ENERGY PERFORMANCE OF PASSIVE SCHOOL BUILDINGS – AN ANALYSIS OF BUILDING PROPERTIES AND BOUNDARY CONDITIONS

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ABSTRACT

To evaluate the requirements for passive school buildings, simplified calculation methods based on EN ISO 13790 are used. For these simplified calculations a fixed indoor temperature is used regardless the building properties, the climatic data or the building use data.

Considering the large impact of this temperature on the heating demand, an accurate estimation is important to obtain representative results. This paper analyses the accuracy of the fixed indoor temperature. Multiple dynamic simulations of a reference school building varying the thermal inertia, the insulation qualities, glazing properties and shading are performed to indicate the effect on the indoor temperature. The results show a rather limited impact of the thermal inertia. On the other hand, a more accurate definition of the fixed indoor temperatures based on the function and use of the rooms is important to obtain better results.

INTRODUCTION

In Flanders (Belgium), the evolution towards more energy efficient schools boosted in 2009 by the approval and subsidizing of 24 passive schools, covering up to 65000 m². The performance requirements for passive school buildings were set by the decree ‘Energy performance in schools’ issued on 07/12/2007 by the Flemish government:

- annual net heating demand $\leq$ 15 kWh/(m².a)
- annual net cooling demand $\leq$ 15 kWh/(m².a)
- air tightness at 50 Pa (n_{50}) $\leq 0.6\ h^{-1}$
- maximum E-level = 55 (energy performance as defined by EPBD, 2006))

To evaluate the requirements for passive school buildings, simplified calculation methods for assessment of the annual heating and cooling based on EN ISO 13790 are used. In Flanders the Flemish EPB calculation method (EPB, 2005), which is the Flemish implementation of the EPBD-directive, and an adapted version (AGIOn, 2010) of the Passive House Planning Package 2007 (PHPP, 2007) software, which has been created as a certification tool for Passive Houses, are commonly used. Both tools consider the building as a single zone at a fixed average indoor temperature.

To guarantee a uniform and objective evaluation of the design of these passive school building in Flanders, a set of boundary conditions, meeting the specific characteristics typical of schools, has been developed by the authors based on the existing European (EN 12464, EN 13779, EN 15251, EN ISO 7730, EN ISO 13790), German (DIN V 18599) and Dutch (NEN 1089) standards concerning energy performance, ventilation and comfort to assess the energy performance of school buildings (Wauman et al., 2010a; Breesch et al., 2010). Among these boundary conditions, a fixed indoor temperature is calculated. Also a fixed temperature set-back, $\Delta\theta_i$ = 0.6 °C as specified in German guidelines (Kah, 2006), is considered to take into account the discontinuous user profiles typical of schools and the interzonal set-point temperature differences. However, the indoor temperatures as well as the temperature set-back are set regardless of the building properties.

Previous simulations of various passive pilot projects in TRNSYS have shown a large discrepancy between the default fixed temperature and the realistic indoor temperatures (AGIOn, 2010). To reassure more accurate and realistic energy demands, this paper evaluates the accuracy of the fixed indoor temperature and examines the impact of the building properties on the indoor temperature. Therefore multiple dynamic simulations of a reference school building, implementing the newly developed boundary conditions for schools are performed. The insulation qualities are varied and the structure is altered from very light to very heavy. Besides, the solar heat gains are fluctuated. Based on these results, the influence of the building properties on the indoor temperature and heating demand is illustrated.

HVAC efficiencies are not considered in this study.

SIMULATIONS

Building simulation model

In this study, a detached nursery school building is used as a reference school. It consists of 4 floors including class rooms, circulation zones, sanitary and storage rooms (Figure 1).

The total heated volume equals 14003 m³ while the heat loss surface A_T equals 5112 m², leading to a compactness level of 2.74.

Balanced mechanical ventilation is provided by an air-handling unit. The heat load is covered by an all-air heating system. The ventilation air is preheated by an air-to-air heat exchanger with an efficiency of 75%. The supply ducts to the different zones are equipped with heating coils to foresee local post-heating.

According the performance requirements for passive school buildings, a minimum air tightness of n_{50} = 0.6 air changes per hour has to be obtained. For this research, not only passive buildings are considered but also a wider range of energy levels is implemented. Therefore, an average value of 1 air change per hour is used.

The operative indoor temperature and heating demands for a reference school building has been studied with the dynamic multi-zone building energy simulation program TRNSYS version 16_1 (Klein et al., 2004). The thermal behaviour of different cases was studied with a time step of 1 hour for the moderate climate of Uccle, Belgium (Meteonorm).

On the one hand, a reference calculation is used to approximate the results of the simplified calculation methods which are used to evaluate the energy performance criteria. Therefore, the building is treated as a single zone. Fixed boundary conditions based on averages over time and space for indoor temperature, ventilation rates and internal heat gains have been implemented. On the other hand, an adjusted calculation is performed where the building is modelled as a multi-zone building. For the boundary conditions, more realistic time schemes and set points are implemented. All other parameters remain constant. This approach is similar as done by Deurinck et al. (2011). In both cases, the specific characteristics typical of schools (Wauman et al., 2010b) are implemented.

Variation of building performances

Considering the large impact of the mean indoor temperature on the calculation of the heating demand, this paper analyses the impact of the building properties and evaluates the accuracy of the fixed indoor temperature to reassure more realistic energy demands. Therefore, multiple dynamic simulations of the reference school

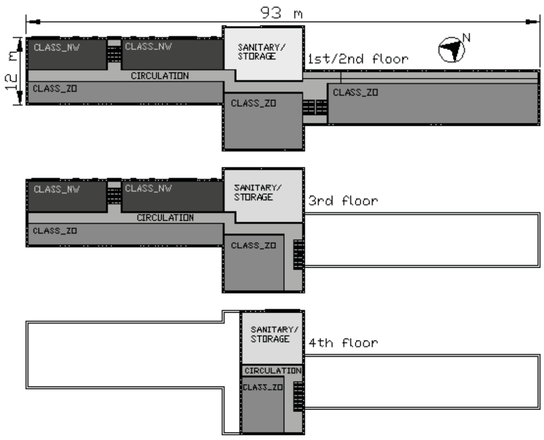

Figure 1 Schematic representation of the school.

Table 1 Variation of thermal mass

	HEAT CAPACITY	CONSTRUCTION
very heavy	102 Wh/(K.m²)	heavy external and internal walls
heavy	72 Wh/(K.m²)	heavy external, light internal walls
light	44 Wh/(K.m²)	heavy floor & roof, light ext. & int. walls
very light	30 Wh/(K.m²)	light roof, ext. & int. walls, heavy floor

Table 2 Composition of structural elements (from inside to outside)

	MATERIAL	CONDUC-TIVITY [W/m.K]	THICK-NESS [m]
roof_light	gypsum board	0.24	0.012
	mineral wool (MW)	0.040	Table 3
	OSB	0.13	0.018
	EPDM	0.25	0.002
roof_heavy	plaster finish	0.52	0.010
	heavy concrete	1.70	0.150
	light concrete	0.32	0.100
	PUR	0.030	Table 3
	Bitumen	0.23	0.002
ext_wall_light	gypsum board	0.24	0.012
	OSB	0.13	0.015
	MW	0.040	Table 3
	wood fibreboard	0.50	0.018
ext_wall_heavy	plaster finish	0.52	0.010
	brickwork	0.54	0.140
	PUR	0.030	Table 3
floor	tiles	1.2	0.010
	light concrete	0.32	0.100
	PUR	0.030	Table 3
	heavy concrete	1.70	0.150
	bitumen	0.23	0.002
int_wall_light	gypsum board (2 x)	0.24	2 x 0.012
	MW	0.04	0.14
	gypsum board (2 x)	0.24	2 x 0.012
int_wall_heavy	plaster finish	0.52	0.010
	brickwork	0.54	0.140
	plaster finish	0.52	0.010

building are performed, altering the structure from very light to very heavy (Table 1).

The materials used for wall and roof constructions are changed to show the effect of the thermal inertia on the indoor temperature (Table 2).

The insulation quality of the floor, roof, external walls and windows are varied according the values as shown in Table . For each case, the thickness of the insulation materials is chosen so that the U-values of the heavy and light walls and roof are identical. The minimum thicknesses of the insulation materials correspond to the minimum legal required values (EBPD, 2006). The maximum values correspond to the maximum values found in different passive school projects. The combination of all the possible thicknesses lead to insulation qualities, characterized by the total U-value, U_{glob}, varying from 0.19 W/(m².K) to 0.41 W/(m².K).

Table 3 Overview of material properties

	MATERIAL	THICKNESS [m]
roof_light	mineral wool	0.19/0.23/0.45/0.56
roof_heavy	PUR	0.08/0.1/0.2/0.25
wall_light	mineral wool	0.11/0.19/0.38/0.50
wall_heavy	PUR	0.06/0.1/0.2/0.25
floor	PUR	0.06/0.1/0.2/0.25
	FRAME	**GLAZING**
window_1	thermally insulated	U=1.12 W/(m².K) g=0.57
window_2	thermally insulated	U=1.12 W/(m².K) g=0.39
window_3	thermally insulated	U=0.78 W/(m².K) g=0.55

To vary the solar heat gains, the solar heat gain coefficient g of the glazing is altered and three different control strategies for the mobile blinding systems are implemented ($q_{control}$ = threshold of total solar radiation on the surface when blinds are closed or opened):

- automatic controlling: $q_{control}$ = 300 W/m²
- manual controlling: $q_{control}$ = 150 W/m²
- no shading

In case of closed shading, it is supposed that 70 % of the solar radiation on the shaded surface is blocked.

The combination of all these various constructions types, structural elements, insulation qualities and different controlling systems for the shading device leads to 2304 different building configurations.

Boundary conditions

As mentioned before, a set of boundary conditions, meeting the specific characteristics typical of schools, has been developed by the authors to guarantee an objective evaluation of the design of school buildings (Wauman et al, 2010). For each school zone specific boundary conditions are set. Ventilation flow rates, user profiles, internal heat gains (IHG) from lighting equipment, appliances and occupants, etc. are defined as shown in Table 4. The operative indoor temperature during occupancy, θ_i, is determined by the function of each room. For the class rooms, a set-point temperature of 20°C in case of occupancy is set according to EN 15251 (Table 4). Taking into account the very high insulation and airtightness level of passive buildings, it is considered that the temperature of unheated rooms as circulation zones, sanitary and storage rooms are equal.

Table 4 Overview of boundary conditions for each type of school zone during occupancy

	θ_I [°C]	Q_{VENT} [m³/PERS.h]	IHG_{LIGHT} [W/m²]	IGH_{APP} [W/m²]	IHG_{OCC} [W/PERS]
class	20	22	6	1	60
circ.	20	-	2	-	-
sanitary	20	-	4	-	-
storage	20	-	-	-	-

Based on the fixed occupancy and ventilation rate, the total design hygienic ventilation rate is set to be 17286 m³/h (IDA3). The supply of fresh outside air is provided into the constantly occupied rooms (class rooms, gyms, refectories, etc.). Part of the air from the class rooms flows through the circulation zone to the sanitary rooms where it is extracted. This operation of the ventilation system is simulated in TRNSYS as interzonal flows to circulation (0.30 vol/h) and sanitary/storage (1.56 vol/h) areas.

The operation of the fans is controlled by a time schedule according to the user profile of the school: Monday to Friday from 8h15 till 15h45, except for Wednesday afternoon, where the school closes at 11h50 h. Also school holidays are taken into account. Besides the weekends, a school year counts a total of 99 days off: 5 days in January, 3 at the end of February, 2 at the beginning of March, 12 in April, 3 in May, 1 in June, 3 in October, 2 in November and 6 in December. During July and August it is supposed that the schools are closed.

Because of the intermittent ventilation schedule, it is required that each room is pre-ventilated for one hour before the aforementioned school hours. According to EN 15251, 2 air changes per hour are necessary to guarantee a sufficient indoor air quality.

In many schools heating is only enabled during a specific period. In order to consider this habit, heating is only allowed during the heating season, which typically lasts from October till April.

Reference calculation

For the reference calculation, the building is treated as a single zone at a fixed mean indoor temperature $\theta_{i,heat}$. In order to take into account the intermittent user profile and heating pattern of the school and the interzonal set-point temperature differences, the operative indoor temperature during occupancy of each room, θ_i (Table 4), is lowered by $\Delta\theta_i = 0.6$ °C as specified in German guidelines (Kah, 2006).The mean indoor temperature for the whole building, $\theta_{i,heat}$, is then calculated as:

$$\theta_{i,heat} = \max\left(\frac{\sum \theta_{i,m} A_i}{\sum A_{tot}} ; \frac{\sum \theta_{i,m} V_i}{\sum V_{tot}}\right) \qquad (1)$$

where $\theta_{i,heat}$ = mean indoor temperature for the whole building ; $\theta_{i,m}$ = mean indoor temperature of room i; A_i = treated floor area of room i, V_i = volume of conditioned room i.

Based on the boundary conditions set for school buildings (Table 4), a mean indoor temperature of 19.4°C is calculated. For each month, a fixed ventilation rate and internal gains are implemented. The fixed values are averages for each month based on realistic time schedules as determined by Wauman et al. (2010b) (Table 5).

Table 5 Fixed boundary conditions for each month in case of the reference calculation

	Q_{VENT} [vol/h]	IHG_{LIGHT} [MJ/h]	IGH_{APP} [MJ/h]	IHG_{OCC} [MJ/h]
january	0.196	19.5	0.9	6.8
february	0.209	20.9	0.9	7.2
march	0.220	21.9	1.0	7.6
April	0.101	10.1	0.4	3.5
May	0.215	21.2	0.9	7.4
June	0.227	22.7	1.0	7.8
July	0.0	0.0	0.0	0.0
august	0.0	0.0	0.0	0.0
september	0.227	22.7	1.0	7.8
october	0.220	21.9	1.0	7.6
november	0.227	22.7	1.0	7.8
december	0.165	16.4	0.7	5.7

Adjusted calculation

A more realistic building use can be modelled by implementing realistic time schedules, user profiles and heating patterns that differ in time and space.

For the adjusted calculation, the building is modelled as a multi-zone building. Based on different user profiles and orientations of the rooms, the building has been subdivided into 4 different zones: class_NW (zone I, V_I = 1069 m³), class_ZO (zone II, V_{II} = 61789 m³), circulation (zone III, V_{III}= 4484 m³) and sanitary/storage (V_{IV} = 2272 m²) as shown in Figure 1.

For the class rooms, a set-point temperature of 20°C in case of occupancy is set according to EN 15251 (Table 4). In case of absence, a set back of 5°C is assumed. Besides, a constant set-point temperature of 15°C is used for the circulation zone and sanitary/storage rooms based on realistic set-point temperatures of Flemish pilot projects.

DISCUSSION

Figure 2 shows the net annual heating calculated by the reference and adjusted method. An important difference between both results can be noticed.

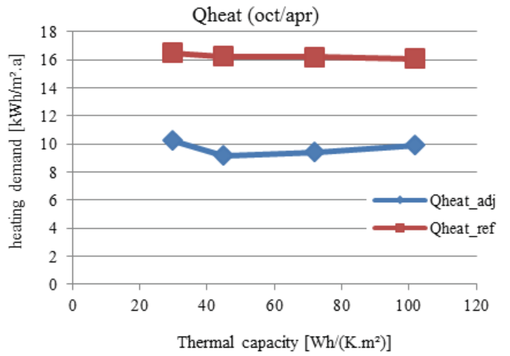

Figure 2 Impact of varying internal thermal capacity [Wh/(K.m²)] on the net annual heating demand [kWh/(m².a)]of the whole building for the adjusted (Qheat_adj) and reference (Qheat_ref) calculation

On average, the net annual heating demand of the single zone building is 6.54 kWh/m² higher than the net annual heating demand calculated by the adjusted method. This difference can be partially explained by the difference in the mean indoor temperature.

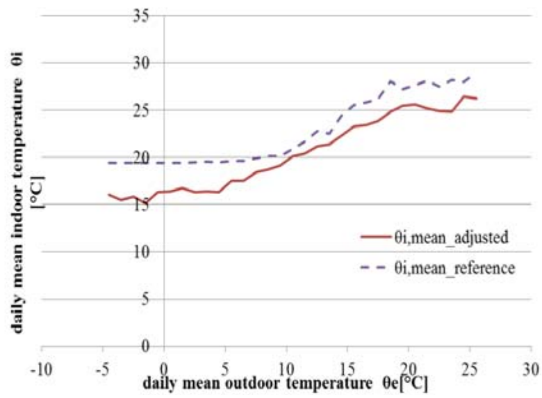

Figure 3 The average daily mean indoor temperature θ_i [°C] in function of the daily mean outdoor temperature θ_e [°C] for the adjusted and reference calculation

Figure 3 shows the average daily mean indoor temperature, θ_i, in function of the daily mean outdoor temperature, θ_e, according to the assessment method as found in Kalamees et al (2006). The average daily mean indoor temperature is calculated by sorting the daily indoor temperature for each of the 2304 building models according to the external temperature, using intervals of 1 °C. Averaging the values per interval leads to a mean value for a specific external temperature. The figure shows the daily mean indoor temperature during the heating season averaged over all case for the reference and adjusted calculation. As the temperatures are generally higher in the reference this results in consistently higher heating demands.

For the adjusted calculation (full line), the building is modelled as a multi-zone building using realistic time schedules and heating patterns. As mentioned before, a heating pattern with $\theta_{i,set,max}$ = 20°C/ $\theta_{i,set,min}$ = 15°C is imposed, resulting in mean indoor temperatures changing in relation to the external temperature with an absolute minimum of $\theta_{i,mean,min}$ = 15.14°. For the reference calculation (dashed line), the building is treated as a single zone at a fixed mean indoor temperature $\theta_{i,heat}$ = 19.4°C, indepent of the external temperatures lower than 10°C (heating season) as shown in Figure 5.

Assuming indoor temperatures of 20°C (Table 4) in non-heated rooms as circulation areas, sanitary and storages rooms is however not realistic. Furthermore, taken into consideration the typical very large available surfaces for circulation, storage and sanitary in schools (up to 30% of the total surface), these high indoor temperatures result in too high mean indoor temperatures and too high heating demands for the reference calculation.

Additional simulations are done changing the indoor temperature of the circulation and sanitary/storage zone into 15°C, resulting in a fixed mean indoor temperature $\theta_{i,heat}$ = 17.6°C.

The results are shown in Figure 4 and Figure 5. Lowering the temperature of the non-heated areas to more realistic values results in a better correspondence between the adjusted and reference calculation. The net annual heating demand of the single zone building model is now on average 1.67 kWh/m² higher as the net annual heating demand calculated by the adjusted method.

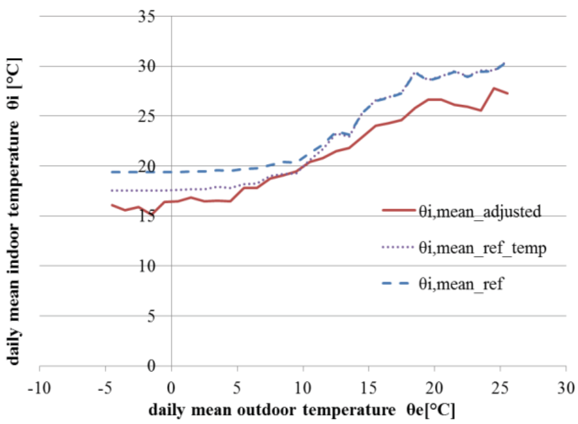

Figure 5 The average daily mean indoor temperature θ_i [°C] as a function of the daily mean outdoor temperature θ_e [°C] for the adjusted and reference calculations at 17.6°C and 19.4°C

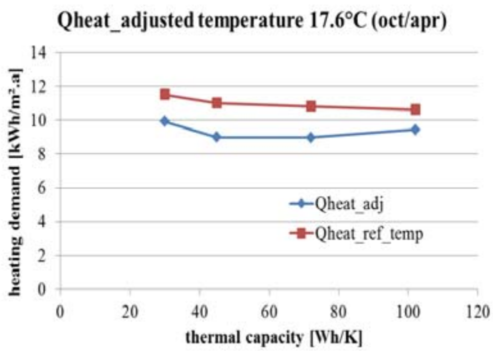

Figure 4 Impact of varying internal thermal capacity [Wh/(K.m²)] on the net annual heating demand [kWh/m².a]of the whole building for the adjusted and reference calculation at an adjusted temperature of 17.6°C

Thermal capacity

Furthermore, the influence of changing the materials used for wall and roof constructions according to Table 1 and Table 2 is analysed. Figure 4 shows the effect of the thermal inertia on the net annual heating demand for the adjusted and reference (adjusted temperature) building models. The results in the figure represent the averages of all calculation results.

The impact of the thermal capacity on the net annual heating demand is limited for both the adjusted as the reference calculcation (Figure 4). Varying the thermal capacity of the construction from very light = 30 Wh/(K.m²) to very heavy = 102 Wh/(K.m²) shows to have a limited effect on the net annual heating demand.

For the reference calculation (single zone model) a slight decrease of the heating demand of 0.40 kWh/(m².a) is noticed while raising the thermal capacity from very light to very heavy. For the adjusted calculation, no similar decrease is noticed in relation to a raising thermal capacity. As shown in Figure 4, the largest heating demands are found for very light and very heavy constructions.

In order to analyse more in detail the effect of the thermal capacity on the heating demand of the multi-zone building model, four additional dynamic simulations with a time step of 15 minutes are done with the adjusted calculation method. In these simulations, only the thermal capacity of the building model was varied.

Figure 6 shows the indoor air, operative and mean surface temperature of $zone_I$, respectively for a very light and very heavy building model on a regular school day in winter (Tuesday 23rd of January). Figure 7 shows the indoor air temperature and the corresponding heating demand for a regular school week in winter (Monday 17th of December – Sunday 23rd of December) for a very light, light, heavy and very heavy structure. Both figures show clearly the damping effect of the thermal mass on

Figure 6 Heating pattern on a regular school day (Tuesday 23rd of January) in winter time for a very light and very heavy structure (calculation time step: 15 minutes)

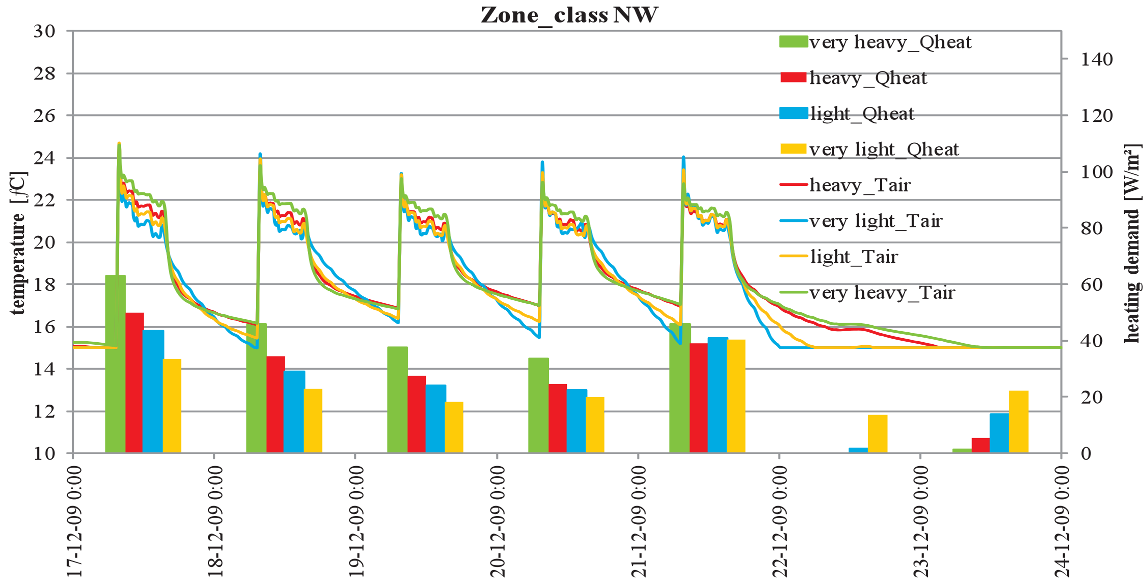

Figure 7 Heating pattern on a regular school week (Monday 17th of December - Sunday 23th of December) in winter time for a very light, light, heavy and very heavy structure (calculation time step: 15 minutes)

the temperature drop during the night and weekends: temperatures drop slowlier in heavy and very heavy school buildings. Due to the damping effect of the thermal mass, the operative temperature in $zone_I$ at the beginning of the school day (Figure 6) is 15.05°C for the very light and 15.96°C. Besides, for heavy structures, the set-point temperature $\theta_{i,set,min}$ = 15°C is reached much later, resulting in lower heating demands in the weekends as shown in Figure 7. On the other hand, during the day, the heating demand of the (very) heavy structures is larger as more constructive mass needs to be heated. This phenomenon is more important at the beginning of the week as the temperature of the constructive mass gradually increases during the week resulting in smaller differences between the heating demand for heavier and lighter structures by the end of the school week as shown in Figure 7. Both abovementioned effects explain why the largest heating demands are found for very light and very heavy constructions by the adjusted calculation (Figure 4). The impact of the thermal capacity on the net annual heating demand is however limited to less than 10%.

Insulation level

Secondly, the insulation quality of the floor, roof, external walls and windows are varied according the values as shown in Table 3. The minimum thicknesses correspond to the minimum legal required values. The combination of all the possible thicknesses lead to insulation qualities, characterized by the mean U-value, varying from 0.19 W/m².K to 0.41 W/m².K.

Figure 8 shows the effect of the insulation level on the net annual heating demand, $Q_{heat,}$ for both the adjusted and reference building models. Logically, higher heating demands are found for lower insulation levels (higher U_{glob}). Lower insulation levels cause higher transmission losses and therefore higher heating demands.

Using a single zone building model at a fixed mean indoor temperature $\theta_{i,heat}$, and averaged ventilation rates and internal heat gains leads generally to higher heating demands. Furthermore, Figure 8 shows that the absolute difference between the heating demand calculated by both methods increases with rising U-values. The larger the global U-value of the building, the more the net annual heating demand is overestimated by the reference calculation method. The results are shown in Table 6.

Table 6 Absolute different $Q_{heat,ref} - Q_{heat,adj}$ [kWh/(m².a)] for both the reference calculations

U_{GLOB}	$\theta_{I,HEAT}$ 19.4°C	$\theta_{I,HEAT}$ 17.6°C
0.19 W/(m².K)	2.82	-0.22
0.41 W/(m².K)	11.37	3.73

Similar results are found in (Deurinck et al., 2011) indicating the need for a correlation between indoor temperature and insulation level, especially for less insulated buildings.

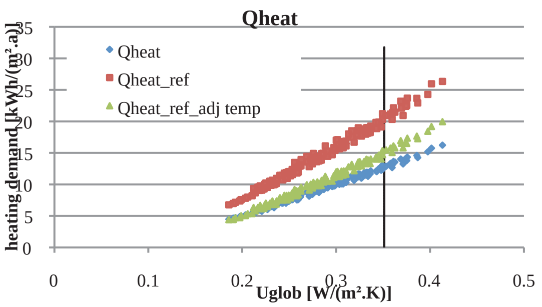

Figure 8 Impact of the global insulation level U_{glob} [W/(m².K)] on the net annual heating demand [kWh/(m².a)]

As set by the decree 'Energy performance in schools', the net annual heating demand for passive school buildings, calculated by the simplified calculation method, should be lower than or equal to 15 kWh/(m².a). Assuming that the temperatures in hall ways, circulation areas, toilets and storage rooms is lowered to 15°C as suggested, the dashed line on Figure 8 marks out all the cases meeting the performance requirements for passive school buildings as regards the heating demand. For this school building, all cases with a mean U-value lower than 0.35 W/(m².K) meet these requirements. For $U_{glob} < 0.35$ W/(m².K) the difference between the adjusted and reference calculation is limited to 2.27 kWh/(m².a) concluding that the fixed value for the set-back, $\Delta\theta_i$, regardless of the building insulation in this case seems a good assumption.

CONCLUSION

In a previous research study a list of boundary conditions was determined for the evaluation of the designs of passive school buildings. Among these boundary conditions, a fixed indoor temperature was defined regardless of the building properties, the climatic data or the building use. Considering the large impact of the average indoor temperature on the calculation of the net energy demand for heating, the aim of this paper is to evaluate the accuracy of the fixed indoor temperature and assess the effect of the building properties on the indoor temperature to reassure an accurate estimation of the latter to obtain more realistic energy demands.

The analysis of the dynamic simulations shows that the daily mean indoor temperature during the heating season is generally overestimated by the reference calculation resulting in consistently higher heating demands. Assuming indoor temperatures during occupancy of 20°C in non-heated rooms such as circulation areas, sanitary and storages rooms, proofs - even in well insulated buildings - to be not realistic. Considering the typical large percentages of available surface for circulation, storage and sanitary in schools, these high indoor temperatures results in too high mean indoor temperatures and too high heating demands for the reference calculation. Therefore indoor temperatures of non-heated rooms should be lowered to more realistic values in simplified calculation methods.

Multiple dynamic simulations of a reference school building, varying the thermal inertia, the insulation qualities, glazing properties and shading proved the impact of the thermal capacity on the net annual heating demand to be less than 10%. Furthermore, it is shown that for well insulated buildings the influence of the insulation level on the set-back temperature becomes smaller.

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