, M. Kilic, Numerical analysis of air flow, heat transfer, moisture transport and thermal comfort in a room heated by two-panel radiators, *Energy and Buildings* 43 (1) (2011) 137 – 146. doi:<https://doi.org/10.1016/j.enbuild.2010.08.034>.
- [7] A. Jahanbin, E. Zanchini, Effects of position and temperature-gradient direction on the performance of a thin plane radiator, *Applied Thermal Engineering* 105 (2016) 467 – 473. doi:<https://doi.org/10.1016/j.applthermaleng.2016.03.018>.
- [8] A. Robinson, A thermal model for energy loss through walls behind radiators, *Energy and Buildings* 127 (Supplement C) (2016) 370 – 381. doi:<https://doi.org/10.1016/j.enbuild.2016.05.086>.
- [9] K.-V. Vösa, A. Ferrantelli, J. Kurnitski, A combined analytical model for increasing the accuracy of heat emission predictions in rooms heated by radiators, *Journal of Building Engineering* 23 (2019) 291 – 300. doi:<https://doi.org/10.1016/j.jobe.2019.02.009>.
- [10] D. Wang, Y. Liu, Y. Wang, J. Liu, Numerical and experimental analysis of floor heat storage and release during an intermittent in-slab floor heating process, *Applied Thermal Engineering* 62 (2) (2014) 398 – 406. doi:<https://doi.org/10.1016/j.applthermaleng.2013.09.028>.
- [11] T. Cholewa, R. Anasiewicz, A. Siuta-Olcha, M. A. Skwarczynski, On the heat transfer coefficients between heated/cooled radiant ceiling and room, *Applied Thermal Engineering* 117 (2017) 76 – 84. doi:<https://doi.org/10.1016/j.applthermaleng.2017.02.019>.
- [12] K.-V. Vösa, A. Ferrantelli, T. M. Kull, J. Kurnitski, Experimental analysis of emission efficiency of parallel and serial connected radiators in en442 test chamber, *Applied Thermal Engineering* 132 (2018) 531 – 544. doi:<https://doi.org/10.1016/j.applthermaleng.2017.12.109>.
- [13] M. Maivel, A. Ferrantelli, J. Kurnitski, Experimental determination of radiator, underfloor and air heating emission losses due to stratification and operative temperature variations, *Energy and Buildings* 166 (2018) 220 – 228. doi:<https://doi.org/10.1016/j.enbuild.2018.01.061>.
- [14] D. I. für Normung, DIN V 18599-6:2018-09 — Energy Efficiency of Buildings - Calculation of the Net, Final and Primary Energy Demand for Heating, Cooling, Ventilation, Domestic Hot Water and Lighting. (2018).
- [15] J.-b. Videau, J.-m. Alessandrini, B. Haas, C. Pelé, J.-r. Millet, P. Jallet, L. Reynier, E. Fleury, An introduction to the development of the french energy regulation indicators and their calculation methods, in: CLIMA 2013, 2013.
- [16] B. W. Olesen, M. de Carli, Calculation of the yearly energy performance of heating systems based on the european building energy directive and related cen standards, *Energy and Buildings* 43 (5) (2011) 1040 – 1050, tackling building energy consumption challenges - Special Issue of ISHVAC 2009, Nanjing, China. doi:<https://doi.org/10.1016/j.enbuild.2010.10.009>.
- [17] J. Seifert, M. Knorr, A. Meinzenbach, F. Bitter, N. Gregersen, T. Krogh, “review of thermostatic control valves in the european standardization system of the en 15316-2/en 215”, *Energy and Buildings* 125 (2016) 55 – 65. doi:<https://doi.org/10.1016/j.enbuild.2016.04.066>.
- [18] C. Brembilla, M. Vuolle, R. Östin, T. Olofsson, Practical support for evaluating efficiency factors of a space heating system in cold climates, *Energy Efficiency* 10 (5) (2017) 1253–1267. doi:10.1007/s12053-017-9506-7.
- [19] Comité Européen de Normalisation, EN 442-2:2014, Radiators and convectors - Part 2: Test methods and rating (2014).
- [20] A. Ploskić, Q. Wang, S. Sadrizadeh, A holistic performance evaluation of ventilation radiators – an assessment according to en 442-2 using numerical simulations, *Journal of Building Engineering* 25 (2019) 100818. doi:<https://doi.org/10.1016/j.jobe.2019.100818>.
- [21] IDA ICE - Indoor Climate and Energy (2013).
- [22] K.-V. Vösa, A. Ferrantelli, J. Kurnitski, Annual performance analysis of heat emission in radiator and underfloor heating systems in the European reference room, in: E3S Web of Conferences, Vol. 111, 2019. doi:10.1051/e3sconf/201911104009.
- [23] K.-V. Vösa, A. Ferrantelli, J. Kurnitski, Experimental study of radiator, underfloor, ceiling and air heater systems heat emission performance in TUT nZEB test facility, in: E3S Web of Conferences, Vol. 111, 2019. doi:10.1051/e3sconf/201911104005.
- [24] International Organization for Standardization, ISO 15316-2:2017. Energy performance of buildings - Method for calculation of system energy requirements and system efficiencies - Part 2: Space emission systems (heating and cooling), Module M3-5, M4-5 (2017).
- [25] International Organization for Standardization, ISO 52031. Energy performance of buildings — Method for calculation of system energy requirements and system efficiencies — Space emission systems (heating and cooling). *Pending*.
- [26] American Society of Heating Refrigerating and Air-Conditioning Engineers, International Weather Files For Energy Calculations 2.0 (IWEC2) (2012).
- [27] Comité Européen de Normalisation, En 15377-1, heating systems in buildings – design of embedded water based surface heating and cooling systems – part 1: Determination of the design heating and cooling capacity (2008).
- [28] A. Bring, P. Sahlin, M. Vuolle, Models for building indoor climate and energy simulation, *Journal of Research and Development* 21 (1999) 350–359. <https://www.equa.se/dncenter/T22Brep.pdf>.
- [29] I. O. for Standardization, ISO 7726:1998 Ergonomics of the thermal environment — Instruments for measuring physical quantities (1998).
- [30] Comité Européen de Normalisation, Energy performance of buildings - Ventilation for buildings - Part 2: Interpretation of the requirements in EN 16798-1 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (Module M1-6) (2019).