ALL-GLASS FACADES IN FIRE CONDITIONS FROM SUSTAINABLE DEVELOPMENT - POINT OF VIEW

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Summary

Existing statistical data about fire in buildings of residential and civic constructions lead to the increase of attention to a design of all-glass facades which used to be the most often reason of fire spread in consequence of glass panel-cracking and free rise of flames into higher storey. Therefore this paper is focused on the one hand on factors influencing fire spread along façade, on the other hand on application of mathematical modelling for optimal selection of double glazing unite for glass panels of light claddings.

Keywords: fire spread, mathematical modelling, all-glass façade

1 Factors influencing fire spread at all-glass facades

Among factors influencing fire spread at all-glass facades belong:

- wind effect,
- height and angle of inclination of facade,
- chimney effect especially at tall buildings and double facades,
- mounting
- of glass panels and load bearing structure – connection,
- size and thickness of glass sheets and type of glass.

1.1 Wind effect

Wind arises by a movement of air particles which are influenced by solar heat, gravitation, rotation and forming of the Earth surface. This movement in large height (about 500m) is approximately uniform and it follows the lines of constant barometric pressure – such winds indicate as gradient. One-storeyed winds are characterized by convection in boundary layer in which air velocity increases from zero at surface up to air gradient velocity. The convection in this layer is interfered by unevenness of the Earth's surface, natural and artificial barriers and development. Consequently one-storeyed winds are very no uniform; they comprehend differently oriented whirlwinds and adjacent flows.

In consequence of convection – unevenness in boundary layer of Earth's atmosphere wind velocity in nearness of the Earth's surface is very various in time. It is suitable to choose some time interval **T** (**Fig. 1**) for assessment of its effect, so-called integration time (e.g. several seconds, minute, hour) in which it is possible to determine average value. This method enables to determine the static (average) component of wind velocity and so-called pulsating (fluctuation) component which represents the fluctuation of wind velocity round this average value. Then the following relation is valid:

$$v(t) = v_{st} + v_p(t) \tag{1}$$

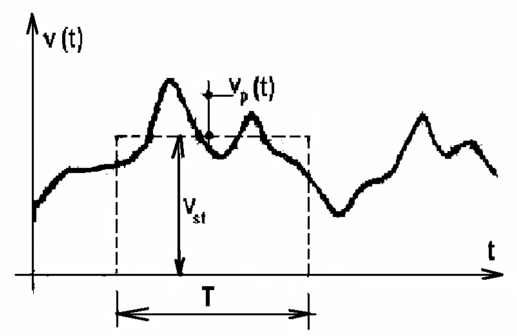

Fig. 1 Variable wind velocity and its decomposition on the constant and pulsating component: T – integration time of decomposition

Pressure of wind characterizing forced effect of wind on flow rounded body is given by the classic Newton relation

$$p = \frac{1}{2}.\rho.v^2 \quad \text{[Pa]} \tag{2}$$

where ρ is specific mass of flowing medium (for air in normal pressure and temperature 1,25kg.m^{-3}.

It is possible to assume for wind pressure approximately the validity of analogical linear relation as for velocity

$$p(t) = p_{st} + p_p(t) \tag{3}$$

Static component of pressure determines from above-mentioned Newton law, pulsating component assesses as a rule approximately from following expression

$$p_p(t) = 2.\frac{p_{st}}{v_{st}}.v_p(t) \tag{4}$$

If air current flows round body it affects on every part of its surface by elementary pressure (sucking). All these forces compose into resultant which it is possible to consider in three components as the resistance **D**, uplift **L** and rotating moment **M** centroid of body **s** (**Fig. 2**).

Wind moving around building will proves higher pressures on windward side and these pressures cause horizontal movement of air by building. Size of pressures will depend on the position of escape places in building, wind velocity and its direction, shape and height of building and in last not least row also on the effect of surrounding development.

Wind velocity changes in dependence on different specific conditions, e.g. articulation of ground, surrounding development, vegetation etc. Air flows from places with higher pressure into zone with lower pressure by roads enabling its penetration. Air convection – size depends on resistance arising during its infiltration or separation. Windows and doors (however open, broken, or closed) and air vents are separated places in building.

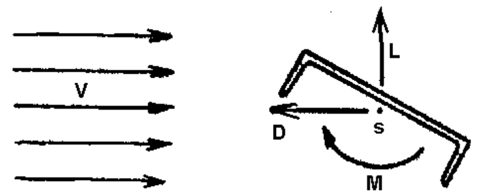

Fig. 2 Components of the wind force-action on body at plane flow rounding: D – resistance, L – uplift, M – moment

1.2 Height and inclination-angle of facade

Wind velocity also increases with height of building especially on windward. This influence adds to fire spread along facade. Besides the inclination of glass panels also share in fire course at facades. Well, suitable location of glass panel with regard to impacting solar energy can influence heat exchange, namely both in glass panel and in air space between two glass panes. The different angle of impacting solar rays on glass panel also evidences about it according to **Fig. 3**.

As the smallest velocity of flame spread is on the flooring (about 1/3 of spread-velocity on a wall) and the largest velocity under floor (about 5x larger than a wall) the minimum favourable conditions for fire spread are at vertical facades. The size of shading is more important because the surface temperature of glass panels reduces with increasing shading. Consequently critical temperature of glass panels, which is the reason of their destruction, also prolongs.

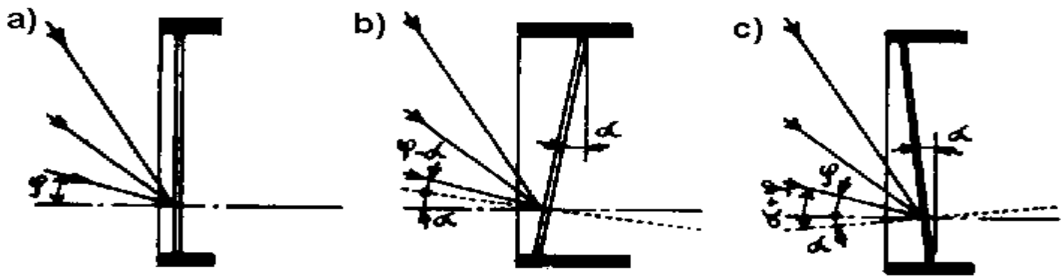

Fig. 3 Influence of position of glass panel to impacting solar rays: a) panel vertical, b) panel oblique, declined indoor, c) panel oblique, declined outdoor

1.3 Stack effect

The principle of stack effect is explained on the **Fig. 4A**. Mentioned graph represents the change of absolute pressure in dependence on the height of building. This phenomenon of air pressure-drop with regard to height of space is observable as unsuitable feeling which we have during fast change of height. External air has namely higher density than internal one providing that outer air temperature is lower. Therefore the pressure of air quickly reduces with height than indoor and absolute pressure in interior is then higher than exterior in all level above any opening. This difference of pressure is to used indicated as

stack effect. Its maximum value is in the highest place and it creates stack effect for the absolute height of building.

Openings, by which air can release, are situated in different levels on the walls of building. Air in building is warmer and in consequence of that also lighter than external. Therefore it tries to mount up and to release by upper opening meanwhile colder air outside releases by downer opening and it substitutes it. The difference of pressure which is to provoke the convection by openings is also called stack effect. If air convection sets in the place with high pressure and it point to the place with low pressure external air must be higher than internal pressure in downer part and lower than pressure in internal upper part (**Fig. 4B**). Straight lines representing absolute pressures grow in half of height. The difference of pressure by external wall increases with regard to the distance from the plane of neutral pressure. According as the difference external and internal temperature increases, the difference between the slant of straight lines representing inner and outer pressures grows up and as well the difference of pressure by external wall.

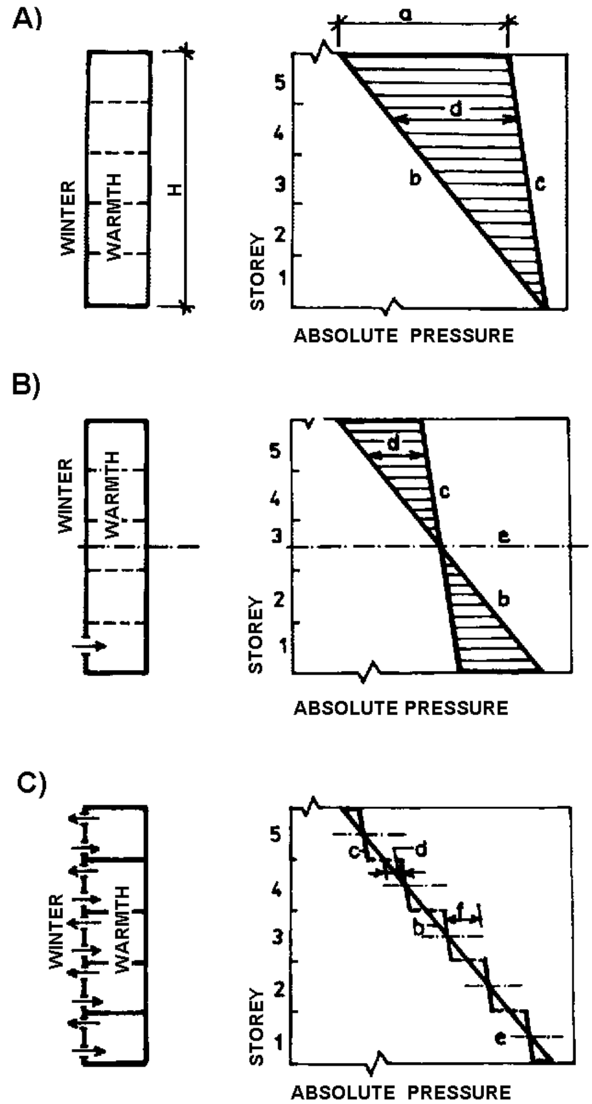

Fig. 4 Stack effect of simple building-interiors [2]: a – absolute stack effect, b – outer pressure, c – inner pressure, d – pressure difference by external wall, e – plane of neutral pressure, f – difference of pressure by floor

The openings in external wall of building which enable the air exchange are not always in the same way dividend bottom-up but the quantity of vent air will be the same as the quantity of exhaust air. **Fig. 4C** represents the building with absolutely impermeable structures in every storey. That every storey is independent and its own stack effect isn't influenced by stack effect of other storey. Air has tendency to penetrate by downer part of every storey and to escape by upper part above the plane of neutral pressure. Absolute stack effect for every height of building is the same as on **Fig. 4B** – it is equal to the sum of pressure-differences by internal walls in downer and upper part of building.

Multi-storeyed buildings aren't in fact completely open (**Fig. 4B**) and the division between storeys aren't quite hermetical (**Fig. 4C**). Internal openings enable to circulate to air straight from storey to storey by stair and lift space between storeys (**Fig. 5**). Air then leaks in building from bellow, it mounts by vertical shafts and openings in floors and it escapes by openings in upper external wall (eventually in roof). Slope of straight lines between storeys representing internal pressure is the same as on **Fig. 4B** but on every storey is some discontinuity as evidenced by **Fig. 2C** demonstrating the difference of pressure by storey. Absolutely stack effect for building remains the same as before. However, some size of absolutely pressure - difference is inevitable for the securing of air convection by opening in floor and vertical shaft. The difference of pressure by external wall on any level is lower than it would be if any resistances would not offer in the course of air convection indoor of building.

Fig. 5 also determines the difference of pressure and air convection for vertical continuous hollow or shaft. Air gets into vertical continuous hollow in downer parts and it mounts from that in upper parts according to symmetric schema and with uniform convection-resistance in the continuous hollow of every floor-level. The plane of neutral pressure for continuous hollow containing adjacent spaces creates approximately in half of height. Absolutely stack effect for building is the same as the sum of pressure - differences by external wall in upper and downer parts. According to the increase of convection - resistance caused by disposition division of building, the differences of pressure by walls and floors of vertical hollows or shafts also elevate meanwhile the differences of pressure by external walls reduce. Air convection caused by stack effect indoor of building is formed by every way demonstrated on **Fig. 5**. Nevertheless, in every case according as the height and number of floor elevate, absolutely resistance of convection by opening in floors increases faster than the resistance by vertical continuous hollows. In this manner the air convection by vertical shaft or continuous hollow arises in tall buildings.

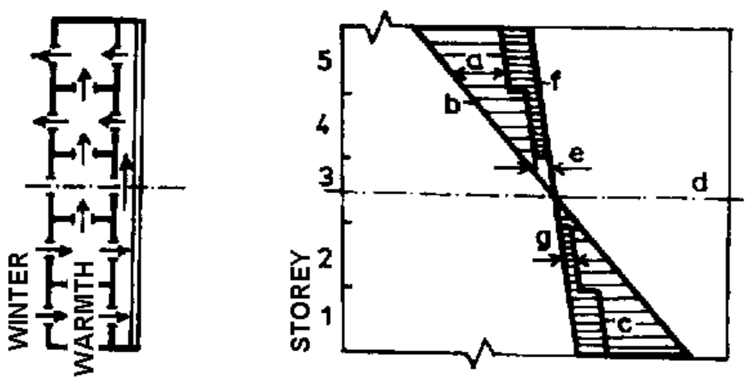

Fig. 5 Stack effect for perfect building: a-difference of pressure by external wall, b - external pressure, c-internal pressure, d-plane of neutral pressure, e-difference of pressure by floor, f- pressure in vertical continuous hollow, g-difference of pressure by walls of shaft

Fig. 5 illustrates that infiltration is under plane of neutral pressure and escape – exfiltration is formed above it. In interior of building is the main air movement nose-up, air flows in vertical continuous hollows from downer to upper storeys. This main system is decisive for spread of smoke, odour and other element of pollution. If fire rises in downer storeys smoke tries to mount up into uppers storeys by vertical continuous hollows, shafts and stair space and communications also remain filled by smoke. This transfer of smoke consequent on stack effect is considered for the main problem in protection of tall buildings against fire.

1.4 Mounting of glass panels and connection on load bearing structure

Glass sheets as building elements creating the panels of all-glass facades are the most often set into framing of metallic (aluminium alloy, thin-walled profiles) profiles or wooden ones, eventually in combination with plastic (**Fig. 6**). Framing then forms bearing element fixed into main load bearing structure so that glass panel is statically depended on the one hand on the system of framing realisation, on the other hand on own bearing capacity (size of area and thickness).

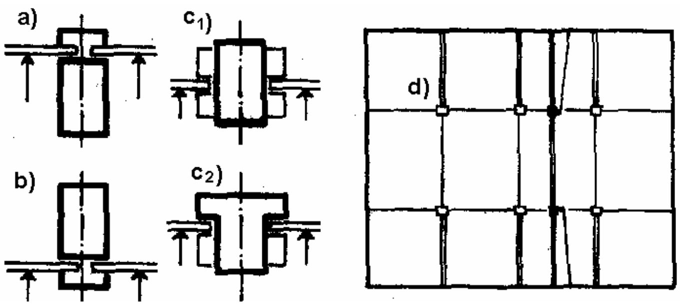

Fig. 6 Variant of glass panels-location [1]: a) on internal faced plane, b) in front of faced plane, c) between faced planes of frame, d) as part of all-glass cladding

Glass panel can be supported by the following systems:

- supporting along perimeter on all four sides (**Fig. 7a**),
- supporting along perimeter on three sides (**Fig. 7b**),
- supporting or hanging on two opposite side (**Fig. 7c**),
- supporting in corners (**Fig. 7d**) or in points (in the middle of sides or in area of panel),
- combination supporting system (**Fig. 7e**).

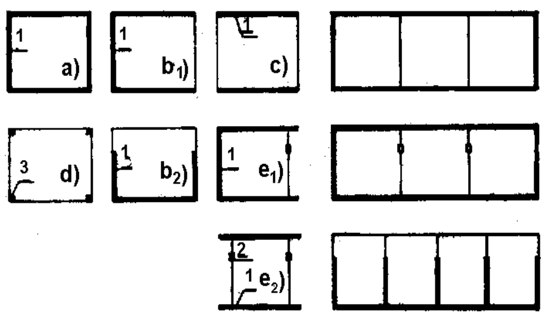

Fig. 7 Variants of glass panel-supporting [1]: a) on four sides, b) on three sides, c) on two opposite side, d) in corners, e) combination system of supporting: 1 – continuous supporting, 2 – point supporting, 3 – supporting in corners

The supporting of glass panel along perimeter is considered as free, the system of location in frame and the possibility of dilatation even directly condition the assumption of free location.

1.5 Size, thickness of glass sheets and type of glass

Glass sheets used in cladding must be dimensioned to resist the following load:

a) applying under perpendicular or oblique angle on the surface of glass panel – stress by bending,
b) applying in the plane of glass panel during which glass panel is stressed by pressure, tension eventually bending tension,
c) by change of temperature in consequence of change in volume – thermal stress which is in case of fire decisive.

The thickness of glass sheets not only that conditions their sizes in loading state but it also influences their location. The bigger the bite of glass sheet is the longer is time in which glass cracks. The lowest resistance has glass sheet thick 6-7mm, sunken into depth about 28mm [3]. Stress of glass sheet again reduces behind this limit because its margin with increasing width already resists to bigger tensional stress. Unless the bite exceeds about 8,5 – 9,5mm glass sheet has sufficient safety coefficient.

Bearing capacity and thermal insulation capability of glass panels increase essentially at the application of double glazing units. Besides the solution of opening panel-connection to structure it is possible to decrease thermal losses by own surfacing of glass panels. Coefficient of heat transfer U [$W.m^2.K^-1$] plays the significant role at the selection of suitable glass panels from thermal and technical point of view.

Thermal losses can release by insulation glass by three manners, i.e. by convection, conduction and radiation.

Convection - in this case glass sheet extracts heat from surrounding circulating air. Circulation and exchange of temperatures accelerates with growing temperature gradient between glass and air. Actual convection realizes in closed space in width of hollow larger than about 50mm. Turbulent flow of circulating air arises under this limit and consequently to retardation of heat exchange between air and glass sheet. Because the thickness of air void pocket between insulated glasses fluctuates in the interval from 10 up to 20mm independent circulation as well as convection in insulated glass is less essential. As a result of that its part on the losses is minimal. The coefficient of heat transfer U reduces in interval from 0,2 up to $0{,}5 W.m^{-2}.K^{-1}$ at application of heavy inert gases (argon, seldom krypton and xenon) as filling of insulated glass-interspaces. Butyl and two-part sealants on the basis of polysulfide belong among the most perfect connected materials from point gas-diffusion of view in contact place of distance aluminium profile.

Conduction – it is possible to apply at glass panel two following variants from the point of view of its thermal conductivity-reduction:

- replacement of glass sheet by other material with lower thermal conductivity at preservation of the same physical requirements as at glass (e.g. strength, high permeability of light, durability etc.) but also price; however, such material wasn't developed,
- the thickness – increase of used glass sheets on 30mm and more; this arrangement would be increase not only the mass of insulated glass (glass would set in useless) but also would reduce light transfer and consequently would raise the consumption of electric energy for lighting.

It results from that not even one of mentioned possibilities is real.

Radiation – the maximum release of heat is cause by thermal radiation (as late as 2/3 of total radiation). It is possible to beware against this way of heat transfer by reflection impacting thermal energy back into interior. This reflective plane can be form by the use of microscopic thin layer of various metallic compounds applying on one side of glass sheet. According to type of applying metal-layers we distinguish two type coated glasses:

- glass with hard coating:
  hard layer is produced by metallic oxides of Cr, Ni, Ti, Zn, Sn etc. They apply only for one layer of glass both for simple glazing and for insulated glasses. Although they enable unlimited storability, they are sensitive for damage by deep sleek. Using this surfacing we can achieve the coefficient of heat transfer about U = 1,9W.m^{-2}.K^{-1}, at filling of air void by inert gas even U = 1,5W.m^{-2}.K^{-1};
- glass with soft coating:
  these glasses are applicable only for insulated glasses with electroplated layer into air void. Their disadvantage in comparison with usual glasses is delimited storability and bigger predisposing to deep sleek. This surfacing enables to reduce coefficient of heat transfer to U = 1,5W.m^{-2}.K^{-1}, at filling of interspaces by inert gas even on lower value.

Designers are often set in situations at the selection of suitable double glazing unit when they must decide according to various criteria. These situations needn't be always to solve definitely and designers spend much time to claimed discussions or they select the optimum solution only by intuition. Therefore, it is suitable to use mathematical modeling based on a multi-criterion decision. The mathematical model can be demonstrated on the following example.

2 Example with the most optimum selection of reflexive double glazing unite Stopray

It considered the selection the best variant from 6 following types of double glazing unite Stopray with the same thickness 6-12-6mm:

a_1 - Lagoon 58/42,
a_2 - Silver 53/34,
a_3 - Emeralda 36/20,
a_4 - Topaz 40/31,
a_5 - Ocean 34/21,
a_6 - Elite 67/37.

These glasses will evaluated according to energetic properties and price included in 6 criteria:

f_1 - reflection ER [%] (max)
f_2 - absorption EA [%] (max)
f_3 - total permeability SF [%] (min)
f_4 - shielding factor Sc (min)
f_5 - coefficient of heat transfer U [W.m^{-2}.K^{-1}] (min)

f_6 - price relation with regard to double glazing unite Lagoon 58/42 a Silver 53/34 which have value 1,0 (min).

The basic criterion matrix **Y**:

$$\begin{array}{cc}
 & \begin{array}{cccccc} f_1 & f_2 & f_3 & f_4 & f_5 & f_6 \\ (max) & (max) & (min) & (min) & (min) & (min) \end{array} \\
\begin{array}{c} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{array} & \begin{bmatrix} 30 & 33 & 42 & 0{,}48 & 1{,}7 & 1{,}0 \\ 42 & 28 & 34 & 0{,}36 & 1{,}6 & 1{,}0 \\ 20 & 64 & 20 & 0{,}23 & 1{,}5 & 1{,}06 \\ 15 & 59 & 31 & 0{,}36 & 1{,}5 & 1{,}06 \\ 11 & 73 & 21 & 0{,}24 & 1{,}4 & 1{,}06 \\ 33 & 33 & 37 & 0{,}43 & 1{,}5 & 1{,}13 \end{bmatrix}
\end{array}$$

The criterion matrix is arranged into such a form that all criteria will be at the maximum. For minimum values, the worst values will be determined like this:

$f_3 = 42$; $f_4 = 0{,}48$; $f_5 = 1{,}7$; $f_6 = 1{,}13$;

The criterion values of a given variant are deducted from these values. This process transfers the evaluation of a variant according to minimum criterion on level how many variants are better than the worse variant and by that on the maximum criterion. Then, the amended criterion matrix **Y** (y_{ij}) has the following form:

$$\begin{array}{cc}
 & \begin{array}{cccccc} f_1 & f_2 & f_3 & f_4 & f_5 & f_6 \\ (max) & (max) & (max) & (max) & (max) & (max) \end{array} \\
\begin{array}{c} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{array} & \begin{bmatrix} 30 & 33 & 0 & 0 & 0 & 0{,}13 \\ 42 & 28 & 8 & 0{,}12 & 0{,}1 & 0{,}13 \\ 20 & 64 & 22 & 0{,}25 & 0{,}2 & 0{,}07 \\ 15 & 59 & 11 & 0{,}12 & 0{,}2 & 0{,}07 \\ 11 & 73 & 21 & 0{,}24 & 0{,}3 & 0{,}07 \\ 33 & 33 & 5 & 0{,}05 & 0{,}2 & 0 \end{bmatrix}
\end{array}$$

H_j (maximum preferred values of criterion f_j) = (42; 73; 22; 0,25; 0,3; 0,13)
D_j (minimum preferred values of criterion f_j) = (11; 28; 0; 0; 0; 0)

The user evaluated the criteria according to point scale $\varepsilon \in \langle 0;100 \rangle$. He divided altogether 370 points (80 + 50 + 65 + 40 + 90 + 45).

Criteria	f_1	f_2	f_3	f_4	f_5	f_6
Points	80	50	65	40	90	45
Weights	0,22	0,13	0,18	0,11	0,24	0,12

It is possible to form the normalized criterion matrix **R = (r_{ij})** whose elements can be obtained from criterion matrix **Y = (y_{ij})** by means of transformation formula

$$r_{ij} = \frac{Y_{ij} - D_j}{H_j - D_j} \tag{5}$$

This matrix represents the matrix of utility values from **i**-th variant according to **j**-th criterion. According to formula (5) it is possible to transform linearly the criterion values so that $\mathbf{r_{ij}} \in \langle 0,1 \rangle$, $\mathbf{D_j}$ corresponds to value 0 and $\mathbf{H_j}$ corresponds to value 1. Using the additive form of the multicriterion utility function, the utility from variant $\mathbf{a_i}$ equals

$$u(a_i) = \sum_{j=1}^{k} v_j . r_j \tag{6}$$

$$\begin{array}{c} \\ \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{array}
\begin{array}{c} \begin{array}{cccccc} f_1 & f_2 & f_3 & f_4 & f_5 & f_6 \\ (max) & (max) & (min) & (min) & (min) & (min) \end{array} \\
\begin{bmatrix} 0{,}61 & 0{,}11 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0{,}36 & 0{,}48 & 0{,}33 & 1 \\ 0{,}29 & 0{,}80 & 1 & 1 & 0{,}66 & 0{,}54 \\ 0{,}13 & 0{,}69 & 0{,}50 & 0{,}48 & 0{,}66 & 0{,}54 \\ 0 & 1 & 0{,}95 & 0{,}96 & 1 & 0{,}54 \\ 0{,}71 & 0{,}11 & 0{,}23 & 0{,}20 & 0{,}66 & 0 \end{bmatrix} \end{array}
\quad
\begin{array}{c} u\,(a_i) \\ \\ 0{,}268 \\ 0{,}539 \\ 0{,}681 \\ 0{,}484 \\ 0{,}711 \\ 0{,}392 \end{array}$$

$$v = (\,0{,}22 \quad 0{,}13 \quad 0{,}18 \quad 0{,}11 \quad 0{,}24 \quad 0{,}12\,)$$

Variant which reaches the maximum value of utility is selected as the best. Therefore the best variant is $\mathbf{a_5}$ (i.e. glass Ocean 34/21), on the second place $\mathbf{a_3}$ (i.e. glass Emeralda 36/20), on the third place $\mathbf{a_2}$ (i.e. glass Silver 53/34) and further $\mathbf{a_4}$, $\mathbf{a_6}$ and $\mathbf{a_1}$, how results from matrix $\mathbf{u}(a_i)$. Although it is possible to select mathematically the best energetic variant it would be more suitable to use from fire point of view fire double glazing unite. However, this type of double glazing unite begins only to develop.

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