FORM FACTOR LIMITS DEPENDING ON THE BUILDING SHAPES

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***Abstract**: The form factor (ratio of compactness) is the main criterion for assessing the building shape solutions in terms of their energy efficiency. Its values give a general idea of the future performance of the building envelope and determine to a great extent all subsequent actions and measures on energy saving in the operation of the building. His crucial role in energy savings is caused by the fact, that it defines one of the multipliers in calculating the heat loss through the surrounding structures. In case of poor building shape (with bad form factor) the requirements to the heat transfer coefficient U should raise to achieve certain (usually required) energy consumption in kWh/m^2 per year.*

Based on an analysis of different building shapes of a specified volume, there are proposed formulas to receive the limits of variability of f_o according a given volume. These limits of f_o can serve as a quantitative criterion for the quality of project building shape in relation to the energy efficiency.

***Keywords**: Shape factor, Compactness, Energy efficiency, Thermal Insulations*

1. Introduction

The form factor is a key criterion for assessing the building shapes in terms of their energy efficiency. Its values give a general idea of the future performance of the building envelope and determine to a great extent all subsequent actions and measures on energy saving in the operation of the building.

The form factor f_o is the ratio of the envelope surface A to the required volume of the building V by design:

$f_o = \dfrac{A}{V}$ – form factor, m^{-1}, where:

A – envelope surface, m^2;

V – volume of the building, m^3.

According to the chosen approach the floor area of the surrounding structure can be included or not to the envelope surface. In this particular case the entire surrounding area of building shape will be taken into account and because of that the analysis will be performed with the added area of the floor surrounding structure.

In some sources, such as [1, Art. 6.3.2] the form factor is named “ratio of the compactness”.

The crucial role of the form factor f_o in energy savings is caused by the fact, that it defines one of the multipliers in calculating the heat loss through the surrounding structures [2]. In case of poor building shape (with bad form factor) the requirements to the heat transfer coefficient U should raise to achieve certain (usually required) energy consumption per year in kWh/m^{2}a [3].

2. Case 1 – calculations and analysis

An analysis of change in the f_o at different volumes V and some typical planning solutions is made. As a unit base volume was taken a cube with side a = 1 m (geometric minimum) or the base volume in this case is equal to 1 m^3. For these assumptions a volume V is formed, for which the following parameters are set or calculated:

n – set number of base volumes on one side of the cube;

N – calculated number of all base volumes in the cube;

V – calculated volume of the cube (subsequently, with this volume are analyzed different planning solutions), m^3.

There are considered typical planning solutions that differentiate the next schemes:

0 – Sphere. The ideal theoretical solution (geometric body with a best f_o). It is calculated with such a radius that the volume is equal to V .

1 – Cube. The ideal practical solution (after the sphere with the best value for f_o). This solution fits the prerequisites for a basic volume.

2 – Area. All basic volumes are arranged in a rectangle on one floor.

3 – Wall. There forms a wall with thickness – 1, width – n and height – nn base volumes.

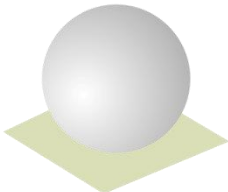
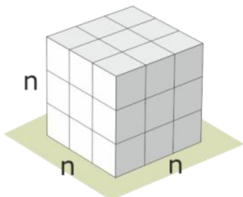
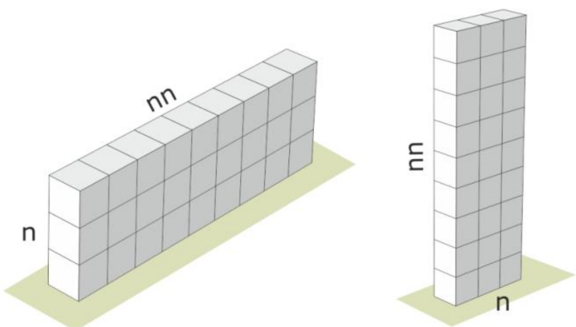
4 – Line. There forms a shape with a thickness – 1, width – nnn and height – 1 basic volume.

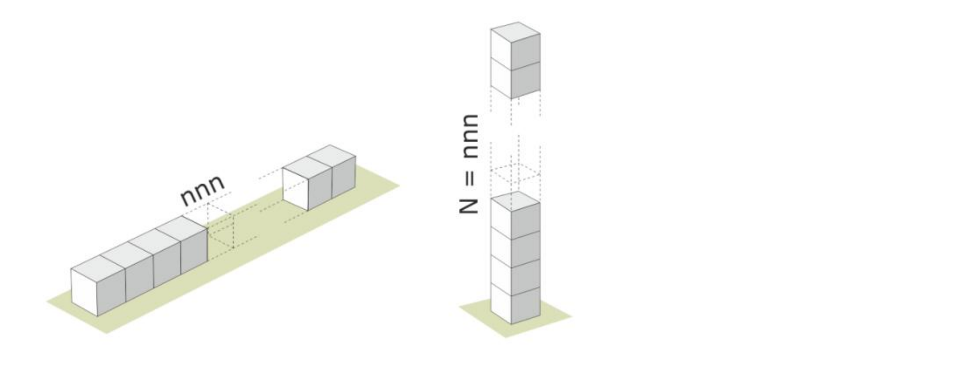
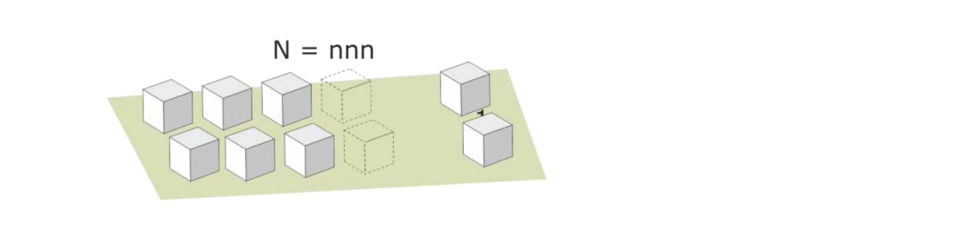
5 – Tower. There forms a shape with a thickness – 1, width – 1 and height – nnn base volumes. Practically, this is the worst planning decision for the agreed base volume, therefore the highest value for f_o .

6 – Module. There are formed nnn independent spaces of the individual base volumes. It does not depend on the total volume V , but depends on the assumed base volume in that case – 1 m^3.

The input data, diagrams and the calculated values f_o for the relevant volumes are grouped in table 1.

Table 1. Input data, diagrams and values of f_o for each scheme with a=1

n	1	2	3	4	5	7	10	15	20
N	1	8	27	64	125	343	1000	3375	8000
V, m^3	1	8	27	64	125	343	1000	3375	8000
0 Sphere									
A, m^2	4,8	19,3	43,5	77,4	120,9	236,9	483,5	1087,9	1934,1
f_o, m^{-1}	4,835	2,418	1,612	1,209	0,967	0,691	0,484	0,322	0,242
1 Cube									
A, m^2	6	24	54	96	150	294	600	1350	2400
f_o, m^{-1}	6,000	3,000	2,000	1,500	1,200	0,857	0,600	0,400	0,300
2, 3 Area, wall									
A, m^2	6,000	3,000	2,000	1,500	1,200	0,857	0,600	0,400	0,300
f_o, m^{-1}	6	28	78	168	310	798	2220	7230	16840

n	1	2	3	4	5	7	10	15	20
N	1	8	27	64	125	343	1000	3375	8000
V, m^3	1	8	27	64	125	343	1000	3375	8000
4, 5 Line, tower									
A, m^2	6	34	110	258	502	1374	4002	13502	32002
f_o, m^{-1}	6,000	4,250	4,074	4,031	4,016	4,006	4,002	4,001	4,000
6 Module									
A, m^2	6	48	162	384	750	2058	6000	20250	48000
f_o, m^{-1}	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000

Graphics of the calculated values of f_o for each scheme and volume are displayed in fig. 1.

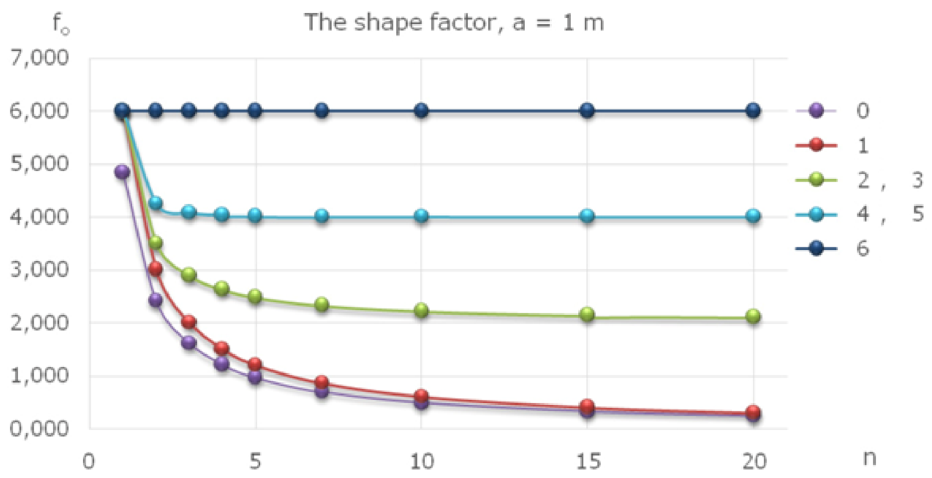


Fig. 1. Interdependence between n and f_o for each scheme with a=1

It is clear that for each volume (on the X axis) is differentiated limits amendment for the f_o (on Y axis). These values for the minimum are between schemes 0 or 1, and for the maximum are schemes 4 and 5, or exceptionally 6 (fig. 2).

Assuming $a = 1$ m and set volume $V = 1{,}500$ m^3 (~ 550 m^2), the range for amendment of f_o yields the following specific values for practical and theoretical extremes:

- Theoretical minimum – scheme 0: 0,422 m^{-1};
- Practical minimum – scheme 1: 0,524 m^{-1};

- Practical maximum – schemes 4 and 5: 4,001 m^{-1}

For the possible range of practical change of f_o is obtained:

$\Delta f_{o\ 1m} = 4{,}001 - 0{,}524 = 3{,}477\ m^{-1}$.

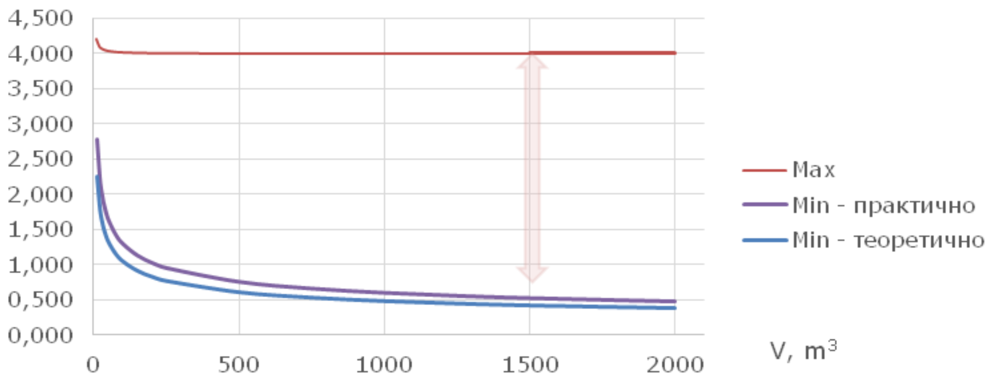


Fig. 2. Interdependence between n and f_o for each scheme with a=1

3. Case 2 – calculations and analysis

In the second case again an analysis of change in the f_o at given volumes V for a base unit volume is made, which is taken with the size of a room, consider cube with a side a = 3 m, or the base volume is equal to 27 m^3. For these assumptions a volume V is formed, for which the following parameters are set or calculated:

n – set number of base volumes on one side of the cube;

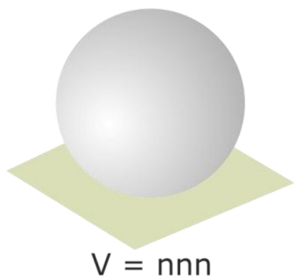
N – calculated number of all base volumes in the cube;

V – calculated volume of the cube (subsequently, with this volume are analyzed different planning solutions), m^3.

Discussed are the same typical planning solutions, subject to the mentioned principles, which form the above schemes: Sphere, Cube, Area, Wall, Line, Tower and Module (the adopted base volume in this case – 27 m^3).

The input data, diagrams and calculated f_o for the relevant volumes are grouped in the following table 2.

Table 2. Input data, diagrams and values of f_o for each scheme with a=3

n	1	2	3	4	5	7	10	15	20
N	1	8	27	64	125	343	1000	3375	8000
V, m^3	27	216	729	1728	3375	9261	27000	91125	216000
0	Sphere								
A, m^2	43,5	174,1	391,6	696,3	1087,9	2132,3	4351,6	9791,2	17406,6
f_o, m^{-1}	1,612	0,806	0,537	0,403	0,322	0,230	0,161	0,107	0,081

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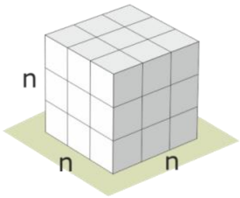
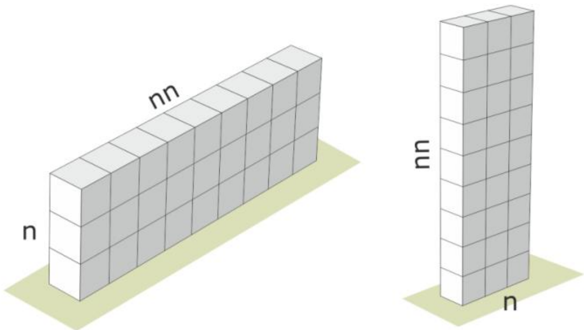
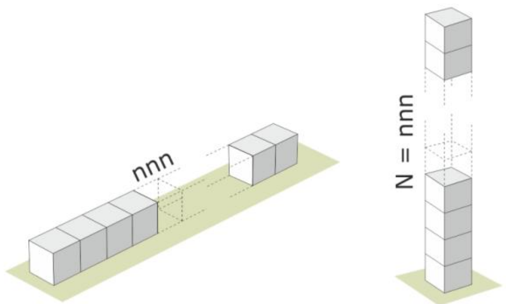
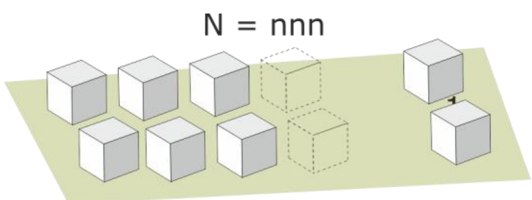
n	1	2	3	4	5	7	10	15	20
N	1	8	27	64	125	343	1000	3375	8000
V, m^3	27	216	729	1728	3375	9261	27000	91125	216000
1 Cube									
A, m^2	54	216	486	864	1350	2646	5400	12150	21600
f_o, m^{-1}	2,000	1,000	0,667	0,500	0,400	0,286	0,200	0,133	0,100
2, 3 Area, wall									
A, m^2	54	252	702	1512	2790	7182	19980	65070	151560
f_o, m^{-1}	2,000	1,167	0,963	0,875	0,827	0,776	0,740	0,714	0,702
4, 5 Line, tower									
A, m^2	54	306	990	2322	4518	12366	36018	121518	288018
f_o, m^{-1}	2,000	1,417	1,358	1,344	1,339	1,335	1,334	1,334	1,333
6 Module									
A, m^2	54	432	1458	3456	6750	18522	54000	182250	432000
f_o, m^{-1}	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000

Graphics of the calculated values of f_o for each scheme and volume are displayed in fig. 3.

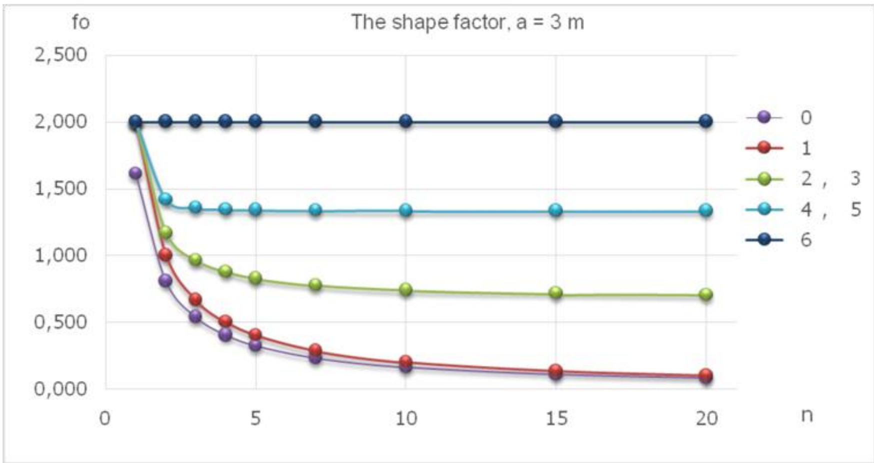


Fig. 3. Interdependence between n and f_o for each scheme with a=3

It is obvious that the values of the individual schemes are subject to similar relationships with those in the first case. And here also the minimum is between schemes 0 and 1 and the maximum is at a schemes 4 and 5 or exceptionally at 6 (fig. 4).

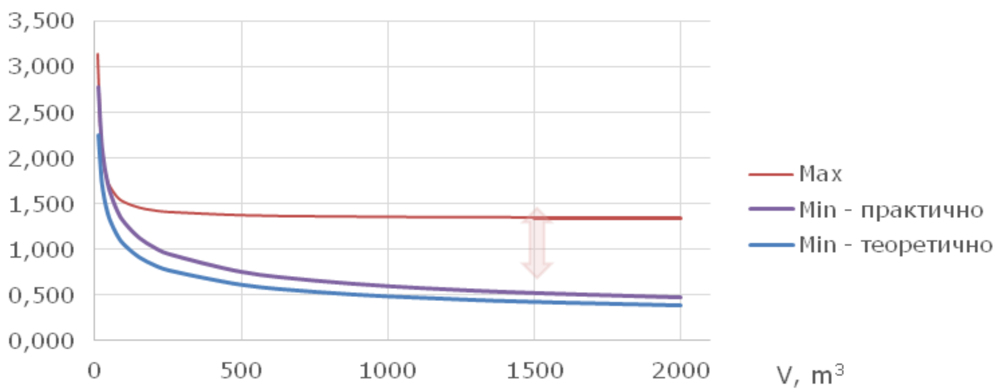


Fig. 4. Interdependence between n and f_o for each scheme with a=3

Assuming $a = 3$ m and set volume $V = 1500$ m^3 (~ 550 m^2), the range for amendment of f_o yields the following specific values for practical and theoretical extremes:

- Theoretical minimum – scheme 0: 0,422 m^{-1} (coincides with the value of the first case);
- Practical minimum – scheme 1: 0,524 m^{-1} (coincides with the value of the first case);
- Practical maximum – schemes 4 and 5: 4,001 m^{-1} (the value is significantly lower than in the first case)

For the possible range of practical change of f_o is obtained:

$\Delta f_{o\,3m}$ = 1,345 – 0,524 = 0,821 m^{-1}.

It is obvious that the range of variation when a = 3 m are significantly closer than those for a = 1 m, or $\Delta f_{o\,3m} < \Delta f_{o\,1m}$ and the increase of the base rate a reduces the potential range of variation of Δf_o.

4. Formulas proposed

On the basis of these analyzes the following formulas to obtain any limits amendment of f_o at a predetermined volume can be applied. The expected minimums of f_o are offered:

- Minimum under ideal theoretical solution: $f_{o,\min} = \dfrac{4,835}{\sqrt[3]{V}}$;

- Minimum under ideal practical solution: $f_{o,\min} = \frac{6}{\sqrt[3]{V}}$.

For the expected minimum of f_o as function of the base size a, the following equation is suggested: $f_{o,\max} = \frac{2a^2}{V} + \frac{4}{a}$

The curves obtained on the basis of the above formulas (with adopted in advance a – recommended is 3 m) clearly outline the possible range of variation of f_o at a predetermined volume.

These limits of f_o can serve as a quantitative criterion for the quality of project building shape in relation to the energy efficiency.

5. Formulas check

For the considered volume V = 1500 m3 (~ 550 m^2) and assuming a = 3 m, could check the values obtained for the range of variation of f_o:

$$f_{o,\min} = \frac{6}{\sqrt[3]{1500}} = 0{,}524\ \mathrm{m}^{-1},\ f_{o,\max} = \frac{2.3^2}{1500} + \frac{4}{3} = 1{,}345\ \mathrm{m}^{-1}.$$

These values perfectly match the calculated on conventional approaches. They should be used as borders for the evaluation of the actual form factor f_o. On this basis conclusions about the behaviour of the building in relation to energy efficiency can be deducted.

6. Conclusions

The recommended basic size is a = 3 m (normal room – 27 m^3). The increasing of the base size a significantly reduces the range of variation for f_o. The proposed formulas give a quantitative assessment of building shapes in terms of their form factor as an indirect indicator for energy efficiency.

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