CORRELATION BETWEEN THE MORPHOLOGY OF UNHEATED STAIRCASE AND ENERGY PERFORMANCE OF RESIDENTIAL BUILDINGS

by

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As a side effect of the need for greater energy efficiency of buildings, there is a problem of decrease of the available interior space affected by the reduction in U-value of parts of thermal building envelope, i. e. an increase in thickness of insulating layer, which is especially present in unheated staircase. Having in mind that present methods of calculation of transmission heat losses through elements of thermal envelope include the adjustment factor which regulates designed temperature conditions if the temperature at the colder side of the element of the thermal envelope differs from that of the external environment, this paper strives to demonstrate that in the case of unheated staircases, this fixed value should be reconsidered and treated as a variable depending on the morphology, i.e. form, size and position of the staircase within the building.

This problem has been analyzed on the example of Serbian housing stock and relevant national thermal regulations. Three morphological types of unheated staircases have been distinguished within which three models have been defined and examined with respect to variations in number of floors and percentage of glazing. Average temperatures of staircase volume and temperature correction factors were calculated in following temperature modes: stationary that excluded solar gains and ventilation heat losses and gains, and dynamic with variations in air exchange rates and insolation conditions, expressing in all of the cases variations in calculated values of temperature correction factors in comparison to the prescribed fixed value.

Key words: *staircase morphology, unheated space, design temperature, temperature correction factor, heat balance*

Introduction

The concept of energy performances of buildings that represents the basis of modern regulations in the field of thermal protection of buildings in European Union (EU) is founded on energy performance of buildings directive (EPBD) declared by the EU for the first time in 2002, [1] and revised in 2010 [2]. Expected optimisation of energy flow of a building should be achieved by ensuring both: minimal comfort requirements and limited total energy consumption by means of interventions in the building envelope and the use of efficient heating and cooling

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systems. New demands, in the first place reduction of U-values, resulted in significant thickening of thermo-insulating layers, creating in this way several types of issues that are related to architectural aspects of energy efficiency, such as: unfavourable ratio between gross and net building area, reduction of space along the indoor elements of building thermal envelope, various technical problems regarding implementation of thick layers of thermal insulation, *etc*. The mentioned problem of space reduction has reflections on architectural design, affecting either design of new buildings or renovation of existing ones. Especially prone to the space reduction problem are areas of staircases in multifamily buildings. Due to their variation in size, shape, volume, and position within a floor plan of a building this part of a building became a subject of further analysis.

The authors of the paper have faced this problem when analysing the consequences of implementation of new Regulations on energy efficiency in buildings [3] on the Serbian building practice. This regulatory mechanism was adopted in 2011 and is based on the first version of EPBD [1]. The most obvious change in comparison with previous thermal regulations was a significant reduction of U-values of different elements of thermal envelope of a building, which were reduced to one third of those previously determined, becoming in this way closer to currently declared values in developed European countries. Nevertheless, there is a plan in EU countries to follow the requirements set by the recast version of EPBD [2] to design buildings in compliance with passive house standards from 2021 that would bring further reduction of U-values, and consequently even thicker thermo-insulating layers. [4]

The problem was observed on the example of Serbian housing stock with respect to the conditions set by the current national thermal regulations and the usual building practice, which, as a rule, treats staircases in multifamily buildings as unheated spaces. In the light of the new regulations, such structure requires an additional thermo-insulating layer which inevitably reduces the staircase space. Having in mind that multifamily housing built before 1970's, *i. e.* during the time with no thermal regulations, represent more than 30% of existing building stock in Serbia [5], future renovation actions will, in many cases, require rather thick additional thermo-insulating layers. The range of this problem could be anticipated from tab. 1 that presents the required thickness of thermo insulating layer along typical perimeter walls of a staircase (20 cm thick reinforced concrete wall), with respect to the regulatory boundary conditions – declared value of thermal transmittance. Three typical periods have been compared – (1) period before the existence of any thermal regulations, (2) period from 1990 till 2011 when previous set of thermal regulations were in force, and (3) present period (after 2011) with Regulations [3] as a regulatory mechanism.

Table 1. Minimal thickness of thermo-insulating layer along perimeter walls of a staircase

	Typical building period			
	Before 1970's (no regulation)	(1990-2011) Previous regulation	After 2011 (current regulation)	
			Renovated (existing) buildings	New buildings
Declared thermal transmittance values	No requirements	$U_{max} = 0.8$ [Wm^{-2}K^{-1}]	$U_{max} = 0.55$ [Wm^{-2}K^{-1}]	$U_{max} = 0.4$ [Wm^{-2}K^{-1}]
Minimal thickness of thermal insulation ($\lambda = 0.04$ Wm^{-1}K^{-1})	No thermal insulation	4 cm	6 cm	8 cm

Being the common area of a building, staircases have been designed to cover minimal or almost minimal space needed for this part of a house. Therefore, it could be expected that present thermal and functional requirements of this particular space would not necessarily be synchronized and compatible, in a way that application of required thickness of thermo-insulating layers could create unacceptable reduction of the staircase. The range of this predominantly architectural problem depends on the size and form of a staircase and its position in a floor plan. The idea was introduced to re-assess thermal conditions of unheated staircases in general and to examine whether and how these conditions are dependent on the morphology of a staircase. Somewhat similar research that was focused on the impact factors of final building energy use demonstrated and confirmed the existence of correlation between the relative sizes of a common area of residential building and overall size of a building in the context of total energy consumption [6-8]. Besides, basically architectural requirements related to energy efficiency were subject of a research conducted in the light of the future demands for design of nearly zero-energy buildings set by the EPBD recast [9].

Relevant parameters for thermal performance of staircase

Calculation method and assumption of temperature conditions of unheated staircase in relevant thermal regulations

Since thermal envelope of a building is considered as a boundary envelope between its heated and unheated parts, thermal conditions along this surface are not necessarily the same and variations depend on the type of spaces that are separated from each other. Although thermal regulations define outdoor and indoor design temperatures, when an element of a thermal envelope separates heated from unheated indoor space, as it is the case with walls surrounding unheated staircases, temperature conditions need to be calculated, adopted, or assumed according to a certain simplified method of calculation of heat transfer. By adopting general principles and methods set by the international standard EN ISO 13790: 2008 [10] and other derived standards, the new Serbian thermal regulations [3] accepted a simplified method for calculation of the overall transmission heat transfer coefficient, H_T [WK^{-1}], eq. (1):

$$H_{\mathrm{T}} = \sum_{i} (F_{\mathrm{x}} U_j A_j) + H_{\mathrm{TB}} \tag{1}$$

where U_j [Wm^{-2}K^{-1}] refers to thermal transmittance of element i of the thermal envelope, A_j [m^2] – represents its area, F_x, [–] is the temperature correction factor which regulates temperature conditions at the other side of the construction element when they differ from those of the external environment, and H_{TB} [WK^{-1}] is the heat transfer coefficient due to the effect of thermal bridges. In the case of unheated staircases the adjustment factor equals 0.5.

Since H_T is a parameter used for estimation of the heat transfer through the thermal envelope of a building and reflects to building's total annual energy need, the prescribed value of the temperature correction factor F_x has a direct implication to the calculated total energy consumption.

Relevant morphological characteristics of unheated staircases and selection of typical staircase models

As it is shown, present calculation method of the transmission heat loss treats the staircase area as any other unheated space, disregarding certain spatial specifics and varieties of this particular common area of a building. However, as it has been anticipated [6, 7], thermal perfor-

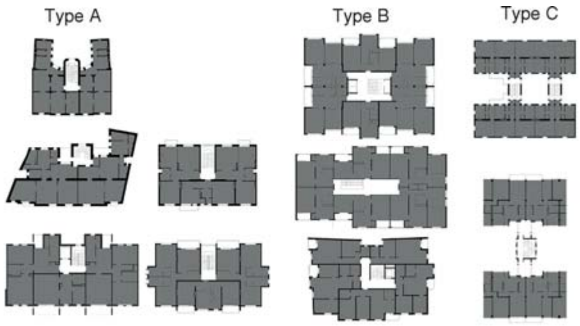

Figure 1. Examples of different positions of a staircase within a floor plan of a building

mance and building's energy demands vary according to different relative size of staircase space. On the other hand, taking into account general observation that morphology, *i. e.* size and shape of the building, has an impact on energy or thermal performance of the building and is calculated through the value of the so called shape factor of a building, the same analogy could be made in case of the staircase space [8].

In general, morphology of a staircase is a variable resulting from different design conditions. However, three basic types of staircase could be recognized, depending on their position within the whole plan of the building. They are presented in fig. 1:

– type A – along the façade of a building, containing one or more perimeter walls as elements of external envelope,
– type B – centrally positioned within a floor plan having internal walls as perimeter walls, *i. e.* without direct connection with external space, and
– type C – which is typical for complex, multi wings buildings, in which case staircase is placed between different wings of a building.

Since types A and B of staircases prevail in the building practice, they were chosen as raw models for further analyses.

Apart from the relative size (width, length, and height) and form of a staircase, thermal performance of this kind of common area is also correlated with the structure of perimeter walls including their glazing percentage and distribution, as well as number and size of door openings along perimeter walls. These are parameters that influence, in the first place, heat distribution within the staircase, and their relevance depends on the particular type of a staircase.

According to the defined staircase typology, three models, presented in fig. 2, which could be considered as the most usual in praxis, have been defined for further analysis:

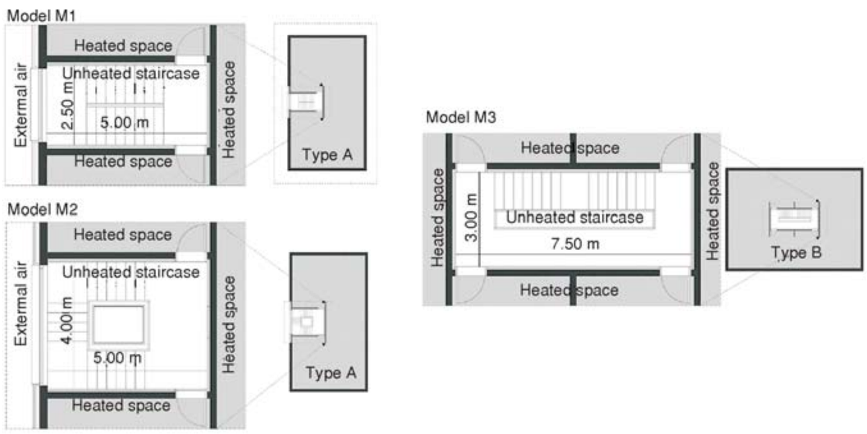

Figure 2. Geometry and disposition within a floor plan of model staircases

- model 1 (M1) – type A rectangular staircase of 2.5 × 5.00 m size, *i. e*. with 1:2 ratio between sides,
- model 2 (M2) – type A rectangular staircase of 4.0 × 5.0 m size, *i. e*. with 4:5 ratio between sides, with optional elevator between the flights, and
- model 3 (M3) – type B elongated rectangular staircase of 3.0 × 7.5 m size, *i. e*. with 2:5 ratio between sides.

Regarding the staircase morphology, for all three determined models – M1, M2, and M3, it was assumed that the staircase represents a part of a building with a flat roof and with height of the building that varies as Ba(sement) + G(round) F(loor) + 2, 4, 6, or 8 floors.

As a part of the conducted analysis, certain parameters that were significant for thermal performance of unheated staircase, such as percentage of glazing also varied for each of the models, in order to distinguish their impact on heat balance, *i. e.* on temperature correction value. In all three models, only one side along the staircase volume was treated as glazed. In the case of models M1 and M2 it was one of the shorter sides of in the floor plan, while in the case of the model M3 which is centrally positioned and without direct contact with external space along the perimeter walls, presence of roof lanterns was assumed. The percentage of glazing varied as 100%, 75% (3/4), and 50% (1/2) of the corresponding external wall, *i. e*. flat roof above the staircase.

Number of doors along the perimeter walls of a staircase was predetermined as 2 doors in case of models M1 and M2, *i. e*. 4 doors in case of the model M3.

Initial hypothesis and applied methodology

In order to examine more thoroughly the impact that staircase morphology has on energy performance of a building by the means of available parameters that are present in the calculation methodology, value of the temperature correction factor F_x which determines temperature conditions of the unheated staircase, has been recognized as a possible variable depending on the exact morphology of a staircase. Therefore, it was assumed that there would be a pattern by which the variations of F_x would occur depending on the position, shape and size of the staircase, the number of floors, the percentage of glazing and other parameters that might be considered relevant for the temperature conditions inside the unheated staircase.

Having this in mind, different combinations regarding the height (*i. e.* number of floors) and glazing percentage on three previously determined staircase models, M1, M2, and M3, have been investigated in two basic temperature modes: stationary and dynamic one. In both cases, calculation procedures were made with respect to the boundary conditions that refer to Belgrade and were in accordance to Regulations [3]. This means that the structure of each of surrounding building elements around the staircase area was considered as uniform and having thermal performances in accordance to defined boundary values (tab. 2). In all three models, additional indirect impact of external space on staircase area was considered through a windshield structure in the ground floor, and through the floor structure towards an unheated basement.

Due to its simplicity in comparison to the dynamic mode, calculation procedure of stationary mode was considered as an initial method for calculation of both, average temperatures of staircase volume and temperature correction factors in order to investigate a pattern of behaviour. In this mode, input boundary temperature conditions were determined and set as $\Theta_e = -12.1$ °C for outdoor design temperature, which corresponds to the value declared for Belgrade according to Regulations [3], while indoor design temperature was set as $\Theta_i = +20$ °C. Assessment of the actual values of temperature correction factor F_x was performed using the heat balance method by calculating the average air temperature of the staircase volume, as a mean

Table 2. Thermal resistance of surrounding structures according to new Regulations

Type of structure	Thermal transmittance, U_{max} [Wm^{-2}K^{-1}]
External wall	0.30
Wall to the unheated space (staircase)	0.40
Glazing	1.50
Flat roof above the unheated space (staircase)	0.30
Flat roof above the heated space (surrounding apartments)	0.15
Floor structure between different apartments	0.90
Floor structure above the unheated space (basement)	0.30

value of calculated average temperatures of each of the floors of a building. As a tool that was used to perform the simulation and calculation of described staircase models and their behaviour, an original software package, T-studio was applied [11]. By forming 2-D/3-D matrix that corresponds to geometrical characteristics of analyzed staircase and relevant thermal properties of surrounding structures, this software is designed for 2-D calculation of heat balance, using calculation procedure which is based on the finite difference method (FDM). For the sake of simplicity of calculation procedure, it was performed excluding the impact of solar gains, as well as ventilation losses from the unheated staircase area towards the external space and ventilation gains from the heated apartments towards the unheated staircase.

In this mode, this, basically 3-D problem, was simplified in the following manner. For models M1 and M2 a three step simplified method has been performed, treating the problem as a two-dimensional in each of the steps, in a floor plan as well as in both sections of the staircase, longitudinal and cross-section. On the other hand, for the model M3 which has no direct contact with external environment in the floor plan level, simplified model that was performed had two steps. Temperature distribution was analyzed in longitudinal and cross-section, which are relevant for this type of staircase. The impact of glazing on thermal performance could have been observed in a floor plan and longitudinal section in case of staircases M1 and M2, while in case of M3 it was relevant and observed in both of analyzed sections (longitudinal and cross). As a final result of the performed calculations, average temperature value obtained from all performed steps (three for models M1 and M2, *i. e.* two for model M3) was calculated and considered as relevant for each particular model. Temperature correction factor was derived from the obtained average temperature value, Θ_{av} (2):

$$F_{xi} = \frac{\Theta_{i.const.} - \Theta_{av}}{\Theta_{i.const.} - \Theta_{e.const.}} \tag{2}$$

Dynamic temperature mode which is more complex by its nature was applied on analyzed 3-D models for the winter temperature conditions, with indoor design temperature which was fixed and set as +20 °C, and variable outdoor temperature conditions according to ASHRAE IWEC2 meteorological data for Belgrade. The problem was observed during the heating period (from October 15th till April 15th) and outdoor temperature was considered as an average daily/hourly temperature change which was $\Theta_{e,const.} = \Theta_{e.av} = +4.046$ °C. Calculated value of F_x is a result of of the corresponding proportional relations (2) and in this sense does not depend on the value of the outside temperature.

Having in mind that this is the mode that could adjust closer to realistic thermal conditions and regime of usage, some predetermined variations in air exchange rates and insolation conditions were assumed and calculated. Air movement along the staircase volume was observed through variations in air exchange rate which varied as 1 or 3 exchanges per hour. Smaller rate of air exchange corresponded to good air tightness of glazed surfaces and rational use of the staircase by the tenants regarding the frequency of opening of doors and windows, while higher rate implicated bad air tightness and/or more frequent opening and was closer to the case of an existing building staircase. On the other hand, variations regarding insolation conditions were observed through opposite orientation of glazed side of a staircase, *i. e*. north, with minimal solar gains, and south, which endures the largest solar gains.

Simulation and calculation of all variations of dynamic temperature mode (regarding the number of floors, glazing percentage, air exchange rate, and orientation) was performed by the use of IES Virtual Environment programme, version 5.6.2 and simulation module ApacheSim within this software package. Shadow analysis, zonal air flow model and advanced HVAC modelling were simplified in the calculation procedure with the use of relevant algorithms within the ApacheSim module.

Results

Stationary temperature mode

Simulation and calculation according to the described simpler, *i. e.* stationary temperature mode (fixed boundary temperature conditions), considered all three staircase models in relevant variations regarding the number of floors and glazing percentage of the façade wall/roof and offered results for 36 different cases in total. Grouped in relation to the model of analyzed staircases, the results indicate certain regularities of manifestation.

Calculated temperature in observed staircase models varies along its volume in all three analyzed staircase models. They are the most illustrative in the case of the staircase model M1 and the most noticeable in its cross-section. As the height of the building raises, differences become greater and hence, more obvious as it is shown in fig. 3. This pattern of behaviour was present in all three of the analyzed staircase models.

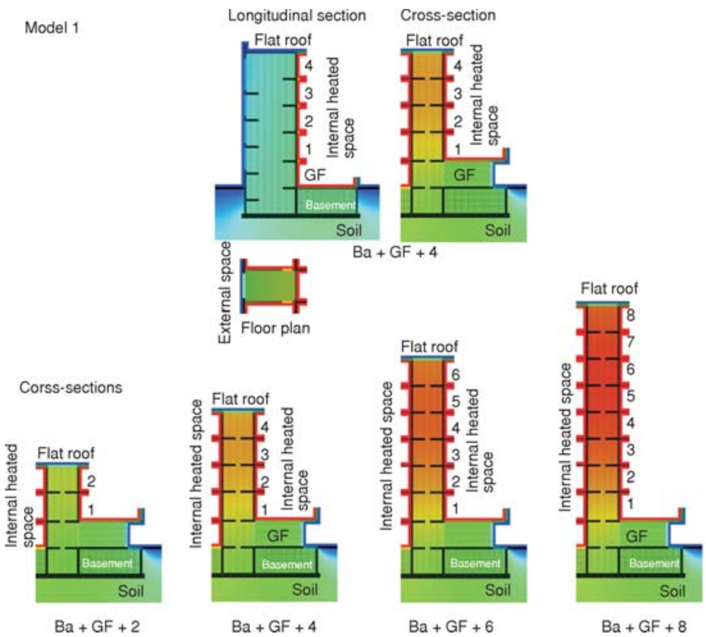

Figure 3. Temperature distribution pattern along the Ba + GF + 4 high model M1 staircase area (top) and variations in temperature distribution due to the change of building height (bottom)
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The calculation shows that average temperature of the staircase volume in all of the analyzed staircase models was dependent both, on the building height and on glazing percentage of the façade wall/roof. On one

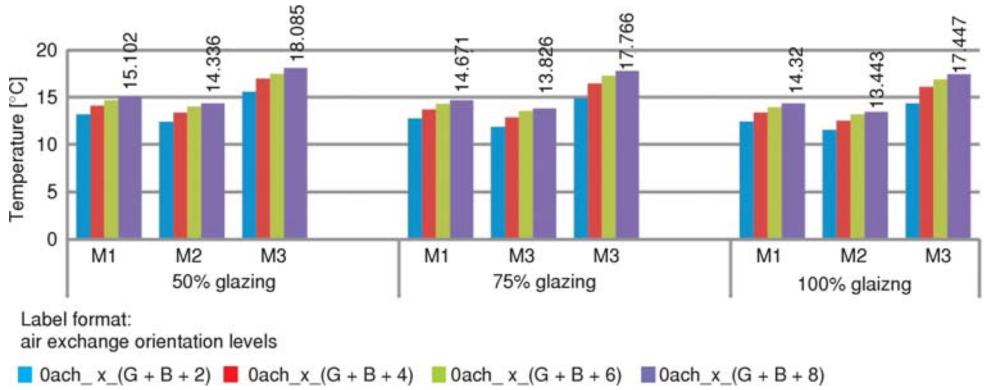

Figure 4. Average temperature values for three analyzed models with respect to the glazing percentage (stationary temperature mode) (for color image see journal web site)

hand, it rises with the rise of the building, while on the other hand, average temperature value was the lowest for the highest (100%) glazing percentage and *vice versa*.

When comparing the same group of results (for the same number of floors and the same glazing percentage) among the three model staircases, M1-M2-M3, the highest average temperature was that of the staircase model M3 while the lowest one is that of the model M2 (fig. 4). This pattern of behaviour indicates the correlation between the position of the staircase in the floor plan of a building and its thermal performances, in a sense that central position within a floor plan of model M3, which is typical for type B staircases, contributed to higher value of the average staircase temperatures in comparison to other two staircase models, M1 and M2, that were placed along the building façade. On the other hand, calculated average temperature values of two variations of type A staircase – models M1 and M2 indicated the correlation that exists between the shape and size of the staircase and its thermal performances. The longer façade wall that model M2 has in comparison to the staircase model M1 contributed to lower values of average temperatures.

Variations of temperature values show the opposite sense compared to the corresponding values of temperature correction factor F_x – they decrease with the raise of the building, and

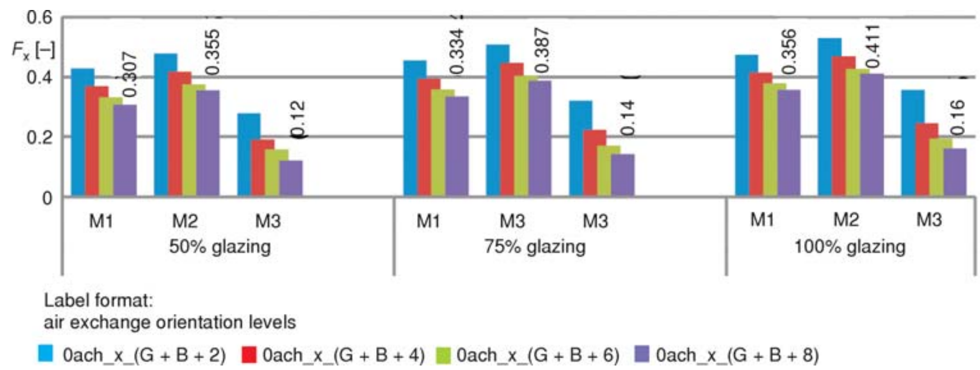

Figure 5. F_x **values for three analyzed models with respect to the glazing percentage (stationary temperature mode)** (for color image see journal web site)

decrease with the decrease of the glazing percentage. Following this pattern, the lowest calculated value among the same group of results was expressed by the staircase model M3, while the highest one is that of the model M2.

Regarding the prescribed value of the temperature correction factor (0.5), calculated values of F_x differ in all of the analyzed variations in relation to either the number of floors, or percentage of glazing of the external wall, as illustrated in fig. 5. The lowest value of F_x that was calculated in a stationary temperature mode as 0.12, corresponds to the high-rise, Ba + GF + 8 floors high building, of model M3, with 50% glazing percentage of a roof lantern, while the highest value of F_x (0.529), was calculated in the case of the low-rise, Ba + GF + 2 floors high building model M2 and 100% glazed façade wall.

Dynamic temperature mode

Dynamic temperature mode that was observed was simulated and calculated in four combinations of referent parameters of climatic conditions: air movement within the staircase models and orientation which was relevant for glazed façade wall in case of staircase models M1 and M2. These combinations are: 1 air exchange per hour in variations of northern, *i. e.* southern orientation, and 3 air exchanges per hour in same variations of northern or southern orientation. Each of these combinations offered results for 36 different cases in total.

In each of four combinations, the same tendency in change of the values of average temperatures as well as of temperature correction factor F_x was present as in the case of stationary temperature mode. This means that average temperature and temperature correction factor were both dependent on the building height and on glazing percentage of the façade wall/roof. The temperature rose with the rise of the building, but decreased with the increase of glazing percentage, while temperature correction factor showed the opposite sense. However, the differences between the adjacent graduations, both in relation to the number of floors and to the glazing percentage are almost negligible and significantly smaller in comparison to those calculated under the stationary temperature mode (fig. 6).

As it was expected, air exchange rate, *i. e.* air movement within the staircase volume had an impact on the value of average staircase temperature, *i. e.* F_x value, so the higher air exchange rate the lower the temperature, *i. e.* the higher the F_x value. Different orientation of a

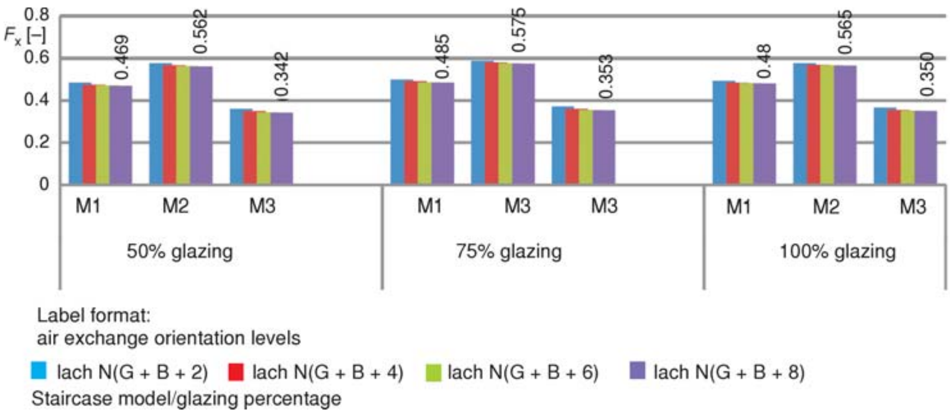

Figure 6. F_x values for three analyzed models with respect to the glazing percentage (dynamic temperature mode: 1 exchange per hour and northern orientation)
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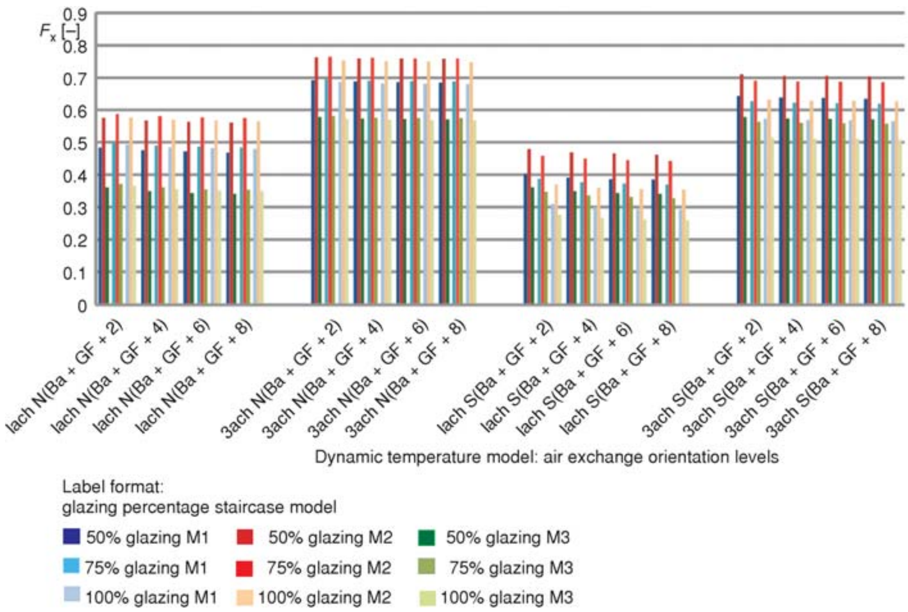

Figure 7. F_x values for three analyzed models with respect to orientation and air exchange rate
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glazed façade wall (northern *vs.* southern) also had an impact to the thermal performance of a staircase. In the case of staircase models M1 and M2, northern orientation resulted with about 20% lower values of average staircase temperatures in comparison to the southern, while temperature correction factor of northern oriented staircase was about 10% higher than the opposite one. However, orientation had almost no impact to the thermal performance of M3 staircase which had glazing surface in a form of roof lanterns (fig. 7).

The results obtained by checking the variations of dynamic temperature mode to the greatest extent deviate from the prescribed value of the coefficient of thermal corrections F_x. It can be said that in the case of moderate air exchange within the staircase volume, models M1 and M2 of the staircase (staircase type A) show the values of F_x that are close to the declared one, but in the rare cases they reach the set value of 0.5. For the same boundary conditions, centrally placed staircase represented in the model M3 expressed significantly lower values of temperature correction factor. However, when air movement along the staircase volume is greater which corresponds to 3 exchanges of air per hour, temperature correction factor rises to values that are up to 35% higher than the prescribed value. In both variations in air movement, south oriented glazed surfaces contribute to the reduction of temperature value of F_x in comparison to the opposite, northern orientation.

Discussion and conclusions

Conducted analysis confirmed that exact values of temperature correction factor F_x are in direct correlation with morphology of an unheated staircase. Variations in values depend on relative size of a staircase and its position within a floor plan, as well as to the height of a building and percentage of glazing of the external envelope of the staircase. The established regularity could be identified as:

– the higher the building, the lower the mean value of F_x, and

– the higher the percentage of glazing along the external envelope of the staircase area, the higher the mean value of F_x.

With respect to the last statement, model M2 which has a rectangular shape in a floor plan that is close to the square, hence has a relatively longer external wall than that of the model M1, expressed higher values of calculated F_x in comparison to the corresponding cases of M1 staircase.

This pattern of behaviour has been confirmed in both temperature modes that were used for assessment of thermal properties of analyzed staircase models. However, dynamic temperature mode offered more uniform results within the variations of the same staircase model, regarding both the variations of building height and percentage of glazing as shown in fig. 8.

With respect to the prescribed value of F_x, in both temperature modes and in the most of the cases calculated values of F_x differed to the great extent from the prescribed value of 0.5 Therefore it can be concluded that, in the case of an unheated staircase, the value of temperature correction factor F_x should not be a fixed value, as it is the case today, but there should be a system of variable values that are dependable on several parameters regarding the morphology of the particular staircase, such as its relative size in a floor plan, height of the building, percentage of glazing of external walls or roof, *etc*.

By keeping the fixed F_x value, regardless the morphological characteristics of the staircase, calculated heat losses of a building would differ to the great extent from the real one, and in the most of the cases they would become overrated.

The established correlation pattern between the staircase morphology and the temperature correction factor could and should not only raise the issue of the prescribed value of the temperature correction factor itself, but also that of the prescribed thermal transmittance or U-value which is prescribed for this particular type of building structure.

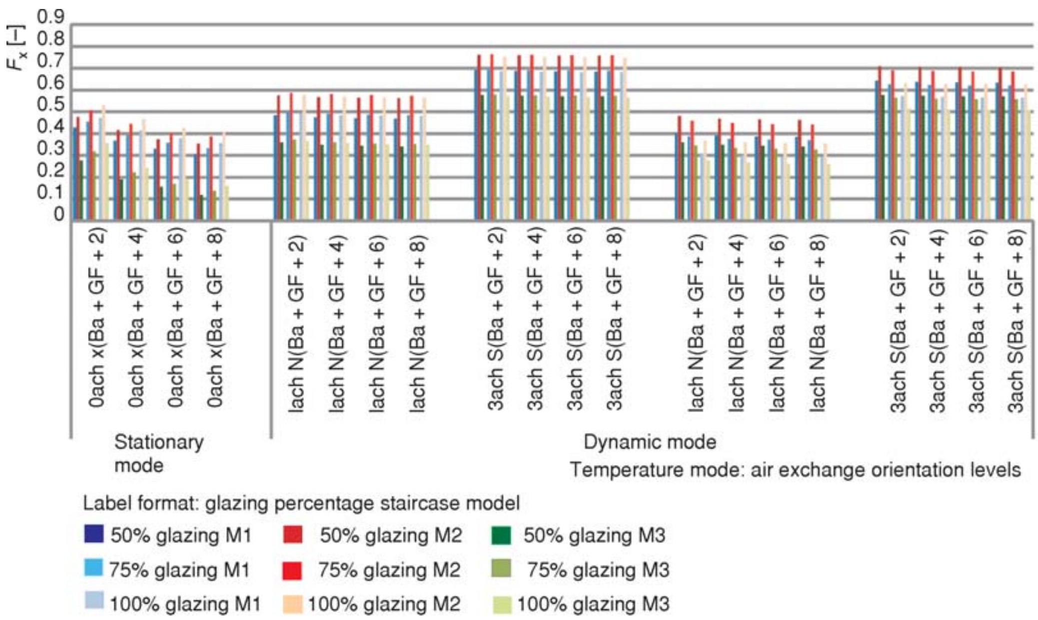

Figure 8. F_x **values for three analyzed models with respect to orientation and air exchange rate**
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Nomenclature

A – area, [m^2]
F_x – temperature correction factor, [–]
H – heat transfer coefficient [WK^{-1}]
U – thermal transmittance, [$Wm^{-2}K^{-1}$]

Greek symbols

λ – thermal conductivity, [$Wm^{-1}K^{-1}$]
Θ – temperature, [°C]

Subscripts

av – average
const – constant
e – external
i – internal
j – index
T – transmission
TB – thermal bridge

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