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“Cube house” refurbishment in Hungary – A simulation-based approach

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ABSTRACT

About 800,000 of “Cube houses” which date back to the socialist era are still in use throughout Hungary. These houses are considered to be “outdated” and they bring not only energy but also social issues. This paper presents a refurbishment design solution for the cube house, combining vernacular architecture with modern solutions within the framework of Solar Decathlon Europe 19 competition. The paper investigates the comfort and energy improvement of the refurbished design. Thermal simulation results revealed considerable improvements, which can be considered and implemented to a big proportion of family houses with analogous dimensions, under similar climate conditions.

KEYWORDS

solar decathlon, Hungarian cube house, “Venturi” ventilation, thermal simulation, energy performance, indoor comfort

1. INTRODUCTION

The energy performance of buildings has been one of the major issues that should be tackled to face climate change. In the European Union (EU), buildings are responsible for 40% of energy consumption [1]; whereas residential buildings alone were responsible for 27.2% of energy consumption in 2017 [2]. Moreover, the building sector is expanding and raising the threat of greenhouse gas emissions [1]. That is why the EU initiated the 2030 Climate Target Plan, which highlights the role of building renovation in improving the energy efficiency and aims to raise the renovation rate, which is currently about 1%, giving the fact that 75% of the EU building stock lacks energy efficiency today [3]. Due to European Commission 2020 country-report for Hungary [4], energy efficiency in the residential sector is still weak and the country was behind the EU 2020 target as the energy consumption per capita was still 12% higher than the EU average threshold. Strict regulations for energy efficiency of new buildings are being implemented from 2021 but refurbishment potentials are still not fully sustained [4]. “Cube houses”, (Fig. 1) as called in Hungary, are detached houses with similar floor plans [5], which have been built in Hungary since the 1960s. It is a family house consisting of 2 bedrooms and usually equipped with a gas boiler for heating and an electric boiler for Domestic Hot Water (DHW). More than 800,000 units were constructed, hence this type can be considered as a typical family house in Hungary [6].

Refurbishment brings more benefits than demolition and new construction; not only in terms of the environmental impact but also the social, while the economic benefits are not always guaranteed [7]. A. Power [8] argues that refurbishment brings saving in time, cost, community impact, limiting of building expansion, reuse of existing infrastructure, and

protection of existing communities. It also brings a significant reduction in building energy consumption in both the short and long term.

In general, demolishing an existing building and the construction of a new one can take up to 80 years to recover the environmental impacts [9]. Moreover, Life Cycle Assessment (LCA) studies analyze the process of building refurbishment. They show a high reduction of CO₂ emissions if buildings are refurbished [10]. Therefore, renovation helps in achieving a clean energy transition. That was confirmed and highlighted by a European-Commission report, which showed the importance of building energy renovation to make the shift to a low-carbon building stock [11].

The vast majority of the traditional “Cube houses” share the same plan and structure, but they can still differ in some insignificant details [5]. The presented case study is a new structure that was designed with the imitation of the Cube house’s most common geometry (single floor, non-extruding entrance door, pyramid-shaped roof, brick walls structure and horizontally attached large symmetric pairs of windows) in an attempt to present new insights for how the refurbishment process can possibly be realized.

1.1. Energy design refurbishment

The new house is a timber structure. The main external feature is the “Venturi” disc that covers a small atrium as a ventilation chimney-tower in the center of the house (Fig. 1). The aim is to stimulate natural ventilation through the house as the “Venturi” disc accelerates the wind flow passing under it, causing a suction effect on exhaust ventilation [12]. In addition, traditional chimney ventilation in a well-sealed house proved to be commonly effective, simple, and low cost [13].

The living space (living room + kitchen) was oriented toward the south with a fully-glazed façade that leads to the partially shaded terrace. The glazed façade enhances solar gains and day-lighting in winter and the external shading protects from overheating in summer. The windows are equipped with sliding shading panels made of recycled aluminum while the terrace and the other facades are equipped with sliding shading panels made of wooden tree branches.

2. METHODOLOGY

The paper proposes a comparative analysis between the old “Cube houses” and the new suggested refurbishment design by applying a zonal thermal simulation method. The simulation is conducted with the aid of the IDA ICE 4.8 indoor climate and energy software tool using dynamic energy simulations for refurbishment is a well-known approach for assessing the set of variations. It aims to filter the variations based on improving energy efficiency and thermal comfort [14].

3. BOUNDARY CONDITIONS

3.1. Location and climate

Hungary has a typical continental climate. The greater part of the country has a moderately warm and dry climate according to the Hungarian Meteorological Service. The annual mean temperature in most parts of Hungary is between 10 and 11 °C. The common wind direction is from the North with velocity varying between 2 and 4 m/s [15]. The weather station (Budapest-Pestszentlőrinc) [16] was adopted for the weather data with a latitude of 47.433 N and a longitude of 19.183 E.

3.2. Model description

The two cases (Fig. 2) were built in the climate and energy simulation modeling framework.

The old “Cube house” possesses a net floor area of 69.3 m². The house consists of a bedroom, a living room, a dining room, a kitchen, a bathroom, a toilet, and an entrance. The external wall is a 38 cm thick brick wall. Windows have double-pane glazing. The thermal bridges are set to “poor” as it is the case in this old building type. The house is traditionally equipped with a gas boiler for heating. Even though having a cooling system was not typical when they were built in the 1960s; but more “Cube houses” are recently being equipped with Air Conditioning (AC) due to climate change. Hence, an air conditioning system was implemented here for cooling in the modeled case.



Fig. 1. The refurbishment design project from SDE19 competition (left), a typical “Cube house” in Pécs, Hungary (right)

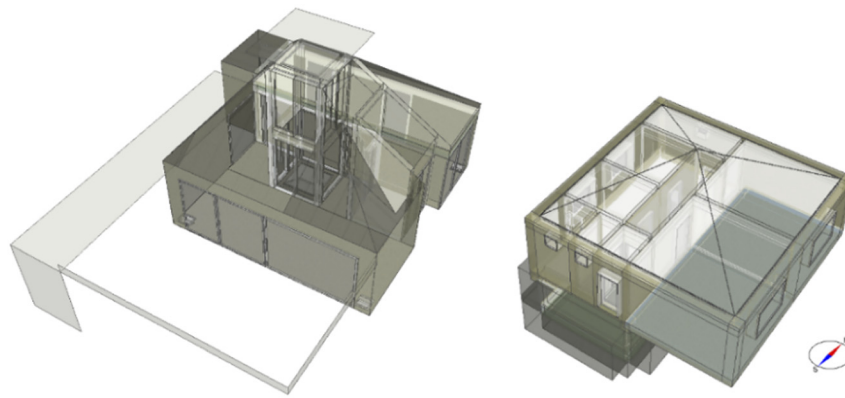


Fig. 2. The simulation models of the refurbishment design (left) and the “Cube house” (right)

The refurbishment design has a net floor space of 64.5 m². The house model consists of two main zones; the bedroom zone including a desk space, and a living zone including a kitchen and dining. The external wall is 38 cm in thickness. The thermal insulation includes cellulose fibers of 20 cm thickness and flexible wood of 5 cm thickness. The thermal bridges are set to the category “good”. The mechanical properties of the building elements in both houses are listed in Table 1, and the initial simulation settings are listed in Table 2.

3.3. Operation settings

The old “Cube house” typically has no mechanical ventilation. It depends on the window opening, which was scheduled to be opened during the night (from 22:00 to 8:00) in summer (from 1st of September to 31st of August) to enhance night cooling. During transition seasons (from 15th of April to 31st of May and from 1st of September to 15th of October), the windows are opened 3 times a day; 5 min each time. The bedroom, living room, dining room, and the kitchen are equipped with an AC system that has a cooling power of 3.9 kW with Energy Efficiency Ratio (EER) of 2.5.

The modeling settings of the building services systems of the refurbishment design were identical to the executed

situation in reality. The supply and exhaust ventilation are balanced at 360 m³/h. The Air Handling Unit (AHU) operation schedule is set in accordance with the opening schedule in each season of the year. The AHU operates during the day (from 8:00 to 22:00) in summer (from 1st of June to 31st of August) where night cooling (passive ventilation) is being used. During the transition seasons (from 15th of April to 31st of May and from 1st of September to 15th of October), the AHU ensures Air CHange (ACH) during the nights (from 22:00 to 08:00), while in the daytime the natural ventilation is on. In the rest of the year (winter), the AHU is always on. The doors that open to the atrium (tower) and the windows integrated into the glazed façade are opened during nights in summer and during the day (4 times; 4 min each) in transition seasons (from 15th of April to 31st of May and from 1st of September to 15th of October). The louvers at the top of the tower and the floor slots are opened during summer and transition seasons (from 15th of April to 15th of October).

Heating and cooling capacities were set identical to reality as well. The total heating capacity is set to 7.8 kW; its Coefficient Of Performance (COP) is 4. The total cooling capacity is set to 8.8 kW, having an Energy Efficiency Ratio (EER) of 3.2. A floor heating system is applied with 70 W/m²

Table 1. Mechanical properties of building elements

	Windows		Walls	Floor	Roof
	U-value W/(m ² K)	T (solar transmittance)	U-value W/(m ² K)	U-value W/(m ² K)	U-value W/(m ² K)
“Cube house”	3.35	0.7	1.127	1.203	5.106
Refurbishment design	0.92	0.21	0.12	0.11	0.606

Table 2. Initial settings for the simulation models

	Infiltration		Lighting		Window/envelope ratio	Average U-value W/(m ² K)
	Air change	Air tightness L/(s.m ² ext. surf.)	Input per unit (W)	Luminous efficiency (l2/W)		
“Cube house”	2	0.55252	18	72	3.20%	0.3793
Refurbishment design	6	1.7427	18	72	12.90%	1.906

of power, coupled with a ceiling cooling system with 80 W/m² capacity in the sleeping area and 60 W/m² of power in the living area. The bathroom is equipped with a radiator of 76.65 W/m² power.

In both models, default schedules for occupancy and lighting were used.

4. RESULTS AND DISCUSSION

4.1. Cooling and heating demand

The load calculations are designed with ideal heating and cooling systems without specifying the exact HVAC systems. It is the initial stage where the investment cost is estimated, conducted in the coldest two months (January and February) and in the hottest two months (July and August). The aim is to define the maximum required power capacity of the mechanical system for cooling and heating to fulfill the necessary indoor comfort. The results show that the refurbishment design achieves 44.1% savings in heating capacity and 7% savings in cooling power (Fig. 3).

Transmission heat loss through walls and roof is 21.6% of the one in the “Cube house” and through thermal bridges is 51.1%, which is mainly responsible for the difference in heating load.

4.2. Visual comfort

Artificial lighting is a major contributor to carbon emissions as it can occupy up to 40% of the building energy consumption [17]. Natural light, on the other hand, has a positive effect on human well-being [18, 19]. Daylight Factor (DF) in definition is the ratio of the internal illuminance (E_i) at a point inside the building to the horizontal external illuminance (E_o) under an International Commission on Illumination (CIE) overcast sky [20]. The value of DF is

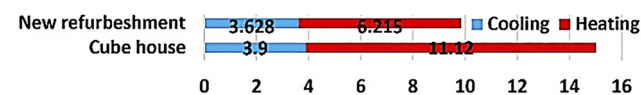


Fig. 3. Heating and cooling load capacity [kW] in the two scenarios

related to the building type, window dimensions and positions, glazing properties, and room surface reflectance [19]. Due to the Active House specifications and EN17037 standard [21], when applying 300 lx as required E_i the DF threshold is 1.7% based on Eq. (1):

$$DF = \frac{E_i}{E_o} 100\%. \quad (1)$$

The refurbishment design showed a 36.1% advantage over the “Cube house” regarding the percentage of floor area that fulfills 1.7% or more of DF, as it is shown in Fig. 4.

On the other hand, the illumination was measured at a threshold level of 300 lx throughout the simulation at 4 time-points (the solstices and equinoxes of the year); 12 p.m. on March, June, September, and December. Figure 5 shows the percentage of floor area that fulfills each level of illumination. The results prove that the refurbishment design is 18.725% better than the “Cube house” in the average of the four seasons, especially in winter where the difference reaches 33.1% more floor area fulfilling 300 lx or more. The improvement in DF and illuminance is due to raising the Window-to-Wall Ratio (WWR) and redistribution of openings mainly to the South.

4.3. Thermal comfort

The main measured indicator for thermal comfort is the Predicted Mean Vote (PMV). The PMV is an index for thermal sensation on a 7-point scale based on the heat balance of the human body [22]. After running the whole year simulation, PMV was measured in accordance with category II from standard EN 15251 [23], which are represented on the PMV scale from -0.5 to +0.5 [24]. Figure 6 shows the mean number of hours that fulfill category II in a

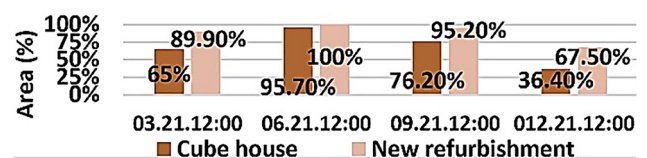


Fig. 5. Illuminance comparison by coverage percentage of floor area over 300 lx

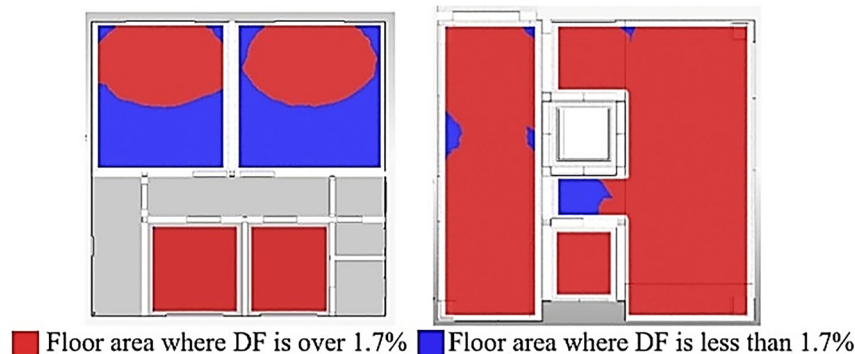


Fig. 4. DF at the threshold of 1.7%; “Cube house” (left); refurbishment design (right)

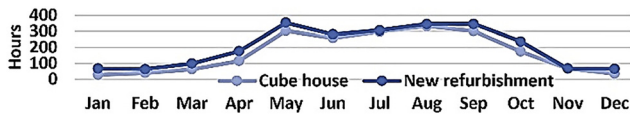


Fig. 6. PMV ratio of the year [h]

year. The PMV results show that the refurbishment design performs 49% better in the sleeping area and 40.5% better in the living area. Overheating in summer was compensated by utilizing both night cooling and mechanical cooling since natural ventilation alone was not enough to avoid overheating.

One reason for the PMV results is the surface temperature. Figure 7 demonstrates a comparison of the surface temperature distribution of walls and windows during the heating season with higher values of the refurbished case, specifically in the coldest heating period.

4.4. Indoor air quality

Indoor Air Quality (IAQ) is considered as the final outcome of both air pollutants and existing ventilation that decreases them. CO₂ concentration level is the main indicator of IAQ and ventilation quality [25]. It was compared by measuring the number of hours when the CO₂ level does not exceed 800 ppm (the threshold of “SDE19” competition standards), whereas the less ppm content is the better air quality.

The simulation results show that the refurbishment design achieve 93% of accepted hours comparing to 44.15% for the “Cube house”. Figure 8 shows the correlation of CO₂ concentration and air age, which are considerable indicators for IAQ. Air age refers to the time since fresh air entered the room, where the smaller the air age, the better the IAQ [26]. The improvement of IAQ is due to the air circulation stimulated by “Venturi” disc, inducing natural ventilation through scheduled window openings, and the AHU operating when natural ventilation is not possible.

4.5. Energy consumption

Identical appliances, schedules and occupants were applied to both models. Figure 9 illustrates the final energy consumption results of a whole year simulation. The refurbishment design shows a 52.3% reduction in total delivered energy over the level of the “Cube house”. The reduction is

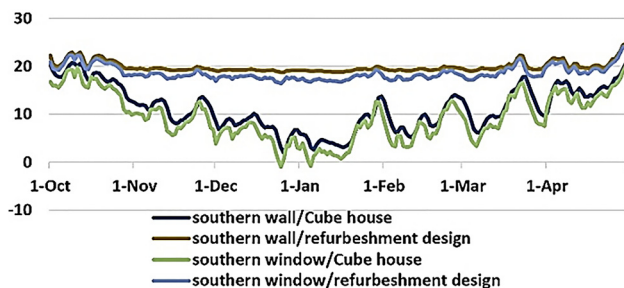


Fig. 7. Surface temperature comparison from 1st October to 30th April, [°C]

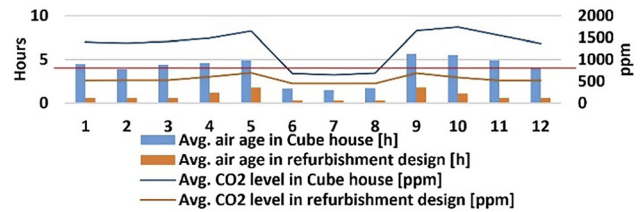
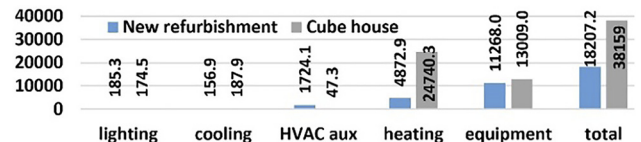
Fig. 8. The average CO₂ concentration and air age in all rooms on a monthly basis

Fig. 9. Comparison of delivered energy, [kWh/year]

especially significant in heating, where it reaches 80.04%. The total energy produced by the PhotoVoltaic (PV) panels is 17,006 kWh, which equals 93.4% of the total delivered energy.

The main energy conservation is observed in the heating consumption. Based on the simulation results, envelope transmission during the heating season through walls and thermal bridges are 90.4 and 94.6% higher respectively in the “Cube house”, which is related to the improved thermal insulation and thermal bridges in the refurbishment design. Though the WWR in the refurbishment is 4 times bigger than in the “Cube house” (12.9–3.2%), the transmission heat loss through the windows is almost the same during the heating season and the significant higher window transmission loss in the refurbishment design during the cooling season supports the cooling and saves cooling energy. Infiltration heat losses in the refurbishment are reduced to half, due to tighter joints in the envelope and due to the AHU ventilation performance, including a heat recovery unit with 80% efficiency rate. The “Cube house’s” window ventilation in the complete year provided larger heating where the new refurbishment design depended on heat recovery and less dependency on the window opening. The mechanical ventilation resulted in 1,020 kWh/year heat loss during heating, but it was compensated by the heat recovery and less needed window ventilation.

5. CONCLUSION

The paper demonstrates a new approach in tackling an important housing problem within the Hungarian context since the issue of “Cube houses” has not only an environmental perspective but economic and social ones. The paper shows the possible beneficial outcome of refurbishing “Cube houses” and represents a vision of how the refurbishment process might take place. Although, the selected geometry attempted to combine the most common architectural

characteristics of this type of house considering the fact that some varieties can be distinguished among them in this context.

Under continental climate conditions, the refurbished version of a typical family house proofed superiority in the PMV, daylight performance, IAQ, and in the energy balance. Based on the calculated results the following main insights can be concluded:

- The designed refurbishment brings up to 52.3% saving in energy consumption. The most crucial saving is provided in the heating system, dominating energy balance throughout the whole year. The main contributors to this improvement are the thermal properties of the opaque and transparent envelope structure;
- The role of cooling is not significant in energy performance of family houses;
- The PMV of the refurbishment improves by 44.75% due to the higher thermal qualities, higher internal wall surface temperatures and operative temperatures;
- The IAQ improvement amounts up to 91.4% lower CO₂-concentration, as the airflow rates increase due to the passive ventilation and the AHU ventilation;
- Daylight provision is 36.1% higher under mixed sky conditions, while by clear sky an average of 20% better illuminance intensity is provided since the refurbishment applies 4 times greater WWR.

The paper proofed previous research regarding the utility of chimney ventilation in dwellings but it strongly recommends further research to realize the specific effect of the Venturi disc and the possible back drafting in the proposed method due to pressure changing. Computational Fluid Dynamics (CFDs) simulations would be suitable for the recommended further investigation and validation of the proposed ventilation method.

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