Estimation of load duration curves from general building data in the building stock using dynamic BES-models

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Abstract Modelling and simulation of building stock is a valuable source of information for investigating the feasibility of implementing new heating and cooling system technologies. Some of these technologies have oversizing problem as the designers rely on their experience and previous knowledge. Building stock modelling can provide a solution for more accurate designing process. However, some of the current building stock modelling methods uses a representative building which can exclude whole ranges of the different combinations of building geometry and physical properties that can be crucial for heating and cooling load estimation. Therefore, we developed a methodology that allows faster and accurate building energy simulation (BES) multizone models from general building information of the whole building stock that is able to estimate load duration. This will help engineers and designers to decide on the system sizing at the early design stages. This paper presents first, the process of generating dynamically heating and cooling load duration curves by using BES-models from general geometrical data of the building stock. Second, we examine the process on a sample of the building stock where geometrical and physical parameters were varied. The workflow of the process has worked successfully, generating heating and cooling duration curves for 14 case studies. We observed that heating and cooling loads are highly influenced by different combinations of parameters. High glazing percentage affects highly the heat losses, thus more heating loads. Besides, for a west oriented building, the high glazing percentage combined with high internal gains can be the reason for significant cooling loads. In next steps, we are going to extend the current methodology to cover different building typologies within different climates across Europe.

1 Introduction

Modelling and simulation of building stock has high potential for developing and testing new strategies for assessing heating and cooling demand. Several studies have used building stock modelling to evaluate the energy performance of buildings [1], [2], [3]. Thus, supporting decisions of future building regulations, identifying new retrofitting measures to decrease CO2emissions as well as testing the feasibility of using new technologies. For estimating heating and cooling demands, most of the studies are using a representative building that characterises a typical geometrical and building physical properties of a certain typology [4]. The choice of the representative building is dependent on the data availability and the experience in the field [1] . This can exclude the variations of different geometrical and physical combinations that can exist in the building stock. As such it could lead to more general recommendations rather than more accurate estimations. For investigating the feasibility of new technologies in the European market, such accuracy in simulations is needed, as it can affect the sizing of the new technology system components.

hybridGEOTABS is a heating and cooling technology that combines a geothermal energy source, a thermally activated building system (TABS) and a fast-reacting secondary system. One of the problems it faces is due to oversizing the system, that leads to high investment costs. To decide if implementing the system is feasible, designers either rely on their experience from previous reference projects or use detailed dynamic simulations. The first choice can result in larger sizing for the system components while the second choice leads to higher design costs due to longer simulation time [5]. By developing a methodology that can help in estimating heating and cooling demand and its resulting load duration curves while using dynamic building energy simulations, a better sizing of the system can be achieved. Therefore, less design and investment costs, and better dissemination of the system.

This paper presents a methodology for generating heating and cooling demand curves and resulting load duration curves from general geometrical data of the building stock. We use 14 case studies as a sample to illustrate the process. This methodology can be extended to cover different building typologies and can be used to examine correlations between the building geometrical and physical parameters for different systems installations. Thus, can support engineers and architects in decision making in the predesign phase of projects.

2 Methodology

2.1 Description of the process

A Six-step process is followed to generate load duration curves based on general geometrical data for a large amount of buildings (Fig.1). The process starts from gathering general building data for individual buildings within the building stock. The National Energy Performance Building Databases EPBD can be a major source for this sort of data. The data usually include general geometrical and building physical properties of individual buildings, for example gross floor area, volume, average U-value for envelope and windows. A second step consists of choosing the building archetype that represents the building geometry for a specific building typology. For example: a form that can be parametrized to represent all office buildings in the building stock data, including the typical spaces and functions that appear in office buildings. This step is followed by applying a geometrical fitting process, where the building stock data that corresponds to one-dimensional information about the building form is fitted to three-dimensional measurable form (building archetype). This method is achieved by using mathematical relationships between geometries. The output of this step is detailed geometrical data (e.g. the building length, width and height) which is an input for a multi-zone Building Energy Simulation (BES) model. This process is based on the work of [6] and extended to cover other building typologies in our research. Fourth step, is identifying all the building physical parameters (e.g. the U-values of building envelope, occupancy profiles, glazing properties, building orientation etc.) that are going to be varied in the BES-model. The fifth step is creating the multi-zone BES-model for the archetype building using Modelica [7]. The final step is performing dynamic simulations of the heating and cooling demand and transformation of these data into heat load duration curves. This process can be applied to large amounts of buildings (with varying geometries and building physical properties) in an automated way. In the following paragraphs we will discuss some of the aforementioned steps more in detail.

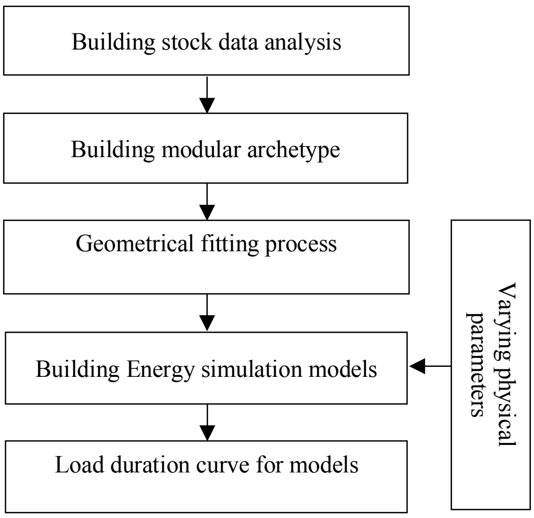

Fig. 1. Building stock modelling process

2.2 EPBD building stock data for Flanders

A first source of data that is used in this study is the EPBD building stock data for Flanders, that was gathered from the Flemish energy agency (VEA). They collect these data for the purpose of performing building energy certifications. The data contains general geometrical information about buildings such as building gross volume, gross surface area, heat loss surface area, building compactness (volume/heat loss surface area), window to wall ratio and building physical parameters such as average U-value of walls and windows. [8]

The focus of this paper is on data for office buildings. From the database we selected newly office buildings that were built during the period 2006 - 2016 and that of gross floor area larger than 1000 m^2, and we have also eliminated cases that have missing data. This resulted in a data record consisting of 371 office buildings. By analysing the building stock data, we observed that 70% of the cases has volume less than or equal to 11000 m^3 (Fig.2). Around 82% of cases has a gross floor surface area less than or equal to 4000 m^2 (Fig.3), and 70% of cases has glazing percentage to heat loss surface area of 15% or less (Fig.4). This ranges gives an indication about the average geometrical building properties within the building stock.

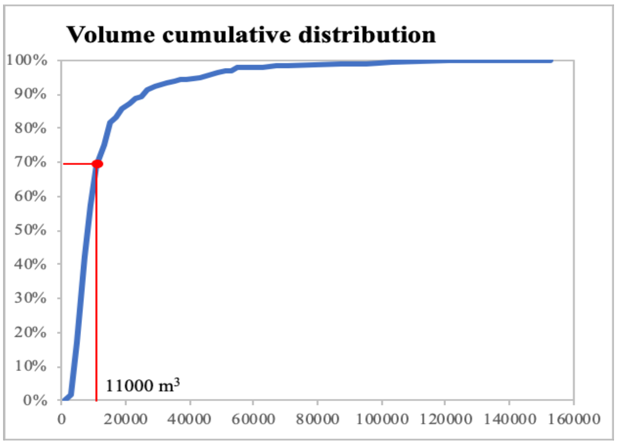

Fig. 2. Office building stock Volume distribution

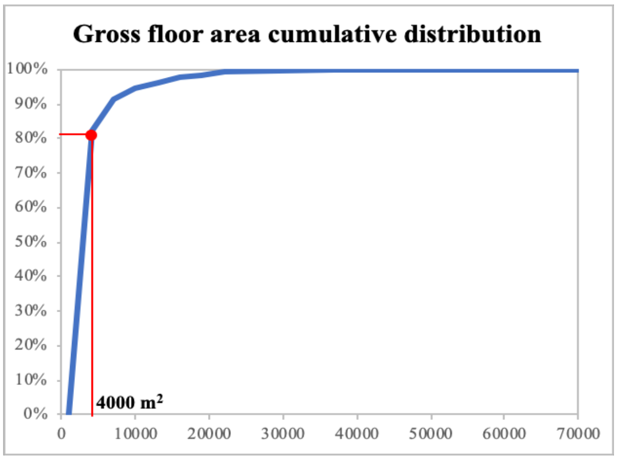

Fig. 3. Office building stock gross floor area distribution

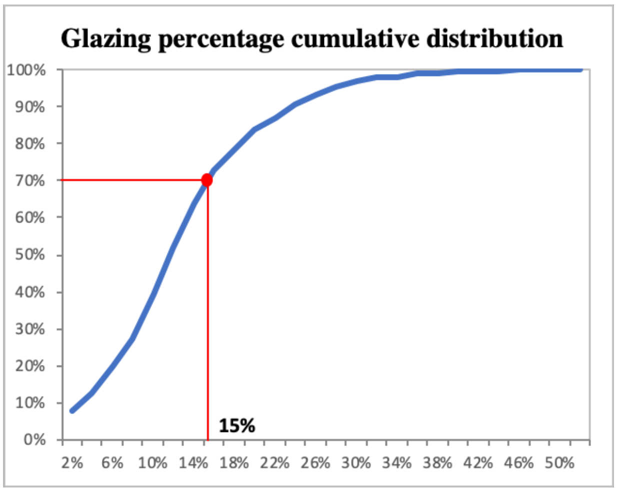

Fig. 4. Office building stock windows to opaque area percentage distribution

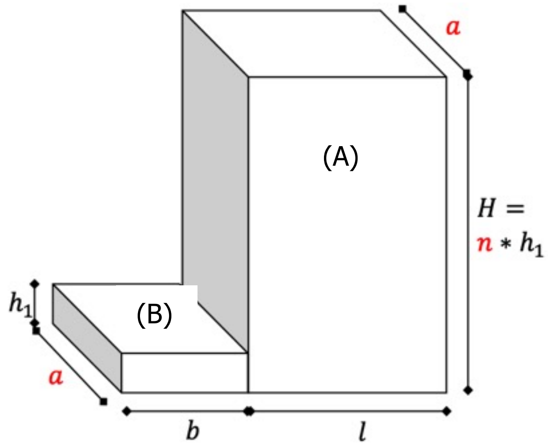

Fig. 5. Three-dimensional geometry of the archetype

2.3 Building archetype and fitting process

When developing the archetype building, the main goal is to find a generic form that includes all typical office building functions / spaces and of which the geometry can be adapted to the building geometrical input data. This was achieved by choosing a modular form that can be parameterized following typical offices zones and dimensions. The archetype typical floor plan is divided into 5 zones. Each zone represents different functions such as, meeting rooms, single offices, landscape offices, restaurants and services area.

In the fitting process we used three equations that describes the building form as a function of volume, heat loss surface area and gross floor surface area that were input from the building stock data. We assumed that the building consists of two volumes (Fig.5). The first volume (A) is of a cuboid form, where (a) is a constant width equal to 15.5 meters. This width represents two offices zones facing each other, each of 6 meters length with a 2.5 meters corridor in between, and total walls thickness of 1 meter [8]. The building length (l) is a variable that is parametrized based on each individual case in the building stock. Building height is a function of the number of floors (n). Number of floors is assumed between 2 and 10 floors, which is representative for office buildings in Flanders. Building floor height (h_1) is derived from the building input data by dividing the volume by the gross floor area. Volume (B) is an extended cuboid form, that is added to represent all the semi-attached buildings in the building stock. All cases were fitted to this form and classification has been made based on the fitting process outcomes, where 25 cases were fitted using only volume (A), 280 cases were fitted as semi-attached building, and 66 cases where fitted as attached building.

2.4 Building energy simulation model

The BES-model describing the archetype was made in Modelica modelling language, using the Dymola tool and the OpenIDEAS library [9]. The building model is made of five classes, each defining a model component. The first class is the building structure that defines the building geometry with different zones. Each zone is defined by the number of surfaces (such as walls, floor, windows, and internal walls) that are connected to adjacent zones. The archetype contains (n) number of floors refer to section 2.2, each floor having five zones, and an external zone that defines the adjacent volume attached to the building. For each surface type, the material is defined where its material thickness is calculated to define a chosen U-value. The second class is the heating and cooling system. We have used an ideal heating system which is modelled with temperature setpoints of 20°C and 25°C, so the temperature in the zones is always between 20 and 25°C.The third class is a mechanical ventilation system with heat recovery that has 85% efficiency with a constant flow rate. The flow rate is 36 m^3/h per person based on the EN 13779 standard [10]. The fourth class is set for the internal heat gains and occupancy schedules. For offices the occupancy schedule, influencing internal gains, starts from 8am till 5pm with a lunch break that starts from 12pm till 1 pm. The fifth class defines all building geometrical parameters, material properties and occupant profiles data. By grouping them in one record, it is easier to automatically vary each input based on the individual building properties from the building stock data.

3 Case study

To test the success of the proposed methodology, it was tested for 14 cases. The main parameters that were varied are building physical parameters (U-values, building orientation, and internal gains) cases (1 to 8), building geometry cases (9 to 12), and glazing to heat loss surface area ratio cases (13 and 14). Since all cases are located in Belgium, a weather file of Uccle was used for simulating all cases. The main properties of the 14 cases are summarised in Table 1. Cases from 1 to 8 are for one building, that represent an average building from the selected Flemish office building stock.

The building has 15% glazing to heat loss surface area, a volume of 8623.6m3, a surface area of 2543.6 m2, and 3.3 m average floor height. For this building two groups of thermal transmittance U-values were chosen (1) the first group corresponds to the U-value that is currently being implemented in Belgium 0.24 W/m^2. k for the building envelope, 1.5 W/m^2. k for windows and n50 = 2 ACH at a pressure difference of 50 Pa for air tightness. (2) The second group is for the U-value that is used in passive buildings 0.15 W/m^2. k for the building envelope, 1.0 W/m^2. k for windows and we selected n50 = 0.5. For each group we varied the internal heat gains, composed of occupants, appliances and lighting. The number of occupants is a function of the zone surface area. Two office profiles where selected: high dense (1 person/10m^2) or light dense (1 person per 18m^2). The total number of occupants per office is then multiplied by occupancy factor that assumes a percentage of the total occupancy during the day. Appliances such as monitors, and computers are based on the number of occupants per office, where each person has one monitor and one computer. Lighting is also considered in the calculations of the internal gains and is a function of the zone surface area (10 W/m^2) that is multiplied by a use factor. Second, we varied the building orientation where the largest façade is either facing south or west.

Cases from (9) till (12) are cases that have been based on the same glazing percentage while different geometrical characteristics and number of floors. On the other hand, cases (13) and (14) are cases where glazing percentage is greatly differing. An external screen shading system was implemented for all cases and the screen is controlled based on the solar irradiation on windows. The shading system is on when solar irradiation on the external window surface is higher than 250 W/m^2.

4 Analysis and Discussion of results

4.1 Load duration curves output of the process

Heating and cooling demand curves have been dynamically simulated for the 14 cases, and the load duration curves were generated. Looking closer to the cases where the geometry is fixed and physical parameters are varied cases (1 to 8), (fig.6), we can see in the load duration curves that case (4) has the highest maximum peak load of all the 8, that is 35.6 kW for heating and 54.8 kW for cooling. The cooling load is relatively high due to the high internal gains since it is a high dense office and the high solar gains due to the orientation of the largest façade to the west. On the other hand, Case (6) has the lowest peak heating load of 17.7 kW, while case (5) has the lowest peak cooling load of 36.7 kW, followed by case (6) 36.9 kW. For both cases the cooling load is low due to the low internal heat gains, however case (5) is facing south and thus has less solar gains than case (6) which faces west. For both categories of U-values, it is clear from analysing the load curves that the lower the U-value (0.15 W/m^2K), the less heat losses to the outside, and therefore the lower the heat demand is.

When looking to the cases where the building geometry is varied, while fixing the U-values, glazing ratio, orientation and internal heat gains (see fig.7), in terms of heating and cooling loads case (10) has the highest maximum peak power of 81 kW for heating and 101 kW for cooling. In terms of duration, for heating it has the longest load duration of 4630 h equivalent to 6.3 months, and for cooling about 1883 h equivalent to 2.5 months.

Table 1. Case studies specifications and parameters

Case number	Glazing (%)	Volume (m^3)	Area (m^2)	Heat loss area (m^2)	Compactness	Number of floors	U-value envelope (W/m^2. k)	U-value windows (W/m^2. k)	Internal gains	Orientation
Case (1)	15%	8623.6	2543.6	2893.7	3.0	4	0.24	1.5	Low	South
Case (2)	15%	8623.6	2543.6	2893.7	3.0	4	0.24	1.5	Low	West
Case (3)	15%	8623.6	2543.6	2893.7	3.0	4	0.24	1.5	High	South
Case (4)	15%	8623.6	2543.6	2893.7	3.0	4	0.24	1.5	High	West
Case (5)	15%	8623.6	2543.6	2893.7	3.0	4	0.15	1.0	Low	South
Case (6)	15%	8623.6	2543.6	2893.7	3.0	4	0.15	1.0	Low	West
Case (7)	15%	8623.6	2543.6	2893.7	3.0	4	0.15	1.0	High	South
Case (8)	15%	8623.6	2543.6	2893.7	3.0	4	0.15	1.0	High	West
Case (9)	15%	5493.9	1389.0	2594.3	2.1	2	0.24	1.5	Low	South
Case (10)	15%	26578.9	7010.0	6749.0	3.9	6	0.24	1.5	Low	South
Case (11)	15%	10084.0	3330.0	4412.5	2.3	3	0.24	1.5	Low	South
Case (12)	15%	12368.9	2905.2	3453.6	3.6	9	0.24	1.5	Low	South
Case (13)	40%	25445.9	6470.3	6773.5	3.8	5	0.24	1.5	High	West
Case (14)	3%	25875.0	4402.2	6877.0	3.8	3	0.24	1.5	High	West

On the other hand, case (9) has the lowest maximum peak power of 24.4 kW for heating and 23 kW for cooling. In terms of duration, case (9) has shortest duration of 4075 h equivalent to 5.5 months for heating, and 1609 h equivalent to 2.2 months for cooling. Case (10) is a large building with larger gross floor surface area and volume than of case (9) that is why case (10) has maximum peak power. However, Case (10) is more compact than case (9). The effect of compactness is clearer when we compare the total heating and cooling demand per square meter annually, where case (9) has much higher total demand of 30 (kW/m^2. a) than case (10) which has 18.39(kW/m^2. a) see Table 2. Cases (11) and (12) are close in terms of the peak power 44 kW, 40 kW respectively with durations of 4147 h, 4454 h.

To examine the influence of glazing percentage we chose two cases from the building stock with different glazing percentage (fig. 8) with same compactness, however case (13) has larger surface floor area than case (14), thus more internal gains, since internal gains is a function of the surface floor area (please refer to section.3). In case (13) where the ratio of glazing to heat loss surface area of the building is 40%, and more internal gains due to larger surface area has the highest maximum peak power of 131 kW heating, and 258 kW cooling, with the shortest heat duration of 3499 h equivalent to 4.7 months. The low heating load duration is due to the large surface of glazing that is exposed to solar gains in winter and the higher internal gains. For cooling load duration, it has the longest duration of 2572 h equivalent to 3.5 months due to the large surface of glazing exposed to solar gains and facing the west orientation in summer. Case (14) has the lowest glazing percentage of 3%, the maximum peak load is 71.5 kW for heating and 72.9 kW for cooling. The heating load duration is longer than case (13) as it has smallest exposed area to solar gains in winter, while for cooling loads the duration is very short, thus minimizing the solar gains in summer.

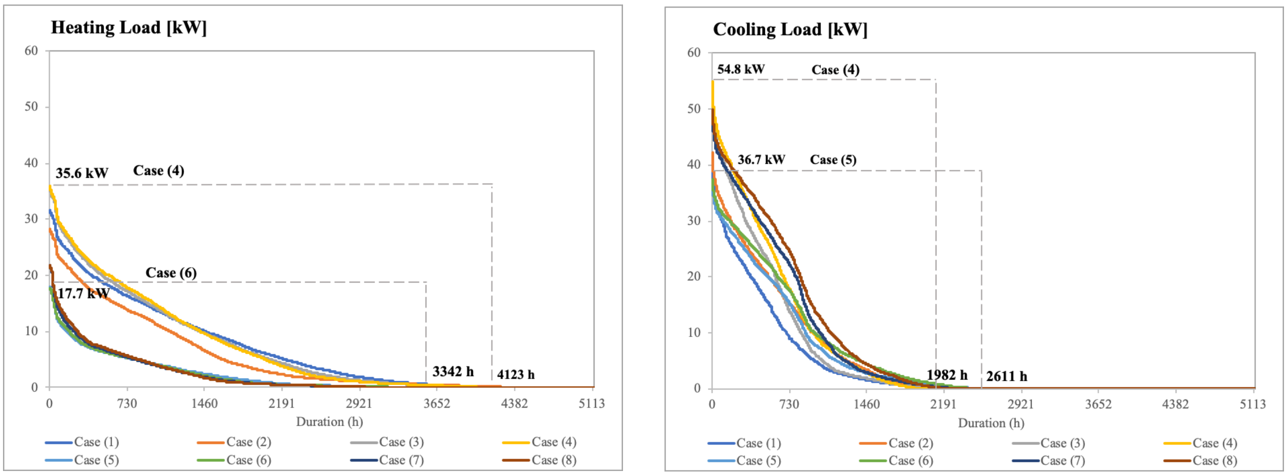

Fig. 6. Heating and cooling load duration curves for the cases from (1) to (8)

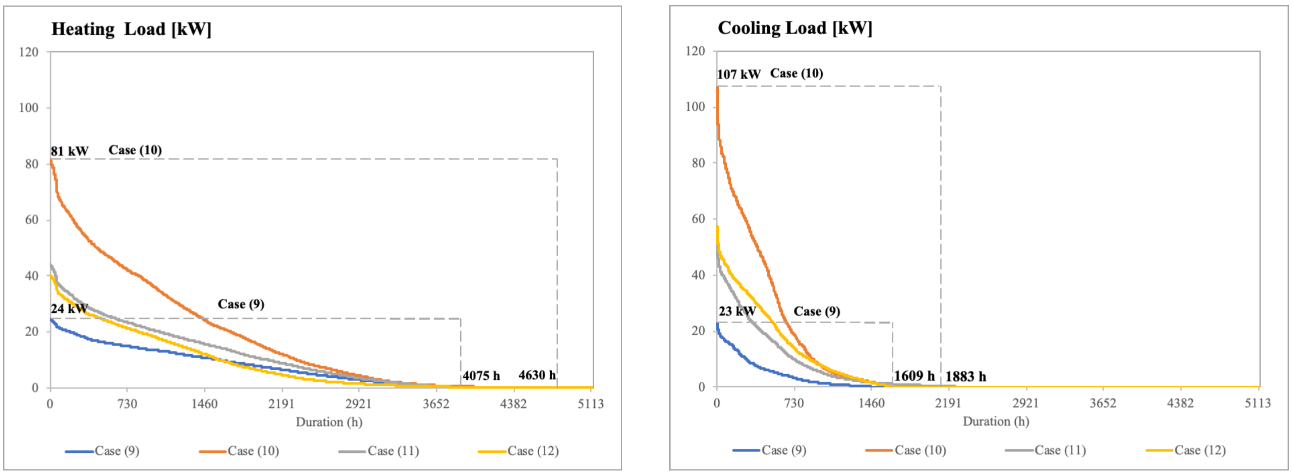

Fig. 7. Heating and cooling load duration curves for the cases from (9) to (12)

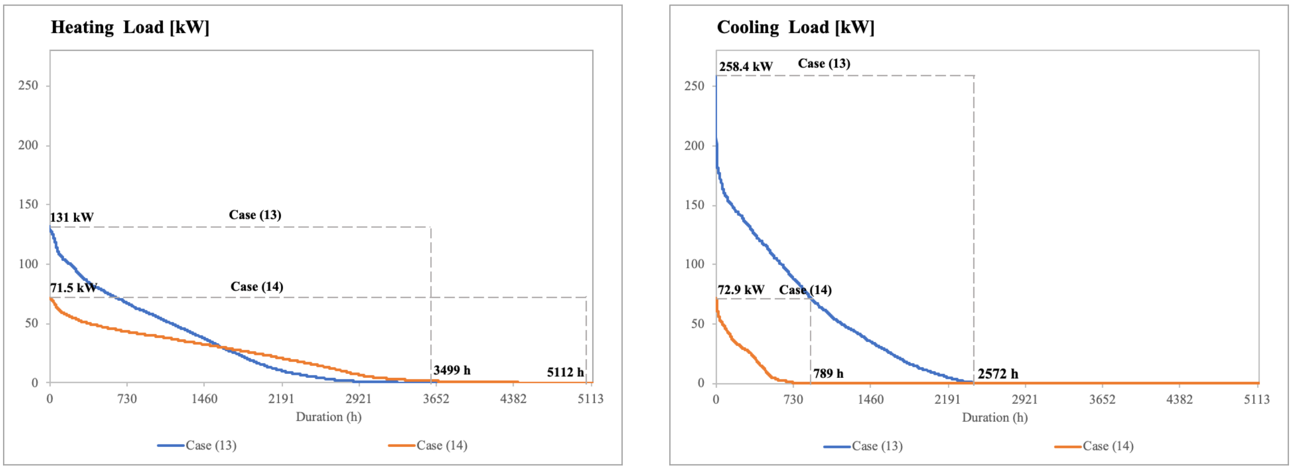

Fig. 8. Heating and cooling load duration curves for the cases of (13) and (14)

In general, as shown in Table 2 the cooling loads are highly influenced by the glazing surface area due to the solar gains when facing west orientation and the internal heat gains and how it affects the heat storage in the building mass. While the increase in heating loads are a result of the building thermal insulation, the glazing surface are due to heat losses.

4.2 Discussion

Heating and cooling load duration curves are valuable input for designers to identify the sizing of the heating and cooling systems and deciding which part of the demand will be covered by the different systems. In this section we will show one of the possibilities for choosing the different system combinations to cover the total heating and cooling demand and illustrate how the choice of these systems influences the primary energy based on systems performance factors.

In this exercise we assumed that the total heating and cooling demand will be covered by two types of systems (fig.9): a primary system (1) that covers 70% of the minimum peak load for heating and cooling. A geothermal heat pump was chosen to be the primary system. For the heat production, we assumed that the heat pump has a performance factor of 5. For cold production, we compared between two scenarios, the first scenario is active cooling using the heat pump with performance factor 5 as used for heating, and the second scenario we assumed that the whole demand will be covered by passive cooling with a performance factor of 12. The secondary system (2) covers the remaining demand of heating and cooling. For heat production we assumed a gas fired boiler with performance factor of 1, and for cold production, we assumed an electrical chiller with performance factor of 3.5. To calculate the primary energy, we divided the performance factor of each system by a primary conversion factor. We used a primary energy conversion factor for natural gas of 1.0 for the gas fired boiler, and primary energy conversion factor for electricity of 2.5 for the chiller, heat pump and passive cooling [11].

Table 2 presents the yearly total demands for each of the cases, the total primary energy demands obtained by considering the performance factors and primary and secondary system shares for 2 scenarios. Furthermore, the average performance factor of the entire system is estimated by dividing the total demand by total primary use.

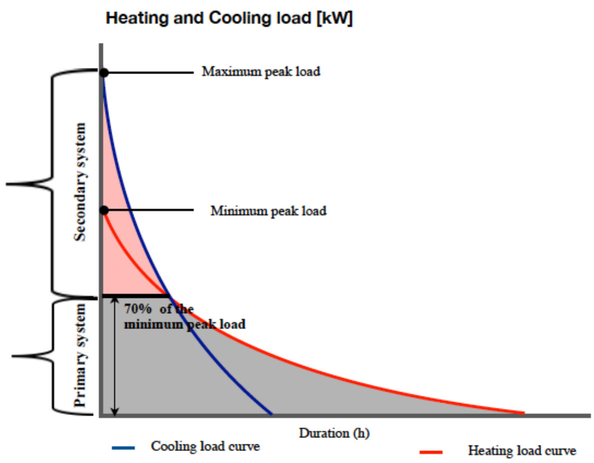

Fig. 9. Division of primary and secondary systems

The primary energy consumption is in alignment with the heating and cooling demand per square meter. In scenario(1), cases (11) and (14) has higher performance factor for the entire system, since most of the demand is covered by the primary system (heat pump) that has higher total performance factor than the secondary system. While case (8) has the lowest performance factor since the cooling load covered by the secondary system was as much as the one covered by the primary system. In scenario (2) cases (13) and (2) have the highest systems

Table 2. Primary energy, heating and cooling demand per square meter annually

	Heating demand (kWh/m². a)	Cooling demand (kWh/m². a)	Total energy demand (kWh/m². a)	Total primary energy scenario1 (kWh/m². a)	Total primary energy scenario2 (kWh/m². a)	Performance factor Scenario 1	Performance factor Scenario 2
Case (1)	13.4	7.3	20.7	10.7	8.8	1.94	2.37
Case (2)	10.3	9.8	20.1	10.6	8.2	1.90	2.45
Case (3)	13.4	10.2	23.6	12.4	9.9	1.91	2.38
Case (4)	13.5	11.9	25.5	13.5	10.7	1.89	2.39
Case (5)	4.0	9.4	13.4	7.4	5.7	1.80	2.35
Case (6)	3.9	10.7	14.6	8.2	6.3	1.78	2.33
Case (7)	4.1	12.6	16.6	9.5	7.4	1.75	2.26
Case (8)	4.2	14.0	18.2	10.4	8.1	1.74	2.24
Case (9)	24.5	5.6	30.1	15.7	14.0	1.92	2.14
Case (10)	12.2	6.2	18.4	9.5	7.9	1.93	2.33
Case (11)	15.3	6.5	21.9	11.2	9.5	1.95	2.31
Case (12)	14.2	9.4	23.6	12.3	10.0	1.92	2.36
Case (13)	19.1	23.3	42.4	22.4	16.8	1.89	2.52
Case (14)	22.6	3.8	26.4	13.5	12.5	1.95	2.12

performance factor for the entire system, where the percentage of the cooling demand covered by the primary system was much higher, thus covering this demand with passive cooling that has higher performance will result in a better overall performance factor for the entire system. By comparing the two scenarios of using different cooling systems to cover the cooling load in the primary system we observed that by replacing the active cooling by passive cooling system a range of 8% to 26% decrease in the primary energy consumption per m² can be achieved.

In the previous paragraphs we have showed one possibility for dividing the total demand that will be covered by the primary and secondary systems. Other possibilities can be also used such as achieving balance in the borehole field, this means that the amount of heat extracted from the ground during winter, shall be equal to the amount of heat injected to the ground in summer, thus the primary system will cover the total energy demand that meets this criterion.

5 Perspectives

This paper has shown a sample of 14 office building, to demonstrate the potential of using the proposed methodology. In addition, an application of the load duration curves for sizing and performance calculation of primary and secondary heating and cooling system was illustrated. This principle will be further explored and elaborated for sizing of hybridGEOTABS systems. In next steps, we are going to expand the methodology to three other typologies: school buildings, elderly homes and multi-family buildings. Then, the methodology will be applied on a larger set of buildings, representing the European building stock for these four typologies and located in different climatic zones appearing in Europe.

6 Conclusion

In this paper we have presented a process of generating heating and cooling load duration curves from multi-zone building energy simulation models that uses building stock geometrical data as input. The process was illustrated for a sample of 14 office building cases with varying physical parameters and geometrical parameters. The initial analysis of these case studies has demonstrated the importance of glazing percentage on heating and cooling loads. When it is combined with other influential parameters such as building orientation and internal gains this will lead to high cooling loads.

The illustrated process will allow the simulation of a large amount of buildings representing the EU building stock for a number of typologies. The analysis of the obtained heating and cooling load duration curves will allow the system sizing and feasibility assessment of hybridGEOTABS technology for various building typologies throughout Europe, while taking into consideration variations in typology, geometry, building physical parameters and climate. Furthermore, the obtained load duration curves for this variety of buildings, may be of use for other sizing and research purposes.

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