

Comparison Between Energy-Optimized and Cost-Optimized Design of Multi-Family Buildings Through Automated Optimization

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Abstract

Living in multi-family buildings is very common in Italy. Towards the implementation of economic sustainability principles, it is important to consider the effect of the design strategies in the energy demand of these buildings and their related operational costs. This is particularly important for low-income tenants, and is pursued by many social housing developments by which a good energy performance design is reached. In this work, a simulation-based optimization methodology that combines the use of TRNSYS® with GenOpt® is applied in order to minimize two different objective functions, one related to the primary energy demand and the other related to the operational energy cost, and to verify the extent to which an energy-optimized design differs from a cost-optimized design in the northern Italian climate. The study is performed on a 7-flat typical floor of a real multi-family building for social housing. The design of the building envelope is optimized, leading to reduce the primary energy demand for heating and cooling of the floor by 36 % and the energy costs by 35 %. Higher equality between the energy performances of the flats is also reached. Both objectives lead to very close values of primary energy and costs, but the resulting optimal building design is different according to optimization objective. The comparison between the energy-optimized and the cost-optimized scenarios leads to the conclusion that, in order to reduce the risk of energy poverty, the design solution that minimizes the energy cost can be preferred, as it can minimize the energy bill of low-income tenants while being close to the environmental optimum.

1. Introduction

In Italy, more than 50 % of people live in multi-family buildings. That is why increasing the energy

efficiency of new and existing multi-family buildings can have a significant impact on the reduction of the energy consumption of the Italian residential building stock. Furthermore, multi-family is the common building typology for social housing interventions; therefore improving their energy performance also constitutes a challenge for contrasting the risk of energy poverty for low-income households (Faiella et al., 2014).

Copiello (2016) demonstrates that energy efficiency allows the low-income tenants to be neutral about the rent increase that may occur for new social housing interventions under the current Italian regulation. Moreover, after the introduction of the 2012/27/EU Directive and the principles of heat accounting, many problems have emerged related to cost repartition and the non-homogeneity between the different flats in multi-family buildings (Ficco et al., 2016; Fabrizio et al., 2017).

The development of a building dynamic simulation and its combination with automated optimization constitutes a powerful tool for designers to evaluate thousands of different building design solutions (Xing et al., 2016), leading to accurately optimize the building design according to different objective functions that imply the dynamic calculation of the building energy consumption (i.e. primary energy, life-cycle cost, etc.). The choice of the optimization objective clearly affects the resulting building design and many researchers are dealing with the problem of developing strategies for the economic feasibility of an environmentally optimal building design, as there is often a gap between economic optimum and environmental optimum (Ferrara et al., 2014; Pikas et al., 2015; Zacà et al., 2015).

1.1 Aim of the Work

The aim of this work is to further develop some previous works of the Authors (Ferrara et al., 2016a, and 2016b), where primary energy and energy cost optimization objectives were addressed separately. The aim of this paper is to study and compare the two objectives in parallel by providing an answer to the following questions:

- Which is the potential performance optimization of a new multi-family building for social housing in Italy?
- How and to what extent does cost-optimized design differ from energy-optimized design?
- Which design variables are mostly influenced by optimization objectives?
- Which design variables are mostly resilient to the variation of the optimization objectives?
- What are the differences in energy performance and thus in energy costs between the different flats of a multi-family building? How and to what extent a design optimization can help in reducing the differences?

The analysis is based on a case study that is representative of recent social housing in Italy.

2. Simulation

2.1 Case Study

The case study is a real multi-family building located in Cremona, Italy. The construction of external wall includes bricks (30 cm) and an external thermal insulation (10 cm), for a wall thermal transmittance U equal to $0.26 \text{ W}/(\text{m}^2 \text{ K})$. Transparent surfaces are double low-e glass windows with metal frame, with a mean thermal transmittance equal to $1.45 \text{ W}/(\text{m}^2 \text{ K})$, and a solar factor equal to 0.59. As shown in Fig.1, some windows are shaded by external loggias, a typical feature of the Italian architecture. Details can be found in Ferrara et al. (2016a). For the purpose of this study, one typical floor of the case study building was selected for carrying out optimization studies. As reported in Fig. 1, the floor is composed of 7 flats, each with a different floor area and surface-to-volume ratio (Table 1), for a total floor conditioned floor area of 466 m^2 .



Fig. 1 – Case study building. South façade view and plan of the typical 7-flat floor

The building is connected to a district-heating network with radiant panels as heating terminals (the total seasonal efficiency ratio of the heating system is 0.88, based on the Energy Performance Certificate; the primary energy conversion factor declared by the supplier is equal to 0.62). A gas boiler produces DHW (energy efficiency ratio equal to 0.85, primary energy conversion factor equal to 1.05). A mechanical ventilation system with a heat exchanger is also present; the medium seasonal efficiency of the heat recovery was considered equal to 0.5. For calculating the cooling energy consumption and primary energy, a reference air conditioner system was considered (energy efficiency ratio EER equal to 2.05; total primary energy conversion factor for electricity equal to 2.42). For energy cost calculation, the prices of 0.10 €/kWh_t for the thermal energy provided by the district heating system (Linea Reti e Impianti, 2016), 0.08 €/kWh_t for gas, and 0.20 €/kWh_e for electricity (Eurostat, 2016) were considered. The energy simulations were carried out with the IWEC weather data for Milan.

Table 1 reports the specific primary energy consumption and the operational costs related to each flat and the average value related to the entire floor of the case-study building in its actual configuration, which is the so-called “initial scenario” for the optimization. The energy rating, according to the current Italian energy performance certification regulation (DM 26/06/2015), is A1 for each flat and for the floor.

Table 1 – Initial scenario. Annual primary energy consumption and annual energy costs for each apartment and floor values.

	A	B	C	D	E	F	G	Floor
Floor area (m ²)	86.0	48.7	77.5	77.5	47.4	47.6	81.1	465.8
S/V (m ⁻¹)	0.74	0.66	0.26	0.26	0.32	0.27	0.45	0.46
Heating EP _H (kWh/m ²)	26.5	17.7	19.2	18.9	15.5	13.6	26.9	20.7
CH (€/m ²)	4.27	2.85	3.10	3.04	2.50	2.20	4.34	3.34
Cooling EP _C (kWh/m ²)	15.3	18.3	10.0	9.7	20.7	20.2	14.4	14.7
Cc (€/m ²)	1.26	1.52	0.82	0.80	1.72	1.68	1.18	1.22
DHW EP _W (kWh/m ²)	21.9	25.0	22.4	22.4	25.2	25.1	22.2	23.1
Cw (€/m ²)	1.58	1.80	1.62	1.62	1.82	1.82	1.60	1.66
Vent EP _V (kWh/m ²)	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
Cv (€/m ²)	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
Tot EP _{gl} (kWh/m ²)	78.8	76.1	66.7	66.0	76.5	74.2	78.6	73.6
C _{gl} (€/m ²)	8.35	7.41	6.78	6.70	7.28	6.94	8.36	7.46
Energy rating	A1	A1	A1	A1	A1	A1	A1	A1

2.2 Optimization Methodology

The methodology that was used to investigate the objectives presented in the scope of the work was set up in previous works (Ferrara et al., 2016c) and involves the coupling between TRNSYS® and GenOpt® in a simulation-based optimization process, as shown in Fig. 2.

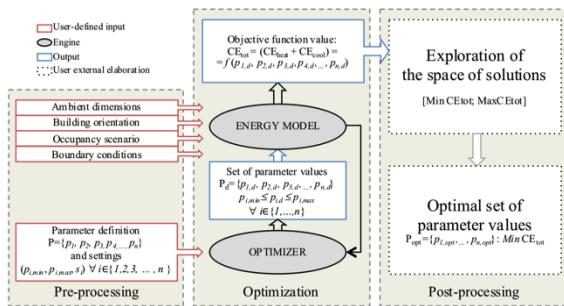


Fig. 2 – Simulation-based optimization methodology

In the pre-processing stage, the TRNSYS model is created including the building boundary conditions, and the set of design parameters to be optimized is defined. These parameters are related to the thermal resistance of the insulation panels and the solar absorption coefficient of the external walls, the type and size of the windows, the horizontal overhang and fin dimensions of the south-oriented

windows, the depth of the loggias facing north and south. The range and the step of their variation were set according to regulation requirements, technical feasibility, and market criteria. Table 2 reports the selected options for variation of window type parameters, which are related to different combinations of glass thermal transmittance, solar factor, and visible transmittance. In the nomenclature, all defined parameters are reported. The set of parameters with their dimension and constraints, defines the space of solutions of the problem, in which the search for the optimal design solutions according to the objective is conducted. See (Ferrara et al., 2016c) for details about the parameter definitions.

Table 2 – Options for window type parameters

ID	Design	U _g (W/m ² K)	g (-)	τ _v (-)
1	4/16/4	1.27	0.59	0.71
2	4/15/4	1.10	0.61	0.78
3	6/12/4/12/4	0.70	0.29	0.58
4	6/16/6	1.10	0.33	0.64
5	6/16/6	1.29	0.33	0.66
6	2.5/12.7/2.5/12.7/2.5	2.00	0.70	0.74
7	4/16/4/16/4	0.70	0.50	0.64

At the optimization stage, the iterative process driven by the optimization algorithm leads to evaluate a great number of design solutions, each related to a different value of the objective function, until the objective function is minimized. The optimization process was run with two different objective functions, calculated for the all the floors (Fig. 2 refers to the energy cost optimization process). The primary energy objective function is defined in (1), as the total sum of heating and cooling primary energy annual consumption of the entire case-study floor (kWh/m²).

$$PE_{H+C} = \frac{Q_H}{r_H} \cdot f_H + \frac{Q_C}{EER} \cdot f_C = \frac{Q_H}{0.88} \cdot 0.62 + \frac{Q_C}{2.05} \cdot 2.42 \quad (1)$$

The energy cost objective function is defined in (2), as the total sum of heating and cooling annual operational cost of the case-study floor (€/m²).

$$C_{H+C} = \frac{Q_H}{r_H} \cdot c_H + \frac{Q_C}{EER} \cdot c_C = \frac{Q_H}{0.88} \cdot 0.1 + \frac{Q_C}{2.05} \cdot 0.2 \quad (2)$$

Only the heating and cooling energy needs (Q_H and Q_C) were included in objective functions, as DHW and ventilation needs cannot be reduced with the variation of the defined set of parameters.

The optimization process was run also to maximize the objective functions, so that at the final stage, as post-processing, the space of solution could be explored from its minimum to its maximum. This process led to the evaluation of 6,893 different design solutions. Then, the optimal set of parameter values related to the minimization of one or the other objective function was found. Once the performance of the floor was optimized, the values of primary energy and energy costs were calculated for each flat of the floor in the resulted optimal design configurations.

3. Results and Discussion

Fig. 3 reports all points evaluated within the optimization processes that were run for the primary energy objective Function (1) and for the cost objective Function (2). Each point is reported in the graph having its PE_{H+C} value on the horizontal axis and its C_{H+C} value (heating and cooling energy cost) on the vertical axis. The points of the space of the solution that were evaluated within the energy optimization

are reported in orange, while blue points are referred to the cost optimization. Since the optimization process was run for both minimizing and maximizing the objective function, the graph shows that the space of solution led to primary energy values within the range of 20-70 kWh/m² and to operational energy cost values in the range between 2.9 and 7.4 €/m².

It is interesting to note that the two objective functions lead to a similar range of possible solutions in both dimensions and thus to optimal points that are very close to each other in the graph. The graph clearly shows that reducing the primary energy consumption also leads to a reduction of operational energy costs.

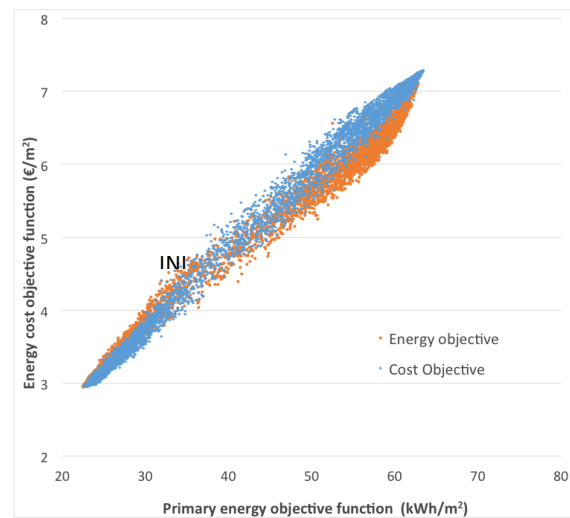


Fig. 3 – Primary energy (x-axis) and cost values (y-axis) of the points in the space of solution evaluated within the energy optimization (orange) and the cost-optimization (in blue)

However, looking at the parameter values related to the optimal scenarios (Table 3), it appears that similar objective function values can be reached with different building design configurations.

This means that different combinations of parameter values can lead to similar values of primary energy consumption and cost with different shares of cooling and heating demand.

This is because of the different weights given to the heating and cooling needs. According to the definition of the objective Functions (1) and (2), cooling energy needs have the highest weight in the primary energy objective function, while heating needs weight the most in calculating the operational energy costs. However, it has to be noted that, in the

initial scenario, the heating needs are 40 % higher than the cooling energy needs.

In Table 3, the parameter values defining the initial, the energy-optimized, and the cost-optimized building design configurations are reported.

It is shown that the values of the parameters related to the external wall insulation in all orientations (sISOLN, sISOLEW, sISOLS) are significantly increased to the upper bound of the variation range of parameters in both optimal scenarios. Also the parameters related to the window dimensions (WWidth parameters, where the letter indicates the flat in which the window is located) have equal values in both energy and cost optimized scenarios, in which the width of all windows is equal or smaller than in the initial scenario.

The grey color highlights the parameter values where differences occur. These are related to the absorption coefficients of the opaque envelope, to the external shadings and to the window type.

It is clear that cost-optimization is heating- driven. In fact, higher values of solar absorption coefficients and a smaller depth of horizontal overhangs and of loggias increase heating gains in winter, allowing solar radiation to enter the cost-optimized building more than in the energy-optimized building.

Following the same principle, window type 7 that is selected for the south windows in the cost-optimized scenario, has the same thermal transmittance of window type 3, but a higher solar factor.

The different shares of cooling and heating energy needs in the two optimal scenarios are also shown in Table 4, where the different values of heating and cooling primary energy, and the related energy costs are reported for each flat of the floor in both the energy-optimized (Eopt) and the cost-optimized (Copt) scenario. Savings in terms of percentage reduction of each term with respect to initial scenario are also indicated. Fig. 4 reports the reduction achieved by optimal scenarios considering also DHW and ventilation energy uses (that are not affected by optimization). Interestingly, the energy cost of the Eopt scenario is close to the one obtained in the Copt scenario, and the same is for the primary energy in the Copt scenario, where the related primary energy is close to the minimum found in the Eopt scenario.

The data related to each flat, reported in Table 4 and in Figs 5 and 6 clearly show that the optimization of

the energy performance of the floor (Fig. 5) leads to different reductions of the energy consumptions between flats, where the highest reductions are achieved for flats related to the highest energy needs in the initial scenario. As a secondary effect, the optimization of the performance of the floor as a whole leads to a greater equality between flats in terms of energy performance. In fact, the difference between the highest (flat G) and the lowest (flat F) PE_{H+C} values decreases from 12.8 kWh/m² in the initial scenarios to 6.3 kWh/m² in the Eopt scenario. Concerning the cost objective function (Fig. 6), results follow similar trends. Major reductions are achieved by the flats A and G (the ones related to the highest energy cost in the initial scenario) and the difference between the highest and the lowest C_{H+C} values decreases from 1.69 €/m² in the initial scenario to 1.23 €/m² in the cost-optimized scenario, leading to major equality between flats in terms of specific energy costs for heating and cooling.

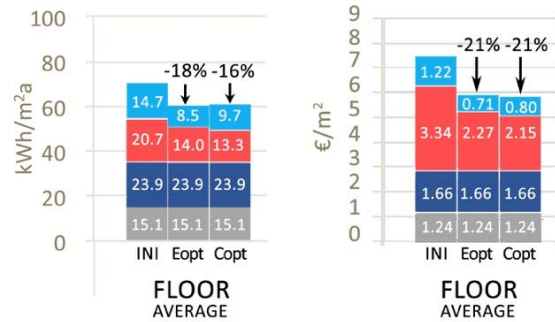


Fig. 4 – Primary energy and energy costs of the initial (INI), energy-optimized (Eopt), and cost-optimized (Copt) scenarios, floor values of ventilation (grey), DHW (dark blue), heating (red), cooling (light blue)



Fig. 5 – PE reduction for all flats in an energy-optimized scenario with respect to the initial scenario. Colors are the same as in Fig.4

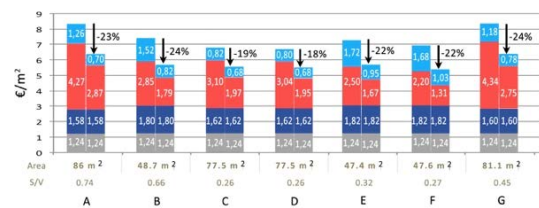


Fig. 6 – Cost reduction for all flats in a cost-optimized scenario with respect to the initial scenario. Colors are the same as in Fig.4

Table 3 – Value assumed by parameters in the initial scenario and in the two optimal solutions (energy and cost). The grey color indicates the parameters of which the optimal value changes according to the objective function

Parameter name	Initial value	Energy-optimal value	Cost-optimal value	Parameter name	Initial value	Energy-optimal value	Cost-optimal value
sISOLN (m ² K/W)	1.73	5.40	5.40	WWidthA1 (m)	1.0	1.0	1.0
sSOLEW (kWh/m ² K)	1.73	5.40	5.40	WWidthA2W(m)	0.9	0.9	0.9
sISOLS (m ² K/W)	1.73	5.40	5.40	WWidthA2S (m)	1.2	0.8	0.8
abs-back (-)	0.2	0.2	0.5	WWidthA3 (m)	1.8	1.8	1.8
abs-backS (-)	0.2	0.2	0.2	WWidthB1 (m)	1.8	1.6	1.6
abs-backEW (-)	0.2	0.2	0.5	WWidthB2 (m)	1.2	1.2	1.2
S_overhproj (m)	0	0.8	0.6	WWidthC1 (m)	2.4	2.0	2.0
S_LRwproj (m)	0	0.8	0.6	WWidthC2 (m)	2.7	2.7	2.7
PLOGGIA (m)	1.8	1.8	1.4	WWidthD1 (m)	2.4	2.0	2.0
LRw_LOGGIA (m)	1.8	1.8	1.4	WWidthD2 (m)	2.7	2.7	2.7
PLOGGIAN (m)	1.8	1.8	0.6	WWidthE1 (m)	1.2	1.2	1.2
LRw_LOGGIAN (m)	1.8	1.8	0.6	WWidthE2 (m)	1.8	1.6	1.6
WT (-)	1	3	3	WWidthF1 (m)	1.2	1.2	1.2
WTS (-)	1	3	7	WWidthF2S (m)	0.9	0.9	0.9
WTW (-)	1	3	3	WWidthF2 (m)	1.8	1.6	1.6
WTL (-)	1	3	7	WWidthG1N (m)	0.9	0.9	0.9
				WWidthG1L (m)	3.0	2.2	2.2
				WWidthG2L (m)	1.2	1.2	1.2
				WWidthG3 (m)	1.2	1.0	1.0

Table 4. Comparison of the heating and cooling energy demand between the energy-optimized and the cost-optimized solution. Colors refer to Fig. 1; the reported energy and cost savings are referred to the initial scenario (Table1)

Flat	PE _H (kWh/m ²)	PE _H savings	CH (€/m ²)	CH savings	PE _C (kWh/m ²)	PE _C savings	C _C (€/m ²)	C _C savings	Energy rating
A (E_Opt)	17.8	-33 %	2.87	-33 %	7.7	-50 %	0.64	-49 %	A2
A (C_Opt)	16.0	-39 %	2.87	-33 %	8.5	-45 %	0.70	-44 %	A2
B (E_Opt)	12.3	-31 %	1.99	-30 %	9.0	-51 %	0.75	-51 %	A2
B (C_Opt)	11.1	-37 %	1.79	-37 %	9.9	-46 %	0.82	-46 %	A2
C (E_Opt)	12.9	-33 %	2.09	-33 %	7.6	-24 %	0.63	-23 %	A2
C (C_Opt)	12.2	-36 %	1.97	-36 %	8.2	-18 %	0.68	-17 %	A2
D (E_Opt)	12.9	-32 %	2.08	-32 %	7.6	-22 %	0.63	-21 %	A2
D (C_Opt)	12.1	-36 %	1.95	-36 %	8.2	-15 %	0.68	-15 %	A2
E (E_Opt)	11.5	-26 %	1.86	-26 %	10.4	-50 %	0.86	-50 %	A2
E (C_Opt)	10.4	-33 %	1.67	-33 %	11.4	-45 %	0.95	-45 %	A2
F (E_Opt)	9.0	-34 %	1.46	-34 %	11.4	-44 %	0.94	-44 %	A2
F (C_Opt)	8.1	-40 %	1.31	-40 %	12.5	-38 %	1.03	-39 %	A2
G (E_Opt)	17.9	-33 %	2.89	-34 %	8.8	-39 %	0.72	-39 %	A2
G (C_Opt)	17.0	-37 %	2.75	-37 %	9.5	-34 %	0.78	-34 %	A2
Floor (E_Opt)	14.0	-32 %	2.27	-32 %	8.5	-42 %	0.71	-42 %	A2
Floor (C_Opt)	13.3	-36 %	2.15	-36 %	9.7	-34 %	0.80	-34 %	A2

4. Conclusion

This study deals with the envelope design optimization (passive energy efficiency measures) of a recent multi-family building for social housing in Italy according to different objectives. With the defined design parameters, based on the current design of the building, both energy optimization and cost optimization can decrease the amount of heating and cooling primary energy consumptions by more than 35 % and the energy costs for heating and cooling by around 35 %. This demonstrates that there is still a large potential for performance improvement with respect to the current construction practice of multi-family buildings in Italy.

This has a significant impact on the design, as performance improvements derive from increasing wall insulation, selecting window types with an optimal combination of thermal transmittance and solar factor according to the orientation, modifying the depth of loggias, with obvious implications on the flat layout, and adding fixed shadings elements of a specific depth, with implications on the façade design.

Despite the differences in weights assigned to the heating and cooling needs by the two objective functions, the performance improvements achieved in both energy-optimized and cost-optimized scenarios are very close to each other. However, because of these weights, in the analysed climatic conditions of the northern Italy the cost-optimized design results to be heating driven, while the energy-optimized design results to be cooling driven.

It has to be noted that these results were achieved by optimizing the floor as a whole. Better results could be probably achieved by optimizing the performance of each flat, but investigations on how to deal with the possible increase of construction costs due to a greater differentiation of construction components should be carried out.

The comparison between the energy-optimized and the cost-optimized scenarios leads to conclude that, in order to reduce the risk of energy poverty, the design approach that minimizes the energy cost can be preferred, as it minimizes the energy bill of the tenants while being close to the environmental optimum.

Further work should complete the present study and investigate the problem from the building

owner perspective, including in the cost objective function also investment and maintenance costs. Moreover, future developments of the work will investigate the problem in different climate conditions and in different energy tariff scenarios.

Acknowledgements

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Nomenclature

Symbols

abs-back	North wall absorption factor (-)
abs-backS	South wall absorption factor (-)
abs-backEW	East/West wall absorption factor (-)
C _{opt}	Cost-optimized scenario
E _{opt}	Energy-optimized scenario
f _c / f _H	Total primary energy conversion factor for cooling (C) or heating (H)
c _c / c _H	Unit energy cost for cooling (C) or heating (H)
LRw_LOGGIA	Left/right projection length for South loggia (m)
LRw_LOGGIA N	Left/right projection length for North loggia (m)
PLOGGIAN	Overhang projection length for North loggia (m)
PLOGGIAS	Overhang projection length for South loggia (m)
r _H	Seasonal heating efficiency ratio
sSOLEW	East/West walls - thermal resistance of the insulation layer (m ² K/W)
sISOLN	North walls - thermal resistance of the insulation layer (m ² K/W)
sISOLS	South walls - thermal resistance of the insulation layer (m ² K/W)
S_LRwproj	Left/right projection length for South windows (m)
S_overhproj	Overhang projection length for South windows (m)

WT	North window type (-)
WTL	Loggia window type (-)
WTS	South window type (-)
WTW	West window type (-)
WWidthA1	Window width A1 (m)
WWidthA2W	Window width A2 West (m)
WWidthA2S	Window width A2 South (m)
WWidthA3	Window width A3 (m)
WWidthB1	Window width B1 (m)
WWidthB2	Window width B2 (m)
WWidthC1	Window width C1 (m)
WWidthC2	Window width C2 (m)
WWidthD1	Window width D1 (m)
WWidthD2	Window width D2 (m)
WWidthE1	Window width E1 (m)
WWidthE2	Window width E2 (m)
WWidthF1	Window width F1 (m)
WWidthF2S	Window width F2 South (m)
WWidthF2	Window width F2 Loggia (m)
WWidthG1N	Window width G1 (m)
WWidthG1L	Window width G1 Loggia (m)
WWidthG2L	Window width G2 (m)
WWidthG3	Window width G3 (m)

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