Quantification of the Impact of Indoor Temperature Gradients in Dwellings on Useful Recovered Heat of Ventilation Systems

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ABSTRACT

Ventilation in buildings dilutes the indoor air pollutants by replacing part of the air with outdoor air to guarantee an adequate indoor air quality (IAQ). In heating-dominated climates, the exchanged air has a lower mean temperature than the indoor air, which leads to a surplus heating demand in the building. A heat exchanger recovers part of the heat from the expelled air, contributing to the reduction of the extra heating demand. Smart ventilation systems work with reduced airflows, without compromising the IAQ and lowering the heating demand. A simplified way to calculate the heating demand reduction is possible considering uniform indoor temperatures and knowing a few parameters such as the outdoor air temperature. However, the in a real building this is not the case, and the calculation neglects the different temperatures in the zones. When using a central heat exchanger, the warmer airflows from heated zones are combined with colder airflows from unheated zones, reducing the potential of the recovered heat. Moreover, the recovered heat can be distributed among zones that may not need heat, to detriment of the zones that demand it. The useful heat that can reduce the heating demand is then reduced compared to the scenario that uses uniform indoor temperatures. Besides, the internal airflows between zones caused by the ventilation system can affect the heating demand when transferring heat from warmer zones to the colder ones, and vice versa. Smart ventilation systems reduce the latter effect and prevent some heat to be released into the atmosphere, which results in an equivalent effect as the recovered heat. The purpose of this work is to investigate the mentioned effects and determine their importance using building energy simulations. To do so, six typical dwellings were modelled combined with ten ventilation systems representing various commercial solutions and six extra non-smart ventilation systems used as reference. The study calculates three heating demands: when the buildings do not have a ventilation system, when the ventilation system is connected and when the ventilation system works without a heat exchanger (if present) or at maximum design airflows (neglecting the smart controls). On top of that, two heating scenarios are investigated: uniform heating and non-uniform heating. For each, the useful heat can be calculated and expressed as a reduction in the surplus heating demand. Finally, a coefficient is obtained that relates the performance between both heating modes. The results show that, under non-uniform heating conditions, the energy performance of the ventilation systems is typically from 5 % lower to 1 % higher than the energy performance under uniform heating conditions. Furthermore, apart from the ventilation system, the dwelling envelope appears to be the most influencing factor for the energy performance under both conditioning strategies.

KEYWORDS

Temperature gradients, heat recovery, heat exchanger, heating demand, ventilation.

1 INTRODUCTION

In a dwelling, the temperature in different zones (rooms) is normally not the same. Usually, there are some zones that have a higher temperature than other zones. The reasons for higher temperature are multiple: better insulation of the zone, lower exposure to the outdoor environment, solar radiation through the windows, internal heat gains from people and their activities, or a higher setpoint temperature for heating. The zones with lower temperature normally have a low or null occupation. Because of that, the internal gains are smaller, and they may not be heated by the heating system. The colder zones are, for example, toilets or hallways, while the warmer zones are living rooms or offices. The presence of a ventilation system usually increases the internal airflows, tending to reduce the temperature gradients. The indoor air circulates through different zones, exchanging heat between warmer and colder zones. This affects the individual heating demand of each of the zones. Hence, colder zones gain some heat from warmer zones, which are consequently cooled down. Then, the warmer zones require an extra heating demand if they are being heated. However, the colder zones, typically unheated, do not give anything in return, but their temperature is slightly warmer thanks to the ventilation system. This effect is silenced in many EPBD calculations since the indoor temperatures are considered equal in the whole dwelling. Previous works (Faes et al., 2017; Janssens et al., 2018) suggest that that the usability of energy efficient ventilation strategies might be less than theoretically predicted by the EPBD related calculation methods. Those calculations use a simplified approach that let the user estimate the energy performance of a building knowing a few parameters with reasonable results. However, the deviation with respect to the real behaviour of the building can be important, and a more accurate analysis can be carried out to develop methods to reduce the related uncertainty. To do so, it is necessary to know how big the differences are between the simplified calculations and an alternative method that includes the temperature gradients. However, the effect of the temperature gradients cannot be easily determined since many parameters are involved. The geometry of the building and distribution of the zones becomes a pivotal factor, as the internal airflows strongly depend on the connected elements in the airflow network. Moreover, smart ventilation systems, which can regulate the airflows as needed, complicate the issue. This level of complexity can be evaluated using a dynamic approach, through multizone building simulations. Using them, this study tries to determine the impact of the of the indoor temperature differences within well insulated and airtight dwellings in combination with different smart and non-smart ventilation systems, and to compare the energy performance among them. This study is focused on the typical dwellings that can be found in Belgium, the Netherlands and Ireland

2 METHODOLOGY

To evaluate the energy performance, this study uses a variation of one of the coefficients defined by a previous work (Faes et al., 2017). The coefficients are calculated using the annual heating demand of three scenarios: 1) The no ventilation scenario (NV), represented by a dwelling without a ventilation system and, consequently, null ventilation heat losses; 2) the characteristic ventilation scenario (CV), represented by a dwelling with a ventilation system that works with its characteristic controls and heat recovery (HR) function (if available); and 3) the maximum flowrates no heat recovery scenario (MFNHR), representing the CV scenario without heat recovery and working as a constant air volume ventilation system (CAV) which flowrates are the maximum flowrates defined for each dwelling.

The coefficient $\eta_{IV,max,0}$ (derived from η_4 in Faes's work) is shown in equation (1) and it represents the ratio between the heating demand reduction when changing from the MFNHR scenario to the CV scenario, divided by the maximum reduction range, considered to be the difference between the heating demand of the MFNHR scenario and the NV scenario. This ratio shows how close a ventilation system is to the ideal case, which has null ventilation heat losses.

$$\eta_{IV,max,0}\,[-] = \frac{Q_{max,0} - Q}{Q_{max,0} - Q_{nv}} \tag{1}$$

Where $\eta_{IV,max,0}$ is defined as the ventilation heating demand coverage ratio respect to the MFNHR scenario, $Q_{max,0}$ is the heating demand in kWh/m²/year of the MFNHR scenario, Q the heating demand in kWh/m²/year of the CV scenario, and Q_{nv} is the heating demand in kWh/m²/year of the NV scenario.

To see the influence of temperature gradients, the coefficient $\eta_{IV,max,0}$ is obtained from two heating strategies (uniform and non-uniform) and they are compared in form of the ratio shown in equation (2). The terms with the “u” subscript correspond to the parameters obtained from the uniform conditioning strategy.

$$\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}}\,[-] = \frac{\dfrac{Q_{max,0} - Q}{Q_{max,0} - Q_{nv}}}{\dfrac{Q_{max,0,u} - Q_u}{Q_{max,0,u} - Q_{nv,u}}} \tag{2}$$

3 MODEL DESCRIPTION

A series of dynamic multi-zone building energy simulations (BES) were developed to evaluate the effect of the temperature gradients and zoning on the performance of energy efficient ventilation strategies in dwellings. The studied cases are representative of the typical dwellings in the countries observed in this study and some of the ventilation systems available in the market. The models consist of 1) a building envelope representing the zones and the constructive elements of a dwelling, 2) the weather conditions, 3) the occupancy profiles representing people and their activities, 4) a quasi-ideal conditioning system that can set the operative temperature of each zone as required, instantaneously, and 5) a ventilation system that can exchange air between the dwelling and the exterior. The building envelope, the weather, and the occupancy profiles represent the boundary conditions, while the conditioning system and the ventilation system are the proposed variations to evaluate the effect of the temperature gradients. The models are built in Modelica language using open-source libraries (Jorissen et al., 2018; Wetter, 2009) and tailored components coded with them.

3.1 Dwelling envelope

The dwelling envelope represents the thermal and airflow model of an actual dwelling. The zones are represented as air nodes where the thermal and airflow model converge. The thermal part of the model includes the outer walls (facades), roofs, windows (glazing and frames), slabs on ground, walls shared with adjacent dwellings, exterior doors, the interior partition walls and floors and the interior doors that separate the different zones in the dwelling. This part of the model can exchange heat between the zones and their surroundings. The airflow model consists of windows, doors, cavities, and the infiltration network associated to the outer walls, roof and the interior partition walls and floors. All constructive elements in the thermal model, except for the slabs on ground, are included in the airflow network. This part of the model exchanges air masses with the air nodes and their surroundings.

Six envelopes were included to have an appropriate representation of the typical dwellings in the countries considered in this study. The selected dwellings are a Belgian detached house, a Dutch terraced house, an Irish semidetached house, an Irish detached house, and a Dutch apartment. The latter has two variations, A and B, which differ on the division between the kitchen and the living room. The variation A has a partition wall, while in the variation B the wall was replaced by a large cavity. The geometrical parameters of the dwellings are listed in Table 1.

Table 1: Geometrical parameters of the dwellings

Parameter	Detached (BE)	Terraced (NL)	Semidetached (IE)	Detached (IE)	Apartment A/B (NL)
Zones	11	10	14	21	8
Floor area	192.6 m²	124.3 m²	169.9 m²	217.7 m²	102.0 m²
Air volume	398.3 m³	323.2 m³	407.1 m³	566.0 m³	265.0 m³
Area façades	155.5 m²	27.1 m²	114.8 m²	177.9 m²	29.7 m²
Area roof	88.6 m²	77.2 m²	62.7 m²	296.7 m²	0.0 m²
Area windows	28.2 m²	27.3 m²	24.9 m²	35.4 m²	28.2 m²
Area slabs	76.6 m²	45.4 m²	59.0 m²	197.1 m²	0.0 m²
Area Adjacent Dwellings	0.0 m²	136.6 m²	89.0 m²	0.0 m²	261.6 m²
Window-to-wall ratio	0.18	1.01	0.22	0.20	0.95
Compactness	0.88 m^{-1}	0.97 m^{-1}	0.86 m^{-1}	1.25 m^{-1}	1.21 m^{-1}
Shape factor*	1.35	1.40	1.34	2.17	1.63

*(D'Amico & Pomponi, 2019)

Two kinds of insulation levels were considered to represent newly constructed buildings. Each of the previous envelopes have the variations listed in Table 2.

Table 2: Insulation and airtightness of the building envelopes

Parameter	Newly constructed building	Passive building
U-value walls	0.38 W/m²/K	0.15 W/m²/K
U-value roof	0.32 W/m²/K	0.15 W/m²/K
U-value slabs	0.38 W/m²/K	0.15 W/m²/K
U-value windows	1.1 W/m²/K	0.6 W/m²/K
G-value windows	0.589	0.423
U-value frames	0.83 W/m²/K	0.7 W/m²/K
Infiltration	2 ACH50	0.6 ACH50

To reduce the mixing of the indoor air from different zones to the minimum, all interior doors are always closed. However, all interior doors have a leakage area representing a gap between the door and the floor. For the interior doors connected to the kitchen the gap is equal to 140 cm². The rest of the interior doors have a gap of 70 cm². The presence of gaps avoids the installation of interzonal air grilles. Specific trickle vents are added to the habitable spaces for the ventilation systems that use them. They remain disabled for the rest of the ventilation systems.

3.2 Weather

To cover all climate zones of interest (Belgium, the Netherlands and Ireland) Brussels and Cork were selected. The climate in the Netherlands is represented by Brussels, as Belgium and the Netherlands are neighbouring countries that have similar climates. Marseille was included as a comparatively warmer climate, while Berlin was selected as a representative climate of the typical European continental climate. The weather files were obtained using the commercial tool Meteonorm. A description of the outdoor temperature and humidity is shown in Table 3.

Table 3: Statistical description of the outdoor temperature and relative humidity for the different weathers

Parameter		Brussels	Marseille	Cork	Berlin
Outdoor temperature	min	-7.6 ºC	-3.7 ºC	-2.2 ºC	-9.8 ºC
	max	29.4 ºC	35.8 ºC	23.6 ºC	32.6 ºC
	mean	10.8 ºC	15.6 ºC	10.0 ºC	10.3 ºC
	median	10.8 ºC	15.4 ºC	9.8 ºC	10.2 ºC
	std	6.7 ºC	7.9 ºC	4.6 ºC	7.9 ºC
Outdoor relative humidity	min	34.0 %	23.0 %	42.0 %	27.0 %
	max	100.0 %	100.0 %	100.0 %	100.0 %
	mean	77.7 %	65.4 %	84.2 %	72.8 %
	median	80.0 %	66.0 %	87.0 %	75.0 %
	std	14.9 %	17.3 %	11.9 %	14.9 %

3.3 Occupancy profiles

Two occupancy profiles were defined using a variation of the stochastic model StROBe (Baetens & Saelens, 2016). One profile (low) is composed of two full time adult workers, while the other (high) is composed of one full time adult worker, one non-working adult, a teenager, and an infant. Most of the common activities are included in the occupation profiles, such as cooking, sleeping, working on a PC, and taking showers. However, window opening, washing clothes, and drying clothes are not included.

3.4 Conditioning system

The conditioning system is modelled as reactive components that can inject or extract unlimited heat to the zones in the building envelope. In the model, there are as many conditioning systems as there are zones in the building envelope. They can provide or extract heat independently from the other zones, only following their own setpoint temperatures, which are specific for each zone. The control is based on the operative temperature of the zones, which is the arithmetic average between air temperature and the mean radiant temperature. The conditioning systems are connected directly to the air nodes (no intermediate thermal resistors or capacitors to avoid thermal inertia). 70 % of the heat is exchanged to the air volume (convective heat transfer), while the remaining 30 % is transmitted to the surface of the walls (radiative heat transfer), since their temperature is directly related to the operative temperature of the zone. Heating (injection of heat into the zones) and cooling (extraction of heat from the zones) are counted separately. This means that both processes are not compensated if a zone is being heated and other zone cooled at the same time. The conditioning system is activated instantaneously when it is needed. It is activated based on the difference between the setpoint temperature and the operative temperature of the zone. The setpoint temperature is reached in immediately, with a small difference of less than 0.01 ºC, which is accurate enough. These characteristics make the conditioning system quasi-ideal.

The way the dwelling is conditioned is determined exclusively by the setpoints and the control implemented in the quasi-ideal conditioning system. Two main strategies are defined to reach thermal comfort in the dwelling: non-uniform, which represents a dwelling with zones at different temperatures; and uniform, representing a dwelling with no or very small temperature gradients between zones, and closer to the EPBD calculations.

Non-uniform conditioning strategy

The study by (Peeters et al., 2009) about thermal comfort in dwellings defines comfort temperatures for different types of rooms that can be used as setpoint temperatures for the conditioning system. The comfort temperatures are calculated according to an equivalent outdoor temperature ($T_{e,ref}$):

$$T_{e,ref}[\text{ºC}] = \frac{T_{\text{today}} + 0.8 \cdot T_{today-1} + 0.4 \cdot T_{today-2} + 0.2 \cdot T_{today-3}}{2.4} \tag{3}$$

Where the terms $T_{today-i}$ are calculated as follows:

$$T_{today-i}[\text{ºC}] = \frac{T_{\underset{today-i}{max}} + T_{\underset{today-i}{min}}}{2} \;; \quad i \in [0,1,2,3] \tag{4}$$

Where $T_{\underset{today-i}{max}}$ and $T_{\underset{today-i}{min}}$ are the maximum and minimum temperatures in degrees Celsius registered the day *i* before the present day, respectively. Note that the comfort temperature of a day in the equation (4) is based on the temperatures of that day, which need to be known beforehand.

The comfort temperatures are defined for the bathroom, bedroom, and the rest of the zones, such as the living room. They are calculated to represent 5 % of predicted percentage of dissatisfied (PPD). For the bathroom, the comfort temperature is shown in equation (5):

$$T_n[ºC] = \begin{cases} 0.112 \cdot T_{e,ref} + 22.65\ ºC; & T_{e,ref} < 11\ ºC \\ 0.306 \cdot T_{e,ref} + 20.32\ ºC; & T_{e,ref} \geq 11\ ºC \end{cases} \tag{5}$$

For bedrooms, the comfort temperature is:

$$T_n[ºC] = \begin{cases} 16\ ºC; & T_{e,ref} < 0\ ºC \\ 0.23 \cdot T_{e,ref} + 16\ ºC; & 0\ ºC \leq T_{e,ref} < 12.6\ ºC \\ 0.77 \cdot T_{e,ref} + 9.18\ ºC; & 12.6\ ºC \leq T_{e,ref} < 21.8\ ºC \\ 26\ ºC; & T_{e,ref} \geq 21.8\ ºC \end{cases} \tag{6}$$

For the rest of the rooms, the comfort temperature is:

$$T_n[ºC] = \begin{cases} 0.06 \cdot T_{e,ref} + 20.4\ ºC; & T_{e,ref} < 12.5\ ºC \\ 0.36 \cdot T_{e,ref} + 16.63\ ºC; & T_{e,ref} \geq 12.5\ ºC \end{cases} \tag{7}$$

The term T_n is named "neutral temperature" and it could be used as the heating and cooling setpoints for each type of room. To avoid extraordinary heating and cooling demands because of using the same setpoint for heating and cooling, a global limit was added for heating and cooling. Then, the conditioning system is not allowed to heat up a zone over 22 ºC and it cannot cool down a zone below 26 ºC. The resulting setpoint are shown in Figure 3-1.

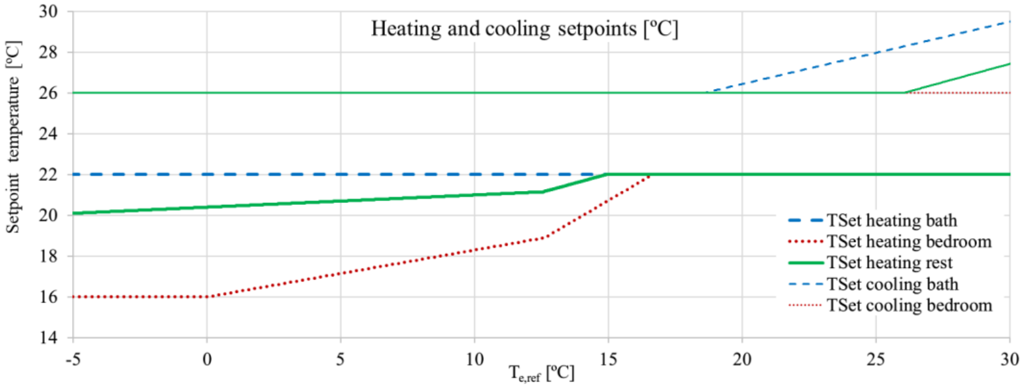

Figure 3-1: Heating and cooling setpoint temperatures

Uniform conditioning

In EBPD calculations, the indoor temperature is defined with the average temperature of the dwelling, which is the weighted average temperature of all zones. In calculations, this is equivalent to consider that all rooms have the same temperature. The heating and cooling demands are then calculated for the entire dwelling, neglecting the overheating and the underheating of the zones. In multi zone approaches, this effect cannot be ignored. To have comparative scenarios between uniform and non-uniform conditioning strategy, one approach is to obtain the average temperature of the dwelling from the non-uniform scenario and use it as an input for the uniform conditioning scenario. In this case, all zones in the dwelling will have the same operative temperature and the average temperature of the dwelling would be the same in uniform and non-uniform conditioning. This approach, however, forces the conditioning system to adapt the temperatures all the time with every small fluctuation. The simulation results show that there is heating and cooling in the same zone several times a day, leading to very high heating and cooling demands at the end of the year, compared to the non-uniform conditioning strategy. An alternative approach is to use the same setpoint temperature for all zones for heating and another setpoint for cooling, leaving a gap of several degrees where heating nor cooling are allowed. This approach brings the heating demand and cooling demands to typical values and keeps the temperature of all zones in the dwelling between the region limited by the heating and cooling setpoints. By using this, the temperature in the dwelling is not perfectly uniform, but the demands are reduced, and no previous simulations are needed. In this study, the latter approach is used with constant setpoint temperatures of 18 ºC for heating and 26 ºC for cooling.

3.5 Ventilation systems

The European Ventilation Industry Association (EVIA) and NEN 1087 (NEN, 2019) define different ventilation system types (VST), from VST1 to VST7, depending on how the rooms in the dwelling are ventilated. This work is focused in VST3, VST4, VST5 and VST7, which are the types of the analysed commercial ventilation systems. VST3 consists of mechanical extraction from the exhaust spaces (ES) (toilets, bathrooms, and kitchens) and natural supply through ventilation trickles located in the habitable spaces (HS) (living rooms, bedrooms, offices). VST4 consist of mechanical exhaust in exhaust and habitable spaces with natural ventilation using trickle vents located in the HS. VST5 consist of balanced mechanical exhaust from the ES and mechanical supply to the HS, with the presence or not of a heat exchanger (HEx). VST7 consist of mechanical exhaust from the ES and decentralized ventilation in HS. In each HS there is supply and exhaust, typically with the presence of a heat exchanger. VST3 and VST4 cannot have a heat recovery strategy, but they can reduce the ventilation heat losses adapting the ventilation airflows using demand control (DC) based on CO_2 or humidity sensors.

Table 4: Ventilation flowrates for each dwelling and mechanical exhaust flows by VST

		Base airflows [m³/h]	**VST3 [m³/h]**	**VST4 [m³/h]**	**VST5 [m³/h]**	**VST7 [m³/h]**
Ventilation systems		**--**	**3a, 3b, 3c, 3d**	**4**	**5a_c, 5d, 5e, 5f, 5g**	**7a_c, 7d**
Detached (BE)	Exhaust	151.2	348.8	500.0	348.8	500.0
	Supply	348.8	0.0	0.0	348.8	348.8
Terraced (NL)	Exhaust	151.2	199.6	350.8	199.6	350.8
	Supply	199.6	0.0	0.0	199.6	199.6
Semidetached (IE)	Exhaust	183.5	183.5	367.0	183.5	367.0
	Supply	183.5	0.0	0.0	183.5	183.5
Detached (IE)	Exhaust	235.1	235.1	470.2	235.1	470.2
	Supply	235.1	0.0	0.0	235.1	235.1
Apartment A/B (NL)	Exhaust	151.2	208.8	360.0	208.8	360.0
	Supply	208.8	0.0	0.0	208.8	208.8

The exhaust and supply flowrates were calculated for each dwelling using the national standards where the dwelling is located. The Belgian dwellings follow the standard NBN D50-001 (BIN, 1991) For the Dutch dwellings, the relevant standard is NEN 1087 (NEN, 2019), and for Ireland the flowrates are calculated according to the Technical Guidance of the Building Regulations (Department of Housing, Local Government and Heritage, 2020). Table 4 shows a summary of the flow rates calculated for each dwelling and the corresponding mechanical airflows for each VST. The numbers correspond to the nominal airflows for CAV systems and for the MFNHR scenario.

Ten ventilation systems with their characteristic DC were defined in collaboration with industrial partners to represent typical domestic ventilation solutions present in the market, named 3a, 3b, 3c, 3d, 4, 5d, 5e, 5f, 5g, and 7b. The digit indicates the VST. For VST5 and VST7 systems, the effectiveness of the heat exchangers varies between 78 % and 93 %. Additionally, three reference CAV ventilation systems were added for VST5, working at 100 %, 66 % and 33 % of the flowrates indicated for the VST5 in Table 4. They are named 5a_c, 5b_c and 5c_c, being the "_c" an indication of CAV system. They have HEx with a constant effectiveness of 85 %. Similarly, other three systems were defined for VST7 with 100 %, 66 % and 33 % of the flowrates indicated in Table 4 with HEx with a constant effectiveness of 85 %: 7a_c, 7b_c and 7c_c. In total, 16 ventilation systems were included in this study.

4 RESULTS

The results were obtained from the combination of the number of dwellings (6), the number of insulation levels (2), the number of climates (4), the occupancy profiles (2), the conditioning strategies (2), the amount of ventilation systems (16) and the number of scenarios (3). However, the NV scenario is common for all ventilation system, so the total number of simulations was 6×2×4×2×2×16×(2+1/16)=6336. The results focus on the main aspects of the ventilation systems, which are the VST and the strategies to reduce the ventilation heat losses (heat recovery: NR and no NH, and demand control: DC and CAV).

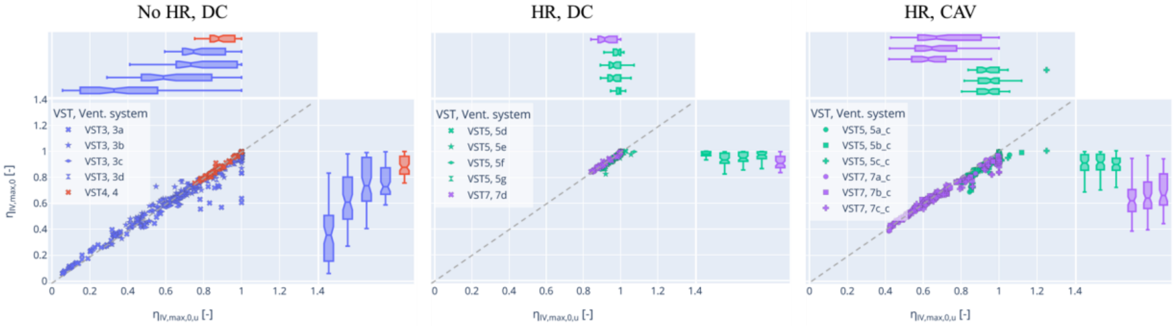

Figure 4-1: Graphical representation of $\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}}$ for the ventilation systems

Figure 4-1 shows $\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}}$ graphically as the ratio between $\eta_{IV,max,0}$ and $\eta_{IV,max,0,u}$. In general, the ratio seems to be below the unit (represented on the graphs by the dashed lines) as $\eta_{IV,max,0}$ increases. For lower values of $\eta_{IV,max,0}$ the ratio tends to get over 1. However, lower values for $\eta_{IV,max,0}$ indicate that the ventilation system has a lower compensation of the surplus heating demand generated by the installation of a non-smart ventilation system. All VST3 systems show the lowest values for $\eta_{IV,max,0}$ and $\eta_{IV,max,u}$, compared to the rest of the VST. VST4 performs similarly to the systems that have heat recovery and better than VST3 systems, even though both VST have similar strategies to reduce the ventilation heat losses. The reason is that VST4 has a better control on the airflows in the different rooms. The VST3 systems have sensors that are in zones which exhaust air is not directly controlled by the ventilation system, resulting in air removal from adjacent zones. VST5 and VST7 are divided into two categories in Figure 4-1. The commercial ventilation systems (HR, DC) show high values for $\eta_{IV,max,0}$, always over 0.8. In some cases, some VST5 systems have a $\eta_{IV,max,0,u}$ over the unit, indicating that the installation of the ventilation system covers more than the surplus heating demand generated by the installation of a basic ventilation system (MFNHR scenario), under uniform conditioning. This behaviour can happen in well insulated buildings, warmer climates and VST5 systems and it is caused by the overheating resulting from the recovered heat. VST7 systems do not usually experience this issue because part of the exhaust air is extracted directly to the exterior without being treated and the heat exchangers do not work with balanced flows. Furthermore, the systems that do not have HR cannot overpass the mentioned limit, since they are not able to recover heat from the exhaust to be injected again in the dwelling. On the right graph of the Figure 4-1, the reference systems have a worse behaviour than the commercial systems, showing slightly lower values for $\eta_{IV,max,0}$. Nevertheless, there are some cases where $\eta_{IV,max,0,u}$ is over the unit, as in the commercial systems.

Figure 4-2 shows the ratio $\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}}$ making distinctions between the strategies present to reduce the ventilation heat losses and the VST. On the upper part of the figure, the systems with DC and HR show values closer to 1 and more concentrated than the rest. Their equivalent versions without DC (CAV, HR) have a lower value and the values are less concentrated. For systems that do not have HR, the points are more spread, and more cases show values over 1, meaning that the system performs better in non-uniform heating than in uniform heating, compared to their respective MFNHR scenarios. On the bottom of the figure, VST4 has the highest concentration of points and the highest median value than the rest. VST3 shows a wide range of points that causes the behaviour seen on the upper graph (DC, no HR). VST7 shows closer values to the unit than VST5, meaning that VST7 tend to perform closer to the uniform conditioning strategy in terms of heating demand reduction, using their respective MFNHR scenarios.

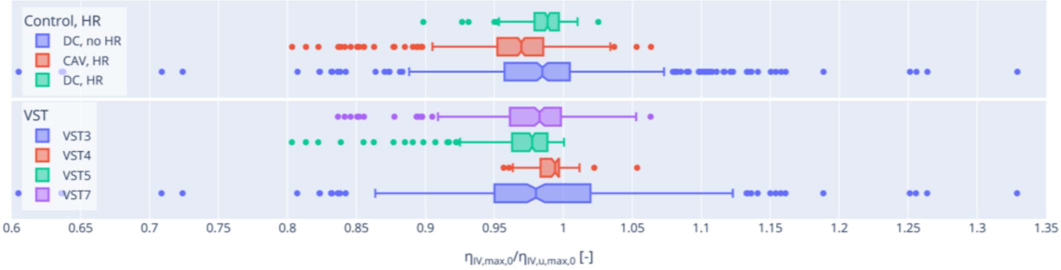

Figure 4-2: Distribution of $\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}}$ by control, HR and VST

Looking at the rest of combinations apart for the ventilation system, the dwellings are the most influencing factor for $\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}}$. Figure 4-3 shows the distribution of the factor for the six dwellings. The detached house in Ireland, which has the most complex geometry and the highest heat losses through its envelope, has the lowest median and the highest spread of values. The apartments are geometrically identical, however, the variation A, which has a partition wall between the kitchen and the living room, shows higher values for the factor, overpassing $\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}} = 1$ in some cases.

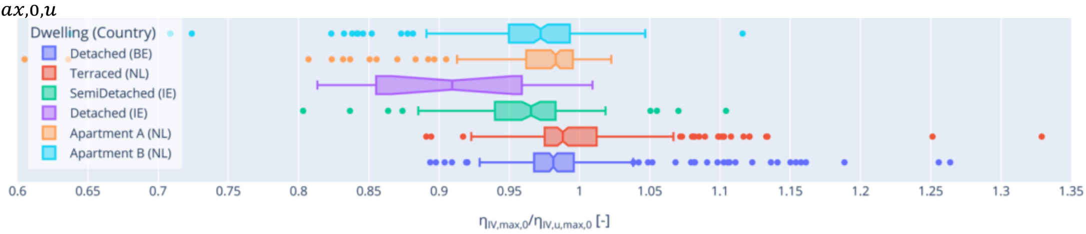

Figure 4-3: Distribution of $\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}}$ by dwelling

5 CONCLUSIONS

DC strategies have a significant impact on the factor $\eta_{IV,max,0}$. VST4 systems have a similar or better effect than the CAV systems with HR, meaning that the DC strategy is aa relevant factor in energy savings. VST3 systems do not show similar results because they have less control of the supply flows and, to compensate, they operate at higher rates, showing more spread values. In systems with HR, the use of DC increases the value of the factor for both heating strategies. For VST7, the impact is more relevant, and it may be influenced by the fact of not having balanced airflows passing through the heat exchangers, which must be further investigated. VST3 systems have a lower benefit compared to the corresponding MFNHR scenarios, showing values that can go from almost 0.1 to 1. VST5 and VST7 systems show higher values for $\eta_{IV,max,0}$ when combining DC with HR.

None of the systems without HR overpass the limit $\eta_{IV,max,0} = 1$, as they cannot recover heat from the exhaust airflows.

The results indicate that the factor $\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}}$ is typically lower than 1, being most of the points in the range [0.95, 1.01] and indicating that, in general, the non-uniform conditioning strategy has a slightly lower energy performance than in the uniform conditioning strategy.

The building envelope is the most influencing variation for $\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}}$. The geometry and the distribution of the zones are important factors to consider for the evaluation of the impact of indoor temperature gradients in the heating demand of the building.

The factors are linked to the corresponding MFNHR scenario, which is different for each of the variations analysed in the study. The heating demand of the used scenarios can be used to complement this information. However, this paper focus on the energy performance of a ventilation system compared to similar situations for that specific system, and comparisons with other ventilation systems are made at this level. The results obtained can be used to develop more accurate calculations in the EPBD, considering that the effect of the temperature gradients may influence the annual heating demand in dwellings depending on the ventilation system. In future work, this analysis can be extended adding realistic conditioning systems and taking into consideration the electricity use of the ventilation systems, also comparing the primary energy use of the different scenarios, instead of just using the heating demand.

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