Assessment of a Simplified Calculation Method for Energy Use for Heating in School Buildings

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Abstract
A quasi-steady-state, sequential HVAC subsystem calculation approach that decouples the building from the system, is used to assess the energy use of buildings in a regulatory context (EPBD) in Flanders (Belgium). An integrated calculation approach that treats building and systems as a complete entity is preferable but is computationally intensive. This study assesses the accuracy of the simplified calculation approach as described in EN 15316 by comparing it against the results of integrated dynamic simulations in TRNSYS in a reference school building with a hydronic heating system and balanced mechanical ventilation system. The overall system efficiency is slightly overestimated by EN 15316 especially for low part load ratios because the standard estimates a constant value while simulations show decreasing subsystem efficiencies when part load ratios are lowered. However the overall effect on the annual energy use is limited.

Keywords - Energy use for heating; School building; EN 15316; HVAC system efficiency; EPBD simulations; TRNSYS

1. Introduction

For the assessment of the energy use of buildings in a regulatory context (EPBD) in Flanders (Belgium), a quasi-steady-state, sequential HVAC subsystem calculation approach is used that decouples the building from the system by calculating the monthly net energy demand and apply tabulated subsystem efficiencies to obtain the energy use. This method is intuitive and simple as no iterations are needed to simulate the performance of the building and its system. Hence, it is an interesting option to be used in a regulatory context. Several researchers have demonstrated however that the efficiency of the HVAC system depends on the building and the mutual interaction between the subsystems. Korolija [1] demonstrated, based on the results of a series of
dynamic integrated building and system simulations of offices in the UK, that
the energy efficiency of HVAC systems depends on the thermal characteristics
of the building. Peeters et al. [2] and Van der Veken et al. [3] demonstrated
the relation between the insulation quality of the building envelope and the
emission and distribution efficiency of heating systems in residential
buildings. Parys [4] analysed the monthly efficiencies for generation,
distribution and emission subsystems for various HVAC systems in office
buildings. Simultaneously, the accuracy of the currently used tabulated data
for the (sub)system efficiencies could be questioned as some of the data might
be (over)simplified, are inaccurate or are simply lacking due to the fast
evolution towards high performance buildings and new technologies [5].

An integrated calculation approach that treats building and systems as a
complete entity is preferable but is computationally intensive and requires a
substantial effort of the modeler. Therefore, this study aims to assess the
accuracy of the simplified calculation approach as described in EN 15316 [6]
by comparing it against the results of integrated dynamic simulations in a
reference school building.

First, the paper defines the school building and HVAC system
configuration. Then, the energy assessment according to EN 15316 and the
dynamic integrated building and HVAC simulations are described. Finally,
the monthly averaged emission, distribution, generation and overall system
efficiencies are compared and the impact of the buildings’ characteristics is
discussed.

2. Building and HVAC system

2.1. School building configuration

This study focuses on elementary school buildings in particular. A
reference school building, representing a current typical Flemish school
building [7], is used for the calculations. Fig. 1 shows the school model used
as a reference for elementary education, consisting of two floors including the
most common rooms: class rooms (41% or 846 m²), a teachers’ room (3% or
63 m²), offices (5% or 106 m²), a gym (13% or 265 m²), a canteen and kitchen
(11% or 236 m²), circulation zones, sanitary and storage rooms (26% or 543
m²). The total heated volume equals 6570 m³ while the heat loss surface A_T is
3694 m², leading to a compactness level of 1.78. The boundary conditions of
these rooms are summarized in Table 1.

For the dynamic simulations this reference school building has been
subdivided into seven different zones. The zone ‘class F’ comprises all class
rooms at the front of the building. The zone ‘class B’ contains all class rooms
at the back of the building. The rest of the building consists of the canteen and
kitchen, the gym, the offices, the teachers’ room and space for circulation,
sanitary and storage.
To assess the impact of the building’s characteristics on the (sub)system efficiencies, a sample of 18 school building design variants is set ranging the thermal capacity (heavy or light) and the insulation and air tightness quality of the building envelope ($n_s$ between 0.4 and 3; $U$-values of walls, roof and floor between 0.11 and 0.37 W/m²K), the glazing properties ($g$-value between 0.47 and 0.57 and $U$-value between 0.6 and 1.12 W/m²K), the window-to-wall ratio WWR (20% or 40%), the shading devices (none, fixed or mobile) and the orientation of the building (main axis along North–South or East-West) to represent the current school building practice.

Fig. 1 Floor plan of the reference elementary school building [7]

Table 1. Boundary conditions typical for schools [7]

<table>
<thead>
<tr>
<th></th>
<th>Heating setpoint (°C)</th>
<th>Occupant density, (m²/pers)</th>
<th>Ventilation rate (m³/h.pers)</th>
<th>Internal heat gains from occupancy (W/pers)</th>
<th>Internal heat gains from equipment (W/m²)</th>
<th>Internal heat gains lighting (W/m²)</th>
<th>Relative absence factor (%)</th>
<th>Partial operation equipment (%)</th>
<th>Partial operation lighting (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classroom</td>
<td>21</td>
<td>3.0</td>
<td>29</td>
<td>60</td>
<td>5.0</td>
<td>6.0</td>
<td>87.5</td>
<td>15</td>
<td>90</td>
</tr>
<tr>
<td>Office</td>
<td>21</td>
<td>14.0</td>
<td>29</td>
<td>80</td>
<td>10.0</td>
<td>10.0</td>
<td>70</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Teachers’ room</td>
<td>21</td>
<td>3.0</td>
<td>29</td>
<td>80</td>
<td>2.5</td>
<td>10.0</td>
<td>50</td>
<td>35</td>
<td>95</td>
</tr>
<tr>
<td>Canteen</td>
<td>21</td>
<td>1.5</td>
<td>29</td>
<td>60</td>
<td>2.0</td>
<td>6.0</td>
<td>-</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>Kitchen</td>
<td>21</td>
<td>10.0</td>
<td>36</td>
<td>100</td>
<td>80.0</td>
<td>10.0</td>
<td>-</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>Gym</td>
<td>17</td>
<td>20.0</td>
<td>44</td>
<td>160</td>
<td>-</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td>95</td>
</tr>
<tr>
<td>Circulation area</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>50</td>
</tr>
<tr>
<td>Sanitary</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>-</td>
<td>-</td>
<td>50</td>
</tr>
</tbody>
</table>
2.2. HVAC system configuration

One of the main characteristics of school buildings is the variability of the user’s schedules and the occupancy which in turn requires flexible heating and ventilation systems. Separate heating circuits are provided for each of the building zones characterized by similar (time) trends of thermal loads and/or occupancy: two separate heating circuits are foreseen for the class zone based on the orientation, one heating circuit for the administration zone, one for the canteen/kitchen and one for the gym.

The heating system comprises a traditional hydronic heating system with a modulating, condensing gas boiler and low temperature radiators controlled by thermostatic radiator valves. Two radiators with a single convection fin element are used with a height of 90 cm, i.e. a specific nominal power of 1961 W/m, and a total width depending on the required heat load.

A common heat distribution system configuration is chosen using one central heating circuit, i.e. primary system, and all secondary circuits coupled to a distribution header (see Fig. 2). The primary and secondary system are decoupled using an open header that acts as a hydraulic separation between the different pump flows. The distribution pipes are all insulated. For the secondary circuits where the supply flow rate to the radiators is controlled by thermostatic radiator valves, variable speed pumps are installed.

The necessary boiler heat output capacities vary from 130 kW to 175 kW. Heating is scheduled according to the school operational profile. After school and during weekends, the heating is switched off. To reassure good thermal comfort at the start of each school day however, the heating starts prior...
to the school opening hours at 4 AM on Mondays and at 5 AM on the other school days. An operative temperature control is used with a room set-point temperature for heating of 21°C in the occupied zones/rooms except for the gym where a set-point of 17°C is implemented. The unoccupied areas such as the circulation area, the storage rooms and sanitary are not heated.

An outdoor temperature reset control, applied on each building zone separately, automatically adjusts the supply temperature to the heating circuit in accordance to the zonal heat load and the average outdoor temperature. The maximum supply temperature is 60°C. An on/off burner control is applied based on the required supply flow set-point temperature. To avoid excessive cycling of the boiler, a minimum on/off time is set.

Balanced mechanical ventilation is foreseen. Three AHU’s are installed: the first AHU serves the classes and offices, the second AHU serves the canteen and the third serves the gym. The AHU’s are equipped with cross flow heat exchangers. The heat recovery devices can be bypassed when necessary. To maintain summer comfort, passive night cooling by mechanical ventilation is used. Further details can be found in Wauman [7].

3. Methods

3.1 Energy use assessment according to EN 15316

The calculation of the final energy use for heating in EN 15316 [6] is a sequential analysis assessing the thermal losses related to the emission (EN 15316-2-1 [8]), distribution (EN 15316-2-3 [9]), storage and generation of heat (EN 15316-4 [10]). The emission losses are included as a heat emission efficiency (EN 15316-2-1 [8]) depending on partial efficiencies for the non-uniform air temperature distribution, room temperature control regulation and for specific losses of the external components (embedded systems). The distribution efficiency is calculated according to the simplified approach in EN 15316-2-3 [9], which make approximations for the linear heat transfer coefficient and the length of the pipes. The generation efficiency is determined by the boiler efficiency method in EN 15316-4-1 [10], which calculates the thermal losses as a linear interpolation between the values for three different part load ratios: full load, intermediate load (i.e. 30%) and stand-by.

3.2 Dynamic integrated building and HVAC simulations

TRNSYS 17 [11] is used to perform the dynamic simulations. The integrated simulation approach is illustrated in Fig. 3 by the conceptual diagram of a school building heated by radiators controlled by thermostatic radiator valves and supplied by a condensing gas boiler [4]. The thermal behaviour of the building and system is studied with a time step of 3 minutes. No hydraulic calculations are included in the simulations.

The radiators are modelled by the dynamic, lumped capacitance radiator model Type362 [12] that calculates both the emitted radiator power and the
radiative fraction of the emitted power based on the water flow, the surrounding temperature and the incoming water temperature.

The thermostatic radiator valves (TRV) on the radiators are modelled based on the IEA annex 10 ‘perfect thermostatic valve’ model as developed by Ast [13]. It is a lumped capacitance model of the temperature sensor including the thermal resistance of the casing and between the sensor and the water. The hysteresis is 0.5°C and the nominal and maximal temperature differences between the valve and ambient is 2°C. All valves are assumed to have an infinite range from 0% (fully closed) to 100% (fully open).

For each combination of building and HVAC systems, two series of dynamic simulations are performed [1]. Series 1 contains the dynamic simulations of the building envelope with ideal assumptions regarding the HVAC operation to calculate the net energy demand \( Q_{H,nd} \). Series 2 comprises the detailed simulations of both the building and the system and is executed to determine the ‘real’ energy demand incorporating the impact of the equipment (sizing), climatic conditions, and the implementation of operational schedules and control systems. These simulation results are then used to calculate the emission efficiency \( \eta_{em} \) (1), distribution efficiency \( \eta_{dis} \) (2) and generation efficiency \( \eta_{gen} \) (3) and overall efficiency (4).

\[
\eta_{em} = \frac{Q_{H,nd}}{Q_{H,emitted}}
\]

(1)

\[
\eta_{dis} = \frac{Q_{H,emitted}}{Q_{H,gross}}
\]

(2)
\[ \eta_{\text{gen}} = \frac{Q_{H,\text{gross}}}{Q_{H,\text{boiler}}} \tag{3} \]

\[ \eta_{\text{overall}} = \frac{Q_{H,\text{nd}}}{Q_{H,\text{final,use}}} \tag{4} \]

where \( Q_{H,\text{emitted}} \) is the energy delivered by the emission systems, \( Q_{H,\text{gross}} \) is the gross heat demand (including distribution heat losses), and \( Q_{H,\text{boiler}} \) is the heat output of the boiler and \( Q_{H,\text{final,use}} \) is the final energy use for heating.

As TRNSYS applies a single (zonal) air temperature, emission losses due to temperature stratification, shielding of emission devices or increased heat losses through locally heated building envelopes, cannot be simulated. Therefore, specific emission losses are calculated manually according to EN 15316-2-1 [8]. The emitted power calculated by TRNSYS is then adjusted accordingly before being coupled to the building model. As a result, only the impact of imperfect control is included in the emission efficiencies.

In accordance with EN 15316, results for the subsystem efficiencies are discussed on a monthly time base and are expressed as a function of the monthly averaged part load ratio of the heating system \( \beta \) \( \tag{5} \)

\[ \beta = \frac{Q_{H,\text{nd}}}{\phi_{\text{boiler}} \cdot t_{\text{op}}} \]

where \( \phi_{\text{boiler}} \) is the nominal power the boiler (kW) and \( t_{\text{op}} \) is the number of heating hours per month. \( \beta \) is chosen as a reference as it incorporates the effect of the thermal insulation of the building, weather conditions and internal loads.

4. Results and discussion

The monthly averaged emission efficiency \( \eta_{\text{em}} \) (see Fig. 4), distribution efficiency \( \eta_{\text{dis}} \) (see Fig. 5) and generation efficiency \( \eta_{\text{gen}} \) (see Fig. 6) for all the investigated school building design variants are shown in relation to the part load ratio of the heating system \( \beta \). For comparison, the according subsystem efficiencies as used in EN 15316 [8], [9], [10] are added to the figures. The annual subsystem efficiencies averaged over all building design variants are summarized in Table 2.

| EN 15316 | \( \eta_{\text{em}} \) | \( \eta_{\text{dis}} \) | \( \eta_{\text{gen}} \) | \( \eta_{\text{overall}} \) |
|-----------|---------------|----------------|----------------|----------------|----------------|
| TRNSYS    | 0.80          | 0.95           | 0.85           | 0.65           |
| EN 15316  | 0.87          | 0.98           | 0.90           | 0.77           |
Fig. 4 monthly averaged emission efficiency for all building design variants in function of the part load ratio of the heating system $\beta$ (with $H =$ heavy and $L =$ light thermal mass; 20 = WWR of 20% and 40 = WWR of 40%; NS = North-South and EW = East-West orientation)

Fig. 5 monthly averaged distribution efficiency for all building design variants in function of the part load ratio of the heating system $\beta$

Fig. 6 monthly averaged generation efficiency for all building design variants in function of the part load ratio of the heating system $\beta$

Overall, following phenomena are noticed. First, the dynamically calculated efficiencies decrease when the part load ratio of the heating system
is lowered, especially noticeable for $\eta_{em}$. Similar results are found by Bauer [13] and Van der Veken et al. [14]. They indicate the decrease of the control efficiency at part load ratios as the most important cause of the loss of $\eta_{em}$. When highly fluctuating internal and solar heat gains occur, accurate control of the heating system becomes difficult: heat outputs of the heating system results easily in overheating and negatively affect the control efficiencies.

Second, a rather good fit is found between the overall and subsystem efficiencies calculated according to EN 15316 [8], [9], [10] and the efficiencies obtained by the integrated dynamic simulations at part load ratios $> 0.1$. The differences between the dynamically and statically calculated system efficiencies increase however significantly at lower part load ratios ($< 0.1$) as in the static calculation the occurring decrease of the emission and distribution efficiencies at low part load ratios are not taken into account.

Third, the effect of the building on the generation efficiency is negligible while the emission and the distribution efficiency depends on the buildings’ characteristics. The impact of the insulation level of the building and the solar heat gains affected by WWR and building orientation on the emission efficiency is demonstrated in Fig. 7. The impact of the energy efficiency of the building on the emission/control efficiency differs in winter and in intermediate season. In winter months, control efficiencies are slightly higher in better insulated buildings. The deviations remain however limited as the heating system and related control settings are designed according to the buildings’ characteristics. An opposite trend is noticed in the intermediate season when higher solar heat gains occur and accurate control of the heating system is more difficult. As shown by Fig. 7 this trend is more pronounced in better insulated buildings.

![Figure 7](image-url)

**Fig. 7** Impact of the buildings’ characteristics, i.e. energy efficiency of envelope and WWR, on the monthly averaged emission efficiency $\beta$ (with H = heavy thermal mass; 20 = WWR of 20% and 40 = WWR of 40%; NS = North-South; energy efficiency level: 1 = moderate, 3 = good, 5 = excellent)
5. Conclusions

The overall system efficiency is slightly overestimated by EN 15316 especially for low part load ratios because the standard estimates a constant value while simulations show decreasing subsystem efficiencies when part load ratios are lowered. As the losses of the efficiency are only noticed in periods of low heat demands, it can be however expected that the overall effect on the annual energy use will be limited.

The impact of the building characteristics on the overall performance of the heating system is limited and can be reduced almost completely to variations of the control efficiency.

References