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NEW FACADE DEVELOPED FOR SUSTAINABLE, ZERO-ENERGY OFFICE BUILDING – THEORETICAL ASSUMPTIONS AND NUMERICAL ANALYSIS

D. Heim, I. Zbiciński, M. Barecka, D. Knera,
A. Machniewicz, E. Szczepańska-Rosiak
Department of Environmental Engineering
Lodz University of Technology, Lodz
Poland

ABSTRACT

Architecture inspirations of modern office buildings draw from new material and construction solution or from philosophical aspects of human living. During last decades there were a lot of trends in building market derive from fashionable mottos e.g.: solar, green, environmental friendly, sustainable, low-energy, zero-net or plus-energy architecture. However, most of the existing office buildings were often design without previous analysis and final effect was worse than it was expected. The presented study was devoted to developed an external wall system dedicated for zero-energy office building. Initial analyses start with architecture and ergonomic considerations taking into account different construction of building elements and it is topology. The second step of analysis determined minimum and maximum window size based on results obtained from daylighting simulation. Thermal analysis using transient heat conduction method show the energy balance of the wall and adjacent zone. Finally, the potential of solar energy as a source of heat and electricity were estimated for assumed configurations and PV – glass ratio. In the second part of the analysis the seasonal and annual energy balance for single components were estimated numerically using ESP-r software. The following component types were considered: opaque - glass and PV or transparent - single or double skin. Based on the obtained results authors proposed a function of energy flux versus number of panels. The functions show that some of the components have a positive energy balance and could be apply to achieve effect of zero or even plus energy façade. The final optimized solution of the façade system will be design and construct at one of the university building within the framework of German- Polish Energy Efficiency Project.

Key words: façade, energy, optimization, photovoltaic, sustainability

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Introduction

The major challenges to sustainable development in countries of the European Union is how to promote energy efficiency, so as to allow those countries to meet their climate commitments and simultaneously maximize their economic potential of building. One of the means through which this challenge can be achieved is fostering energy efficiency in buildings. The general rules of sustainable design are often expressed by the building environmental efficiency (BEE), well known from sets of standards and assessment methods e.g. BREEAM, LEED, CASBEE, etc. [1].

The basic definition of BEE indicator always bases on two opposite factors: maximum built environment quality against minimum built environmental load. Building envelope as a one of the boundary elements separated indoor and external environment play a crucial role in providing high value of BEE. Moreover, developing innovative approaches to facade technology, helping to reach the goal of net-zero energy buildings.

The several approaches from architecture to building technology can easily help to improve building energy characteristics. One of them concerns efficient management of solar energy and its utilization in a different form, from daylight to electricity. Modern, sustainable office buildings are characterized by low ratio of glazing/opaque area in order to avoid overheating and provide proper daylight conditions.

Additional requirements defined for buildings in the area of energy production from renewable sources make it necessary to integrate selected renewable energy systems with the building envelope. Simultaneously heat transmission has to be minimized to reach a positive energy balance of external partition over a year. On the other hand, activation of opaque parts by integration with PV panels can lead to improve the energy balance of the façade and help to achieve, zero-energy standard. The ability to convert surplus energy to the form possible for an on-site use, effective storing or immediate selling to the grid should be also taken into account.

Concept of Environmentally Efficient Façade

The technology developed for the purpose of GPEE [2] project is based on the Ventilated Façade Insulation System (VFIS). Nowadays, the VFI system is less popular than the External Thermal Insulation Composite System (ETICS) because of the cost and versatility for new and existing buildings. However, taking into account future trends and requirements in building energy performance, this relation would be reverse. The main advantages of VFIS versus ETICS are: easy integration with photovoltaic panels, protection against interstitial condensation through air exchange in a cavity, aesthetics and durability.

The general concept of the façade was developed by discretizing façade area on the several elements with different thermo-physical properties. The types of panels considered for possible façade design are following:

- Opaque panel with glass finish,
- Opaque panel with photovoltaic finish,
- Opaque panel with phase change materials and glass finish,
- Opaque panel with phase change materials and photovoltaic finish,
- Window- single skin façade (only for the first two façades),
- Window- double skin façade (only for the first two façades).

The size of panel is 60 cm per 60 cm for all panels apart from PV finish ones; the size of those is 120 cm per 60 cm. The topology of each element was not considered in this analyses. However, because of daylight requirements the window was always, if possible located in a central position to the midpoint of the façade.

Minimum Window Size

The initial numerical analyses were performed to find the minimum size of the transparent elements. Adequate amount of daylight providing visual comfort in buildings, is strongly associated with the proper design of windows size, shape, type and location, as well as the appropriate design of rooms depth and proportions.

To determine the solution of the most efficient use of daylight and minimum effect of overheating, a various of sizes and geometries of window have been analyzed (Table 1). Transparent element was defined as a glass panel with a thickness of 4 mm and visual transmittance τ_{vis}=0.75 (defined using RGB color code). The external boundary condition was assumed as typical meteorological year (TMY) for specific location.

Based on values daylight indexes DF, DA, UDI, DSP received from simulation, minimum window area has been determined. A mean value of each factor, for each analyzed case are shown in Table 2. The best solution with the greatest values of DF, DF > 2%, DA and UDI (100÷2000 lx) are represented by case 4 a and c.

Taking into account the requirement of the smallest, most favorable, in terms of visual comfort, values of the coefficients UDI <100lx and UDI >2000lx most the most suitable are case 4b and the case with the smallest surface of the window. Because of technical requirements due to the geometry of PV panels the square window (4a) were considered as a the most appropriate.

Table 1 : Geometry and size of windows.

Window size [m^2]	Percentage of glazing facade [%]	Window geometry scheme (grey color means window)		
0.36	6.25	Case1		
0.72	12.50	Case 2a	Case 2b	Case 2c
1.08	18.75	Case 3a	Case 3b	Case 3c
1.44	25.00	Case 4a	Case 4b	Case 4c

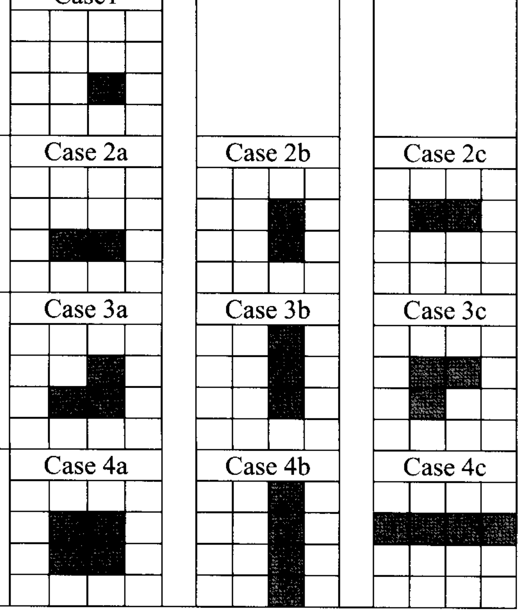

Table 2 : Comfort indexes value for 25 cm of external wall thicknesses.

25 cm of wall thicknesses		DF [%]	DF > 2 [%]	DA [%]	UDI < 100 [%]	UDI (100-2000) [%]	UDI > 2000 [%]	DSP [%]
Work plane = floor area	Case 1	0.2	1.7	3.3	89.4	9.9	0.4	2.0
	Case 2a	0.4	4.4	8.8	76.7	22.1	1.2	5.1
	Case 2b	0.8	7.8	17.3	60.0	38.3	1.8	9.7
	Case 2c	0.9	13.6	27.0	43.8	54.6	1.7	15.8
	Case 3a	1.0	11.4	22.9	53.4	43.8	2.8	13.8
	Case 3b	1.3	17.2	31.0	39.2	57.6	3.3	19.0
	Case 3c	1.4	20.8	35.5	31.7	64.7	3.7	22.2
	Case 4a	**1.7**	**23.3**	**31.9**	**39.3**	**56.6**	**4.1**	**23.0**
	Case 4b	**1.3**	**17.2**	**27.1**	**43.1**	**24.7**	**2.2**	**19.4**
	Case 4c	**1.8**	**40.3**	**42.7**	**24.0**	**71.4**	**4.2**	**32.7**

Heat Transfer Reduction

One of the crucial aspects on the design level of a zero-energy office building is proper assumption of thermal properties of external partitions. Considering the envelope construction, to achieve the standard of zero-energy building, it is necessary to minimize the heat flux through the external surfaces. That goal can be realized using two different approaches. The simplest way to reduce the heat transfer is to increase the thermal resistance of the partition, by changing the thermal conductivity or a thickness of the insulation. The second idea is based on the dynamic response of the active material composed in wall, that induces the counteracting heat flux e.g. received from solar radiation and absorbed in the active material layer. In the presented analysis both approaches were considered.

To evaluate the possibilities to reduce the heat flux through the external wall, initially the effect of the thickness of insulation on energy demand for heating was analyzed. Analysis of the optimal insulation thickness was carried out from 5 cm to maximum value adopted due to the limitations of available mounting brackets systems in VFI technology, equal 50 cm. Nevertheless, despite the theoretical analysis, the minimum value that can be applied, was determined based on the material properties and requirements for thermal resistance of external walls that will be obligatory in EU countries after 2021. According to the assumption that the maximum value of thermal conductivity for the analyzed partitions should not exceed 0,20 W/m2K, the minimum insulation layer thickness is 17 cm (standard insulation material).

Based on the results presented on the Figure 1 it can be stated that reduction of insulation thickness from 50 cm to 20 cm has little impact on the heating demands. Hence, thickness bigger than minimal required will provide comparable energy performance during winter months but is less cost effective (due to higher material consumption). On this basis, optimal insulation thickness was assumed as 20 cm.

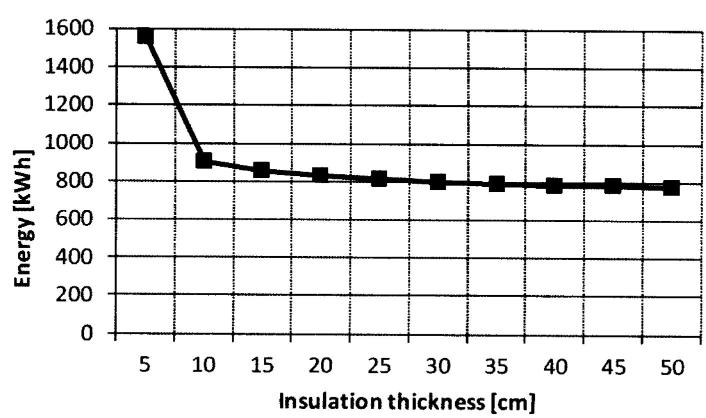

Figure 1 : Dependence of the insulation thickness on the heating energy demand.

The second idea that aimed to minimization of conductive heat flux was based on implementation of additional layer of active – phase change material. That materials are substances characterized by a high heat of fusion which melt and solidify at a certain temperature and are capable of storing and releasing large amount of energy while changing the phase. This effect was used to induce the counteracting heat flux, effecting from releasing heat absorbed during the melting process.

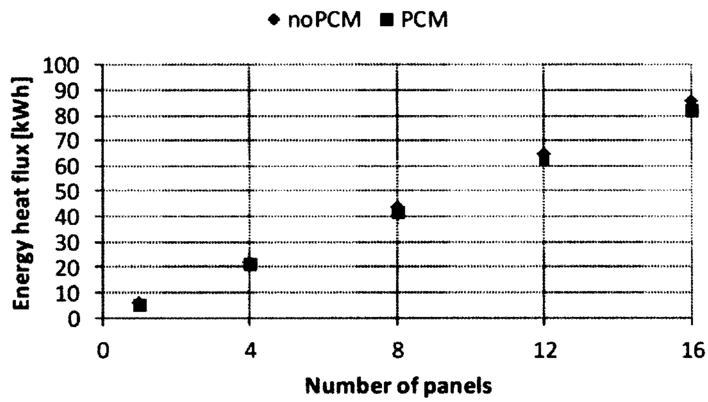

Figure 2 : Dependence of the number of exposed panels on the energy heat flux.

Specific application of PCM needs proper assumption of its thermodynamic, kinetic and chemical properties. One of the most important factors affecting the effectiveness of PCM performance is its melting and solidification temperature. Selection of transition temperature of PCM for a particular application should match the range of heating or cooling temperature as well as external weather conditions. Moreover, assumption of the position and amount of the material in wall component is very important to fully utilize the potential of latent heat storage capabilities. The main assumptions for analysis of the possibility to minimize the conductive heat flux by active layer were made according to the result of previous research work [3]. For the purpose of the optimization task dependence of number of panels exposed to external environment on the energy heat flux transferred through the partition was calculated. As presented on the Figure 2 it can be observed implementation of thin layer of PCM has a little impact on the energy heat flux, even when applied in the whole surface of façade. Nevertheless, phase change materials contribute to lower the fluctuations of heat flux values which can results in improvement of system performance.

Solar Energy Utilization in BIPV

Provide a zero-emission building is very complex issue and requires application of the active systems to obtain energy from the renewable sources like solar energy. Quesada et al. [4,5] give an exhaustive review of both opaque and transparent solar facades which use passive and active methods of solar energy application. Due to the developing market of photovoltaic technology and decrease of its cost, the Building Integrated Photovoltaic (BIPV) becomes more and more popular. The main concept of this technology is to replace traditional elements of building envelope by active system consisting of photovoltaic cells. Application of the BIPV transforms building envelope into energy active surface which produce electrical energy for internal devices like mechanical ventilation or lighting.

Calculations of electrical energy generated by photovoltaic panels were performed with the simulation program ESP-r. Analyses for optimization were carried out using simple model with constant efficiency Photovoltaic panels selected for the experimental facade were provided in the CIS thin film technology with efficiency at the level of 12%. Simulations were performed for four orientations of the façade and the whole year with the 15-minute time step. There were analyzed eight cases due to the number of photovoltaic panels installed at the experimental façade, from one to eight PV panels covering analyzed surface.

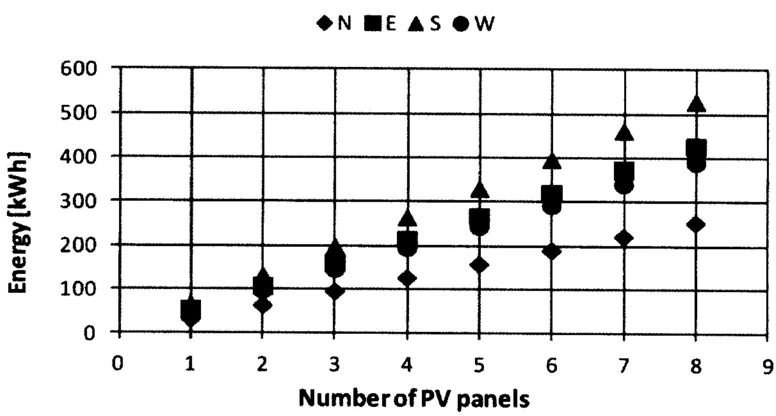

Figure 3 : Total electrical energy generated by photovoltaic panels.

Results of total electrical energy generated by photovoltaic panels through the whole year are presented in the figure 3. It can be noticed that south oriented panels produced the highest amount of energy, over 500 kWh for 8 panels. East and west oriented panels generated comparable amount of energy, near 400 kWh for 8 panels. The lowest energy was produced by north oriented facade. Furthermore, regardless to the orientation, energy produced by PV panels increase linearly together with rise of their number. This noticeable correlation is caused by simple calculation method where amount of energy is direct related to the solar radiation incident on photovoltaic material and the size of active surface.

Energy Balance for Transparent Elements

The main goal of this part of analysis is to express the energy balance of a transparent façade panel as a function of its surface. Two window types were considered: window type as a single and double skin façade. Both panels are based on the same alumina support system. The single skin façade window is built from three layers of glass, characterized by the U value 1.3 W/m^2K. The double skin façade window consists of the base window (the same as in the single skin type) and extra glazing, added from outside in order to improve the thermal performance of the transparent façade system.

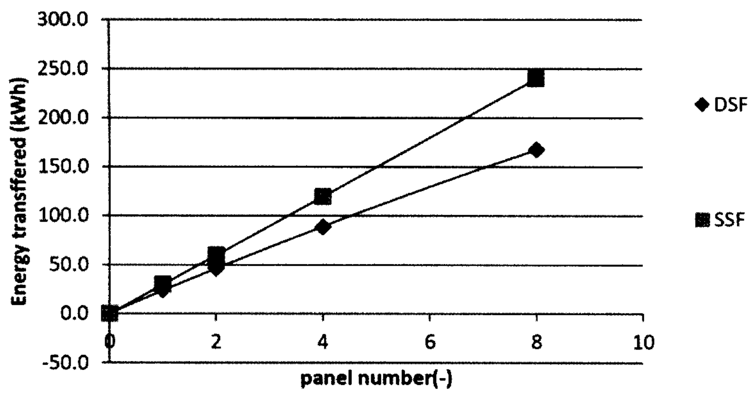

Figure 4 : Energy consumption vs. panel number (east oriented window).

The results of the numerical analysis enabled to estimate the energy transferred by the façade composed of different number of considered panel (1,2,4,8 elements of 60 cm per 60 cm size) during whole year, under specific, moderate climatic conditions. The energy transferred obtained by simulation technique was summed up for summer and winter period separately. (Fig. 4). The fitting was performed on plotted points in order to obtain energy functions, summarized in the Table 2. The simulations were performed for the west orientation of façade, however considering the whole- year energy consumption the results for the east façade would be almost equal.

Multi-objective Optimization Procedure and Final Solution

The multi-objective optimization procedure was performed in following steps:

Normalization of objective functions

Since all objective functions are expressed in different units and the range of their values differ significantly, the objective functions need to be normalized firstly. The following equation was applied for the normalization procedure:

$$f = \frac{f(x) - f_{r1}(x)}{f_{r2}(x) - f_{r1}(x)} \quad (1)$$

where f stands for the normalized value of the function, $f(x)$ is the value of the function before the normalization step, $f_{r1}(x)$ is the minimal value and $f_{r2}(x)$ maximal value of the function considered before the normalization step. As a results, the values of all normalized functions differ between 0 and 1.

Development of optimization code

The optimization code was developed in order to find the minimum value of the objective function (Equation 1). The code was written in MATLAB environment and the procedure fmincon was used for the optimization. Since the procedure is gradient-based, the algorithm usually finds only the local minimum of the function. Therefore, in order to find the global minimum, the optimization procedure was repeated 11 times using different start points. The points were selected so as to ensure highly uniform representation of the set of possible starting points. Subsequently, the global minimal value of the objective function was found.

Table 3 : First step optimization results; w_1 is the wage allocated to the cost function, w_2 to environmental impact and w_3 to energy consumption (first, west- orientated façade)

1st step results												
	w_1	w_2	w_3	*glass finish*	*PV finish*	*glass finish + PCM*	*PV finish + PCM*	*SSF*	*DSF*	**cost [euro]**	**environmental impact [tons of natural res.]**	**energy consumption [kWh/year]**
1	0.11	0.5	0.39	**0**	**12**	**0**	**0**	**0**	**4**	**3921**	**-131**	**-138**
2	0.8	0.1	0.1	**12**	**0**	**0**	**0**	**4**	**0**	**1989**	**375**	**185**
3	0.1	0.1	0.8	**0**	**0**	**0**	**12**	**0**	**4**	**4131**	**-137**	**-142**
4	0.33	0.33	0.34	0	12	0	0	4	0	2826	-94	-108

In the first step of the optimization, random, user-supplied sets of wages for objective functions were used. There were 4 sets considered (table 4), since the following Umeda procedure requires consideration of n+1 sets of wages, where n stands for the number of objective criteria (here 3: economy, environment and energy). In the table 3, the random, user-supplied sets of wages for the first step of optimization and the results of the first step optimization for the wages considered are given. Moreover, the energy consumption, environmental effects and cost for are calculated for the proposed compositions of the façade.

The negative environmental impact means that the environmental savings are higher than the resource consumption in the whole lifetime of façade. This result is mainly obtained for the photovoltaic panels, which enable an efficient production of electricity, and as a result, save more natural resources than there were consumed on a production or disposal phase of a façade panel. Likewise, the negative energy consumption means that the energy production form the façade was higher than the energy demand for heating or cooling.

Expert decision on the worst solution

In the next step, the expert decides which solution of the proposed set is the worst in terms of costs, environmental impact and energy consumption. Basing on the sets of wages for the worst solution, the algorithm will subsequently search for better wages and new set of 4 solutions is generated. The worst solution for the first step of optimization is presented in the Table 4.

Table 4 : The worst solution for the first step optimization (pointed by the expert).

	w1	w2	w3	*glass finish*	*PV finish*	*glass finish + PCM*	*PV finish + PCM*	*SSF*	*DSF*	**cost [euro]**	**environmental impact [tons of natural res.]**	**energy consumption [kWh/year]**
2	0.8	0.1	0.1	**12**	**0**	**0**	**0**	**4**	**0**	**1989**	**375**	**185**

Table 5 : Summary of solutions obtained in the optimization procedure. (first, west-orientated façade)

	w1	w2	w3	*glass finish*	*PV finish*	*glass finish + PCM*	*PV finish + PCM*	*SSF*	*DSF*	**cost [euro]**	**environmental impact [tons of natural res.]**	**energy consumption [kWh/year]**
2nd step results												
1	0.11	0.50	0.39	**0**	**12**	**0**	**0**	**0**	**4**	**3921**	**-131**	**-138**
2	0.29	0.27	0.44	**0**	**12**	**0**	**0**	**0**	**4**	**3921**	**-131**	**-138**
3	0.10	0.10	0.80	**0**	**0**	**0**	**12**	**0**	**4**	**4131**	**-137**	**-142**
4	0.33	0.33	0.34	**0**	**12**	**0**	**0**	**4**	**0**	**2826**	**-94**	**-108**
3rd step results												
1	0.11	0.5	0.39	**0**	**12**	**0**	**0**	**0**	**4**	**3921**	**-131**	**-138**
2	0.29	0.27	0.44	**0**	**12**	**0**	**0**	**0**	**4**	**3921**	**-131**	**-138**
3	0.1	0.1	0.8	**0**	**0**	**0**	**12**	**0**	**4**	**4131**	**-137**	**-142**
4	0.15	0.29	0.56	**0**	**12**	**0**	**0**	**4**	**0**	**2826**	**-94**	**-108**

This step is performed till the new sets of solutions does not present better results than obtained in the previous step. The expert decides whereas the new solutions improve the previous results or not.

Results and Conclusions

Applying the procedure, the set of new wages was generated in each step of optimization so as to replace the set for the worst solution. The following steps are summarized in the Table 5. The worst solution, rejected subsequently by the expert is highlighted in grey. In the third step of optimization, the new set of wages, obtained from the Umeda procedure, did not result in improving the final result, since it has given exactly the same number of panels as in the recently rejected solution. As the wage search procedure brings no more improvements, the optimization procedure was finished at the 3rd step and the expert pointed the solution no. 3 as the best one.

After three steps of the procedure described above and the minimum window size estimated in paragraph 2, the optimal solution was found. According to the results of presented analysis the façade consists of 12 opaque elements covered by 6 PV panels and 4 transparent double-skin elements located centrally.

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