Simplified and Fully Detailed Dynamic Building Energy Simulation Tools Compared to Monitored Data for a Single-Family NZEB House

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Abstract

Building energy automation and control strategies have recently been applied to improve the energy performance of the building and to exploit the integration of the building envelope, HVAC and RES. To optimise their application, reliable data on the dynamic energy behaviour of the building should be available possibly from monitoring, but also from simulation at the design stage.

This paper compares the results of two building performance simulation tools: TRNSYS, which implements a fully detailed model and software implementing a simplified model according to the EN ISO 52016-1 standard. We are interested in investigating the potential of the EN ISO 52016-1 model to capture the dynamic behaviour of the building. A NZEB single-family house in Northern Italy, where the thermal loads are met by a domestic air handling unit (AHU) with heat recovery was taken as a case study. The TRNSYS model is calibrated using data available from the 15-minute monitoring of the indoor/outdoor temperatures, the electrical energy consumption and the source/sink temperatures of the heat pump, and then compared with the result of the standard model in terms of both monthly thermal energy demand and hourly heating demand. The simplified model overestimates the annual heating demand compared to the detained model, but is able to capture the daily maximum both in terms of value and temporal cadence.

1. Introduction

Growing global concern about the rising energy consumption and greenhouse gas emissions from buildings has led to increasingly stringent energy efficiency requirements for both residential and commercial buildings (e.g., the Performance of Buildings Directive in the EU), and a wider use of on-site renewable energy generation to achieve the goal of Nearly Zero Energy Buildings (NZEBs) and Zero Emission Buildings (ZEBs).

In response, the building industry has developed innovative technologies that, to be more effective, need to be properly interconnected and integrated into the building system at the different stages: design, construction and operation. In particular, there is scope to improve the control of the interactions between the building envelope and the active systems, such as HVAC and RES. Thus, building energy automation is increasingly being developed and control strategies can be profitably optimised on the basis of reliable data on the dynamic behaviour of the building. This data is provided by monitoring or predicted by simulation tools.

Building Performance Simulation (BPS) tools have been widely used in building design for several decades, providing architects, engineers and researchers with predictions of the energy performance of buildings in accordance with rapidly changing standard and requirements. The simplified steady-state or quasi-steady-state mathematical models are useful in the design process and when the main requirement is the reproducibility of results. However, the use of default values for input parameters means that these models often fail to accurately predict the actual performance of a building during operation. Conversely, the most detailed dynamic models allow for a greater accuracy and flexibility but have the disadvantage of requiring a higher level of user expertise and a time-consuming simulation process, which hinders the adoption among professionals.

An interesting compromise between accuracy and

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simplicity is offered by tools that implement the Simplified Hourly Calculation Method (SHCM) for the calculation of the thermal loads and the internal temperatures provided by the EN ISO 52016-1 standard (European Committee for Standardization, 2017). It takes into account the hourly variations in weather conditions, schedules for internal gains and for ventilation loads, while using a RC model with a simplified mass distribution in the building components.

The accuracy of the hourly method has been investigated by several authors by comparing the standard with detailed numerical simulation models, such as TRNSYS (Siva Kamaraj, 2018; Zakula et al., 2019; Magni et al., 2022) or EnergyPlus (Ballarini et al., 2020; De Luca et al., 2019). Furthermore, some works (Mazzarella et al., 2020; De Luca et al., 2023) demonstrate the accuracy improvement provided to the EN ISO 52016-1 standard by the Italian National Annex, which implements a more realistic RC model of the building components based on the detailed description of the wall layers.

The previous studies have focused on the evaluation of the discrepancies caused by the simplifications in the standard method, mainly on the thermal energy demand for different building typologies and climates.

In our research, we aim to use the results of a detailed model in TRNSYS, validated with monitored data, to assess the potential of EN ISO 52016-1 model in capturing the dynamic behaviour of the building in order to use it to define control strategies for optimal integration of the building envelope, HVAC and RES improving the energy performance.

In this study, we present the preliminary results of a NZEB single-family house in Northern Italy, where the thermal loads are met by a domestic air handling unit (AHU) with heat recovery. We compare the result of the detailed and standard model in terms of both monthly thermal energy demand and hourly heating demand.

2. Methodology

Two methods have been considered for the dynamic simulation of the building: numerical dynamic simulations carried out with the software TRNSYS 18 (Klein et al., 2010) and the calculation procedure of the EN ISO 52016-1 standard, implemented in a commercial software (EC700).

The *COP* of the heat pump was calculated using manufacturer's data and in compliance to standard UNI/TS 11300-4.

2.1 Detailed Dynamic Model

TRNSYS is a component-based software environment for the simulation of transient systems. In particular, its library includes a multizone building (Type 56) and many components of HVAC and renewable energy systems. The building model is an energy balance model, where the heat balance is set for each zone air node, that is:

$$C\frac{\partial \vartheta_i}{\partial \tau} = \dot{Q}_{TRAN} + \dot{Q}_{VENT} + \dot{Q}_{INF} + \dot{Q}_{SOL} + \dot{Q}_{IG} + \dot{Q}_{HEA} - \dot{Q}_{AC} \quad (1)$$

where C is the effective heat capacity and ϑ_i the temperature of the thermal zone; the terms on the right are, in order: the convective heat transfer from the boundary surfaces; the air infiltration and ventilation contributions, including air flow from other air nodes; the fraction of solar gains that is immediately transferred to the air node; the internal convective gains; the convective fraction of the heating load and the cooling load from the HVAC system. Radiative heat fluxes are modelled for the walls and windows of each zone by taking into account the contribution solar gain through the windows and longwave radiation exchange.

The dynamic behaviour of the building is modelled using transfer functions to calculate the transient heat conduction through the capacitive walls. The simulation time step in TRNSYS can be sub-hourly. More detailed mathematical description can be found in the software documentation.

2.2 Simplified Dynamic Model

The simplified hourly method of EN ISO 52016-1 is also based on the heat balance at the air node (Equation 1), but introduces some simplifications, mainly related to the calculation of the transient conduction in the opaque building elements and the solar energy transmission through glazing (Ballarini et al., 2020). Each opaque element is modelled as an equivalent RC-circuit with five nodes, four thermal resistances, whereas the wall heat capacity is concentrated in one, two or five nodes, depending on the typology of mass distribution in the element (according to the classification in Annex B of Standard EN ISO 52016-1).

2.3 COP Calculation

The UNI/TS 11300-4 standard specifies the procedure for estimating the performance of electrically driven vapour compression heat pumps at source/sink temperatures other than those specified in the manufacturers' data.
Briefly, for a cold source temperature ϑ_c and a hot sink temperature ϑ_h, in the operating range of the heat pump, the COP is calculated as:

$$COP(\vartheta_h, \vartheta_c) = COP_{max}(\vartheta_h, \vartheta_c) \cdot \eta_{II} \qquad (1)$$

where COP_{max} is the Carnot COP for the same source/sink temperature values and η_{II} is obtained through linear interpolation of the ratios between the full load *COP* declared by the manufacturer at specific temperature conditions (in compliance with UNI EN 14825) and the corresponding Carnot COP.
The part load coefficient of performance COP_{PL} is calculated as:

$$COP_{PL}(\vartheta_h, \vartheta_c) = F_p(CR) \cdot COP(\vartheta_h, \vartheta_c) \qquad (2)$$

where the correction factor F_p as a function of the capacity ratio *CR* has been calculated from the interpolation of the data provided by manufacturer's under at partial load conditions at specific temperature conditions. pump.

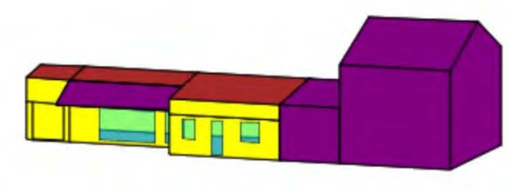

Fig. 1 – Case study 3D model in Google SketchUp

Table 1 – Thermal properties of the building envelope

Component	U-value [W/m²K]	Capacity [kJ/m²K]	Element Class [ISO 52016-1]
External wall	0.17	84.6	M
Ground floor	0.40	61.7	IE
Upper floor	0.20	32.6	IE
	U -value [W/m²K]	**U_{glass}-value** [-]	**g-value** [-]
Windows	1.10	1.30	0.5

3. Case Study Description

3.1 Description

The case study is a NZEB single-family house in Northern Italy, built in 2020. It consists of a 130 m² one floor, the living area is 44.7 m² and has a total height of 4.40 m, a large window to the south and a garage on the west side; the sleeping area is 68.3 m² and has a total height of 2.4 m, it has an attic above and a bordering house to the east. The 3D model in Google SketchUp is shown in Figure 1.
The building envelope includes concrete walls with EPS panels on both the inner and outer surface, thus it falls under Class M of EN ISO 52016-1 (Annex B) with thermal capacity concentrated in the central node. Windows are double-glazed Low-E ones with roller shutters. Thermal properties of the envelope are shown in Table 1.
The thermal loads are met by a domestic air handling unit (AHU), sketched in Figure 2, which is housed in the false ceiling in a central position, in order to supply four linear diffusers with variable flow rates for a total of 850 m³/h as maximum design value. The packaged unit is equipped with hydronic coils for space heating or cooling, an electric heater for occasional reheating, an air-to-air heat recovery exchanger and an economizer with air dumpers to control the recirculation and fresh air flow rates.
The space heating/cooling and DHW demands are supplied by an 8.5 kW monobloc air source heat pump.

The case study is representative of single-family NZEB houses in Northern Italy in terms of square footage and thermal characteristics of the building envelope. On the other hand, low-temperature hydronic heating is much more common than AHUs in residential buildings, although AHU units and mechanical ventilation systems with heat recovery have recently become more widespread. The peculiarity of this heating system, which has a very short response time, is one of the novel features of this case compared to previous studies.

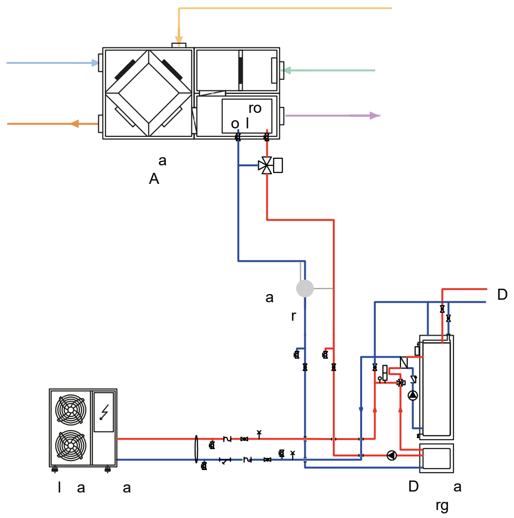

Fig. 2 – Monobloc air source heat pump suppling the domestic AHU and DHW

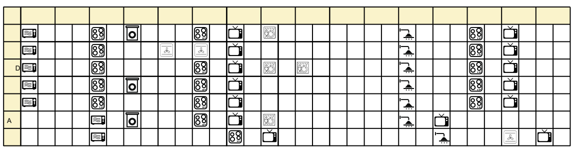

Fig. 3 – Electrical appliances and occupancy schedules from family interview

3.2 Model

The building has been modelled in each software with two thermal zones: the living zone and the sleeping zone, according to the temperature data available from monitoring.

The building is occupied by five people and an interview was made to define the occupancy schedules and the use of lighting and electrical appliances. An example is shown in Figure 3.

The rate of heat gain for electric appliances was calculated using 2019 ASHRAE Handbook Fundamental recommended values.

The maximum mechanical ventilation rates of 1,8 ach in the living zone and 1,7 ach in the sleeping zone are modulated during the occupied and unoccupied periods and a certified heat recovery efficiency of 0.8 have been applied.

3.3 Monitored Data Processing

The monitoring is carried out in the framework of the installed Building Automation System, which controls the operation of the heat pump, AHU unit, air ventilation dumpers, fan system, heating and cooling coil, etc. through a programmable Direct Digital Control (DDC) unit. Control rules for the actuators are defined as a function of data collected from input sensors (temperature, humidity, CO2, water flow). The system also allows remote monitoring and updating of settings via web. From 20th October 2023 to 31st March 2024, we monitored the internal temperature in the two thermal zones and CO_2 concentration, the outdoor temperature, the thermal energy provided by the heat meter installed on the hydronic coil of the AHU (Figure 2), electrical power and supply temperature of the heat pump. Data have been recorded at 15-minute timesteps.

Unfortunately, due to an incorrect installation, the heat counter did not work correctly, and the collected data are not reliable. Thus, the heat pump wattmeter was used to estimate the thermal energy from the COP calculated in accordance to standard UNI TS 11300-4, i.e. for the monitored values of the water temperature $\vartheta_{w,supply}$ at the outlet of the heat pump (supply temperature) and the outdoor temperature ϑ_e (source temperature). The bivalent temperature is -7 °C, and the data interpolated from the manufacturer data given at four source temperature values (-7, -2, 7, 12 °C) for both low temperature (35 °C) and medium temperature (55 °C) applications.

4. Results

The analysis was carried out in the following steps.

1. Calibration of the detailed model. The TRNSYS software allows a greater flexibility in the input data (for example, it is possible to set the internal temperature to follow the trend of the monitored data) and the transparency of the results

(for example, it is possible to check the single contributions of the heating load for each zone and their variation over time) facilitates the calibration process.

2. Updating the simplified model: the input parameters of the simplified model were updated according to the outcomes of the calibration process.
3. Comparison of the results between the detailed and simplified models.

The procedure and the intermediate results are described in detail below.

4.1 Detailed Model Calibration

In the TRNSYS model, we forced the heating set temperature to assume the values of the air temperature monitored in the two thermal zones and carried out the simulation for an ideal heating system. The first step of the calibration process was to implement the real climatic conditions in the monitored period. As the outdoor temperature sensor is influenced by its location and records higher average temperatures, we preferred to use data available from the nearby meteorological station, including humidity, wind speed and solar radiation on the horizontal plane. The sky model of Perez 1999 with a 0.2 ground reflection was used to split the direct and diffuse radiation for the different wall exposures.

The second step was to calibrate the internal gains (occupancy, equipment and lighting) and solar gains which, during the middle hours of the day, are responsible for the air temperature being higher than the set temperature, ideally requiring space cooling to bring the temperature back to the monitored values. This behaviour is illustrated in Figure 4: in the middle hours of the sample day (from 14:00 to 16:00) and around 21:00 the internal temperature deviates from the setpoint by assuming higher values. Once the internal inputs have been calibrated, the temperature returns to values close to the setpoint throughout the period. At the end of the calibration process, the resulting daily average values for electrical appliances, lighting and occupancy were 5.4 Wm^{-2}, 2.5 Wm^{-2} and 1.76 Wm^{-2} respectively. The Root Mean Square Error RMSE, has been calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (\vartheta_i - \vartheta_{i,mon})^2}{N}} \qquad (3)$$

between the indoor air temperature from TRNSYS calculation ϑ_i and the monitored air temperature $\vartheta_{i,mon}$. The period considered for calibration corresponds to the monitoring period, except for the time interval from 14 to 19 February when a system malfunction occurred and a very few bad data from monitoring (24 measurements at 15-min timesteps). During the calibration period, the RMSE value was lower than 0.28. The thermal energy demand was then calibrated by modulating the fresh air flow rates according to the occupancy schedule.

Figure 5 compares the final results of the simulation, in terms of monthly thermal energy demand for space heating, with the values estimated from the monitored data.

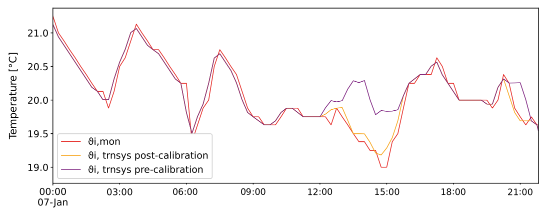

Fig. 4 – Comparison between the set temperature $\vartheta_{i,mon}$ and the simulated values of the internal temperature pre and post calibration

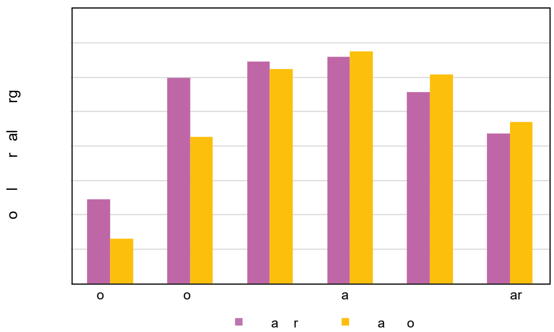

Fig. 5 – Monthly thermal energy demand from TRNSYS simulation ($Q_{heat,trnsys}$) of the calibrated model and that estimated from monitored data ($Q_{heat, mon}$)

In detail, the monthly space heating demand is calculated by subtracting the estimated demand for domestic hot water production from the heat pump heating capacity estimated from the monitored data, as:

$$Q_{HEAT} = \left(\sum_{j=1}^{24 \cdot N_{days}} E_{EL} \cdot COP - N_{days} \cdot Q_{DHW,daily} \right) \quad (4)$$

where the first term on the right is the monthly thermal energy supplied by the heat pump, calculated on an hourly basis from the monitored electrical energy E_{EL} using the COP calculation procedure described above which takes into account the heat pump water supply temperature and $Q_{DHW,daily}$ is the thermal energy for an estimated domestic demand of 150 l/day at 40 °C, and N_{days} is the number of days in the month.

It should be stressed that the October result refers to the last ten days of the month, i.e. since the start of monitoring. The discrepancy seems to be more pronounced in the first two months when the outside temperature was milder. Over the whole period, the simulation result differs by less than 5% from the value estimated by the monitoring. However, it should be pointed out that the discrepancy could be higher as the monthly space heating demand from the monitoring was estimated with several simplifications, such as the rough estimation of the domestic hot water production or neglecting the effect of defrosting. On the other hand, this would not affect the comparison between the simplified and the detailed model.

The annual heating energy need normalized on the conditioned net floor area amounts to 54 and to 52 $kWh \cdot m^{-2}$, assessed by simulation and from monitored data respectively. It is rather high for a NZEB house, due to both the high monitored internal temperatures (which even reaches 24 °C) and the high heat pump supply temperature, which fluctuates between 43 °C and 52 °C over the period, regardless of the DHW demand. The latter trend is shown in Figure 6, over a period of approximatively one month. A marketed change in the temperature control can be seen from 28th March, a few days after the end of the monitoring. This is the effect of the replacement of the actuator supplying the hydronic coil, which restored proper control of the supply temperature to values typical of low temperature applications.

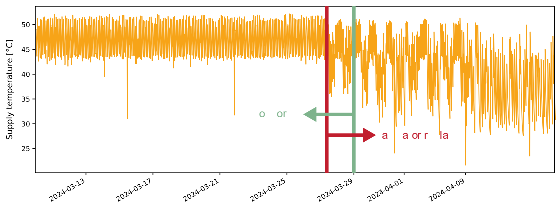

Fig. 6 – Monitored data of the heat pump water supply temperature in the monitored period, before and after the actuator replacement

4.2 Models comparison

The energy model of the building has been implemented in the commercial software taking into account the real climatic conditions and the input parameters such as internal gains and ventilation rates (which includes the heat recovery efficiency) were set to be consistent with the outputs of the calibration process.

The heating setpoint temperature has been set to 20 °C through the day.

The simulation results in terms of monthly thermal energy demand for space heating, from the simplified model (Standard EN ISO 52016-1) and from the detailed model (TRNSYS) are compared in Figure 7. The thermal energy demand of the simplified model differs from a minimum of -4.5 % in January to a maximum of 29 % in March. The simplified method overestimates the yearly heating need of 6.7 % compared to the detained. This result is in line with the results obtained by Ballarini et al. (2020) for the archetype of a two-storey single-family house, although the difference is more pronounced. This is probably due to the fact that the ventilation losses, which are consistent between the two models, are small compared to the other contributions that are model dependent (i.e. transmission losses), thus increasing the discrepancy between the two solutions.

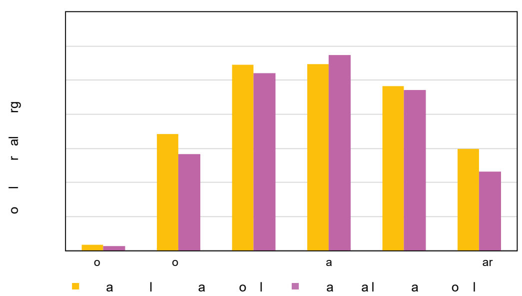

Fig. 7 – Monthly thermal energy demands from simplified dynamic model simulation and from detailed dynamic model simulation

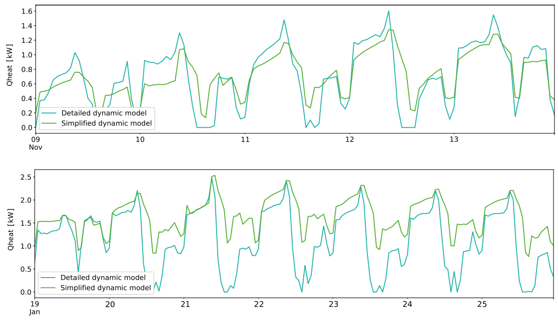

Fig. 8 – Thermal energy demand from simplified dynamic model simulation and from detailed dynamic model simulation on a sample week of November and of January

We are interested in assessing the differences between the two models in capturing the dynamic behaviour of the building. Figure 8 shows the heating flux demand for a sample week of November and January.

The path is similar in terms of the periodicity of the absolute and relative maximum values, and the curve scope changes are well captured by the simplified model. It is particularly interesting that the simplified model is able to capture the daily maximum both in terms of value and temporal cadence. This opens up the possibility of using the simulation with software used by professionals to assess the building energy performance and the design conditions of the heating system, also for predicting demand peaks in the day and heating period. On this basis, control rules can be set to optimize the integration with renewable sources and exploit thermal and electrical storage systems.

On the other hand, the daily heat demand varies within a smaller range in the simplified model, the minimum values are higher than the detailed model thus limiting the flexibility exploitation.

5. Conclusion

The case study of a NZEB single-family house in Northern Italy with a residential air handling unit (AHU) and heat recovery exchanger, is used to exploit the potential of the EN ISO 52016-1 model to capture the dynamic behaviour of the building. A fully detailed model and a simplified model according to EN ISO 52016-1 standard were developed. The detailed model was calibrated with the 15-minute monitoring data and the outcomes of the calibration were implemented in the simplified model. The simplified model overestimates the annual heating demand by 6.7% compared to the detailed model, but is equally good at capturing the daily maximum both in terms of value and temporal cadence. It can be profitably used to predict demand peaks over the heating period and over the day, thus allowing control strategies to be defined for optimal integration of the building envelope, HVAC and RES.

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