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The Dilemmas of Choosing a Suitable Technology for Low Energy and Passive Houses in the Context of their Overheating Issues

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Abstract. In compliance with European Union directives, numerous countries are introducing increasingly stricter legal limits on the estimated energy consumption of newly designed residential buildings. However, the fact, that regulations and designers' efforts are focused on decreasing energy consumption (and consequently carbon dioxide emissions) only at the post-occupancy stage, may lead to a significant increase in the carbon footprint of the buildings during their entire life cycle. A frequent criticism levelled at low-energy and passive buildings is that they are susceptible to the phenomenon of overheating. The reduction of overheating through the choice of "massive" technologies, materials with high thermal capacity as well as a high heat dispersion coefficient, stands in opposition to the requirement to choose the technologies that ensure a low ecological footprint (i.e. timber frame technologies). The development of a tool facilitating decision making in this issue seems to be a challenge. Life Cycle Assessment (LCA) is a well-known, optimal method for forecasting buildings' carbon footprint, however, it is an expensive and time-consuming method. Life Cycle Assessment is a method dedicated to large investments. In practice, such analysis are not carried out for residential buildings. The purpose of this paper is to analyse the foregoing problem on the example of detached single-family houses and to propose a method and tool that can assist architectural design in this regard.

1. Introduction

In compliance with EU directives, numerous countries are progressively introducing more strict legal restrictions on the estimated energy consumption of newly designed residential buildings [1, 2]. The passive and energy-efficient buildings' standards are now more extensive. Tools for forecasting energy consumption are now available and adapted to investments that differ in terms of scale and function. The software used to perform a full thermo-dynamic analysis allows for the optimization of buildings in terms of energy demands and their resident's thermal comfort. However, carrying out a thermo-dynamic analysis is a lengthy and costly process - unsuitable for a limited budget and design time.

In Central European conditions with a humid continental climate, in Poland for example, where average annual winter temperature drops below 0°C, architects primarily focus on the issues concerning energy consumption throughout the winter. The issue of overheating in the summer is given less attention. Difficulties in using thermo-dynamic analyses at an early stage of design often result in architects leaving decisions regarding building overheating to the sanitary installation designers (at a later stage of the design). However, early design decisions and the selection of technologies by architects have a significant impact on the users' comfort and the amount of overheating. While in the case of



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traditional buildings, the margin of design error is quite large, but the buildings designed according to the passive and energy-efficient standards, design errors tend to have more serious consequences.

2. Overheating of buildings in a passive and energy-saving standard - possible causes

According to the principles of designing buildings with low energy demand, overheating is limited by simple, passive methods. The priority is to use solutions that do not consume nonrenewable energy and do not require frequent maintenance. Generally, the recommended method of preventing overheating is night time ventilation, the use of sunshades and the use of building partitions of massive materials, characterized by high thermal capacity and high temperature dissipation factor.

However, in practice, according to a popular opinion, residential buildings designed in the passive and energy-efficient standard are more prone to overheating [3]. This is especially true for Central European countries. While the forecasted energy demand usually corresponds to the real one, the overheating forecast is often turns an underestimation (even when using programs dedicated to passive buildings such as the Passive House Planning Package - PHPP). This underestimate may be due to the following reasons:

(1) Climate change. Typically, overheating is estimated based on average temperatures over many years. Meanwhile, studies report that the increase of the average temperature since 1900 is 0.8°C , which certainly affects the prevalence the amount of overheating [4, 5]. According to the study, the number of hot days following one after the other has increased significantly in recent years.

(2) The occurrence of the effect of "urban heat island". Typically, the forecasts do not take into account the effect of the "urban heat island". For passive buildings, where it is recommended to use night time ventilation as the basic method of combating overheating, it is particularly important that the temperature differences between day and night, as well as wind speed, in urban areas are reduced (10% -30%) [6,7]. In the overheating forecasting methodology, the albedo neighborhood coefficient of the building is also not taken into consideration, which may result in assumption errors.

(3) A fixed limit for overheating. Residential buildings are used in a distinctive manner in terms of the energy expenditure of their users. The optimal temperature in the rooms with low energy expenditure of their users is 20°C , while during sleep it is 18°C . For the occurrence of overheating, a constant limit of 25°C is assumed in most Central European countries. It seems reasonable that the limit temperature of overheating at night should be reduced.

(4) Too general division into the type of technology for the construction of external partitions. Division into so-called "light-weight" and "massive" technologies that crop up in many programs for forecasting energy demand and overheating are inadequate and result in errors. There is a strong relationship between the chosen technology (exact construction of partitions) and the occurrence of overheating. Materials referred to collectively as "massive" or "light-weight" have different properties, such as heat capacity, specific heat, temperature dissipation coefficient and phase shift coefficient (this coefficient is referred to as the phase difference of two temperature waves, i.e. a wave defining fluctuations in the temperature of the outer surface of the partition and the wave defining the temperature fluctuations of the internal surface of the partition defined in hours).

In the case of passive houses, where the main method of tackling overheating is night time ventilation, it is especially important to take into account the phase shift factor. A lot of studies reveal that the selection of materials with an inadequate phase shift factor results in a significant increase of the interior temperature. The effects are more strongly felt if the better isolated buildings because even more accumulated energy is released to the inside of building, not to the outside. Passive buildings are most exposed to sun between 12-15. When the technology of baffle construction is incorrectly selected



and the phase shift factor is too short (6-8h), the wave of heat that is accumulated in the mass of external partitions reaches the interior by the evening. The effect can be such that the outside temperature does not allow the surplus energy to be removed from the building. When it repeats day after day, there is an accumulation of excess energy, and thus overheating.

3. Overheating the building and its environmental aspect

Overheating is not only a problem related to the comfort of use. The occurrence of overheating threatens the basic assumption of the concept of buildings with an almost zero energy demand, i.e. the reduction of carbon dioxide emissions. Cooling the air temperature in the room by 1°C requires more energy than heating it by 1°C. The use of active cooling systems, that users of buildings with underestimated overheating are condemned to, is costly, both economically and environmentally. The environmental impact of cooling agents is very high.

The use of passive methods to reduce overheating, understood as the use of massive materials with a high thermal capacity, can also increase the environmental impact of the building. Figure 1 shows the relationship between the global warming potential (GWP) of the construction of vertical, external partitions with U coefficient = 0,11 W/m²K (typical for passive buildings) and their thermal capacity.

Based on the graph below, it can be stated that the environmental impact of the construction of selected vertical, external partitions increases with the improvement of their properties affecting thermal accumulation and thermal comfort, especially for traditional partitions that are widely used in Poland and other Central European countries. The exceptions are partitions made of solid, wooden elements, and walls made of compacted straw (which, however, for economic, legal and cultural reasons are not very applicable in Central European countries). An insulating material that simultaneously reduces the carbon footprint and improves the thermal capacity of the partition is wood wool. The improvement of both parameters is noticeable in frame technology partitions. The heat capacity of partitions isolated with rock and glass wool, EPS foam insulation, PUR insulation and resole foam are similar. The carbon footprint of the partitions insulated with these materials is also similar, only the use of stone wool visibly worsens this parameter.

The conclusions from this analysis coincide with the dilemma of choosing "massive" and "light-weight" technologies, known from the literature: "light-weight" technologies recommended to reduce the environmental footprint are not usually optimal from the point of view of operational comfort and overheating of buildings (and vice versa: "massive" technologies - better in terms of comfort and preventing overheating - yet have a larger carbon footprint) [8-12].

Figure 1. The relationship between the global warming potential (GWP) and the thermal capacity of selected walls with U coefficient ^a = 0,11 W / m²K

	global warming potential ^b kgCO ₂ e/m ²	thermal capacity ^e kJ /m ² K
reinforced concrete wall, 2% steel, 18cm EPS styrofoam (λ 0,031 W/m ² K), 27cm	104,44 ^c	392,48
calcium-silicate brick, 18 cm mineral wool (λ 0,034 W/m ² K) 33cm	89,32	338,64
Thoma Holz100, solid wood, 36,4cm wood wool (λ 0,038 W/m ² K) 16cm	76,17 ^d	517,30
calcium-silicate brick, 18 cm PIR foam sheet (λ 0,028 W/m ² K), 24cm	64,91	346,06
calcium-silicate brick, 18cm wood wool (λ 0,038 W/m ² K), 37cm	61,04	370,89
calcium-silicate brick, 18cm resole foam (λ 0,021 W/m ² K), 18cm	61,01	342,55
calcium-silicate brick, 18cm glass wool (λ 0,032 W/m ² K), 32cm	60,74	339,70
calcium-silicate brick, 18cm EPS styrofoam (λ 0,031 W/m ² K), 26cm	58,79	339,63
aerated concrete block, 24cm EPS styrofoam (λ 0,031 W/m ² K), 23cm	58,19	144,36
timber frame construction/stone wool, 20cm, stone wool (λ 0,034 W/m ² K), 13cm	46,59	77,67
ceramic block, 25cm, EPS styrofoam (λ 0,031 W/m ² K), 24cm	43,93	189,61
solid wood construction 2x30 cm, blown wood wool (λ 0,038 W/m ² K), 19cm	37,60	444,95
timber frame construction/wood wool, 20cm, wood wool (λ 0,038 W/m ² K), 18cm	18,19	111,00
compacted straw in timber frame, 6% timber (λ 0,066 W/m ² K), 63cm	9,01	254,48

^a U coefficient. For the purposes of the analysis, an identical heat transfer coefficient $U = 1.1 \text{ W / m}^2\text{K}$ was adopted. This is the value recommended by Passivehaus Institut Dramstadt as suitable for passive buildings. Some of the partitions are impossible to implement due to technical reasons, eg lack of fixations of the appropriate length for the chosen insulation thickness or lack of access to an insulation of this thickness. This has been omitted; the graph is purely for research purposes.

^b The global warming potential was counted without CO₂ capture and omitting the transport of material. Calculations were made based on the averaged EPD values of building materials. The internal and external finishing was not included in the calculations.

^c Due to the large discrepancy between the environmental impact of steel and concrete, depending on their manufacturer, taking an average would be improper. The GWP value of the partition was given in terms of the range of the lowest to the highest.

^d The environmental impact of the partition is low (low-processed wood construction -i.e. Thoma Holz 100), however, due to the production taking place in a single location in Central Europe, the transport omission results in a greater underestimation than in the case of other partitions.

^e Heat Capacity. Own calculations in compliant with the PN-EN ISO 013790 standard, made using the exact method, i.e. for all components of the building partition from the internal finish to the first thermal insulation layer including this layer. The values of density and specific heat used for calculations based on the following standards: PN-EN ISO 12524: 2003, PN-EN ISO 6946: 1999, PN91 / B-02020 [13-16].

4. Conclusions

There are sophisticated tools for forecasting the environmental impact. This is primarily an analysis of the full life cycle of the building (LCA). However - as in the case of thermodynamic analysis, as tools for estimating overheating - it is a time-consuming and costly method. Presently, it is not very feasible to put it to widespread use. This is evidenced by the fact that even the BREAM and LEED certification systems, which in their assumptions define the standard of the best practices in the field of sustainable design, but do not introduce the LCA analysis as an obligatory tool (for years LCA analysis in both systems is optional). The same (in both BREAM and LEED certification systems) applies to the use of materials for which the Environmental Product Declarations (EPD) has been prepared. In both systems, optional points are awarded for such practice (this is not an obligation).

For an architect, the LCA analysis and full thermodynamic analysis are not practical design tools, and the selection of materials whose global warming potential is confirmed by the EPD declaration is difficult (there is no system solution that collects a set of materials in one database or search engine). As a result, when designing small objects, such as single-family houses, with the intention to reduce the environmental footprint, architects rely largely on intuition, and this can lead to errors.

The problem of overheating of passive buildings is discussed in scientific literature. This does not mean, however, that it functions as practical knowledge amongst architects. However, an incorrect selection of construction of external partitions of passive buildings has more serious consequences than in the case of conventional construction. Designers facing the choice of partition technology must address the basic dilemma and meet two opposite assumptions: ensuring thermal comfort and reducing the environmental impact.

The available methods for estimating overheating and environmental footprint are difficult to apply in the design practice of small scale objects such as residential houses. Therefore, the challenge is to develop a method and a tool to help make decisions concerning this issue. Building a database containing frequently used technologies of building partitions (extended in relation to the above-described walls with other external barriers - such as roofing and foundations), their features (EPD declarations and thermodynamic properties) would be of great use to practicing architects. The values given in EPD declarations, heat capacity and specific heat are available but difficult to find and compare. In the case of phase shift coefficient, the situation is different - creating a construction materials database containing this value requires prior research. Building a simple, available tool based on systematized environmental footprint values and thermodynamic properties, would allow the application of scientific research results in everyday architectural practices.

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