

Waffle structure optimization in terms of energy efficiency and spatial geometry for a single family house

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Abstract. Sustainable house design represents an integrated complex process, with form rationalization that is to be considered in the early project stages, in order to achieve a set of goals that range from aesthetic and spatial qualities to structural optimization and energy efficiency. Recent research directions in the field of building physics, with regard to the energy efficiency component, focus mostly on environmental aspects, such as carbon footprint reduction. Another contemporary issue that must be addressed concerns establishing a balance between overall energy performance and a comfortable indoor environment. From an architectural standpoint, the passive design principles can adequately respond to the above mentioned issues and have been the focus of specialists during the last years. This paper presents a set of form optimization strategies implemented in the conceptual design stage of a contemporary house. The main objectives of the study focus on energy efficiency maximization and rational use of local resources, without compromising aesthetic criteria.

1. Introduction

The contemporary process of redefining architectural geometry makes reference to liberation from constraints concerning formal organization. Free geometries are emerging as a response to the diversity of factors that influence the development of an architectural project. The concept of performance-based design addresses both technological advances and sustainability issues correlated with a revaluation of traditional established practices such as passive solar layout.

Integrated design involves several aspects that need to be considered in the conceptual phase (materials, orientation, form and space, etc.) in order to satisfy specific performance requirements (spatiality, structural stability, safety in operation, air quality, thermal comfort, energy efficiency).

Therefore, the prerequisites in achieving a performance-based design require an interdisciplinary collaboration (architecture, engineering, sociology), as well as an active involvement of the users (unlike conventional houses, a sustainable solution that embodies passive systems may require a different level of involvement from the occupants).

The building should not be regarded as a mere shelter from the elements, but rather as an adaptive system, that excludes negative influences and admits positive ones, such as light throughout the entire day, solar radiation intake and natural ventilation. Design strategies aimed at increasing the energy efficiency of houses must incorporate both well-established practices of *passive design* (harnessing solar contributions by favorable orientation, natural ventilation, thermal mass, etc.), as well as optimization of geometry by applying *digital technologies*. In performance-based design, objects are



generated by simulating their behaviors. The overall form can be defined and characterized by using the digital simulation of external actions as a driving force [1].

2. Passive design strategies

Architectural principles aimed at improving thermal comfort have been applied empirically since ancient times and have been reaffirmed and perfected in the last century, along with improvements in glass manufacturing technology. Socrates was the first to record that: *“In houses that look toward the south, the sun penetrates the portico in winter keeping the space warm”*, as shown in figure 1.

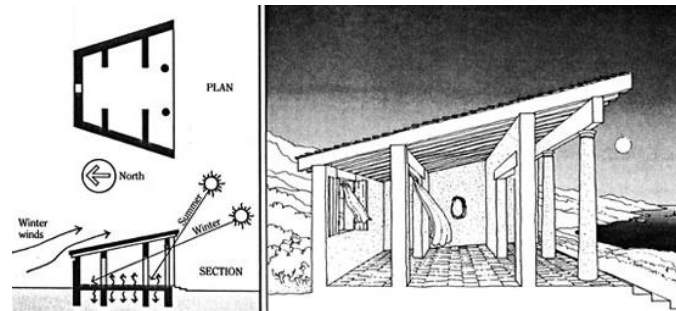


Figure 1. The house proposed by Socrates for the temperate climate, about 400 BC. [Image source: www.naturalbuildingblog.com]

Contemporary passive design strategies still apply the principle of house orientation towards the sun (**solar energy intake**), aspect that is optimized in the conceptual stage through building energy simulations. The local site conditions (specific geographical parameters) should be considered along with building form, opaque versus glazing envelope components, shading systems, etc. [2]

Studies of houses with highly glazed southern facades (for northern hemisphere regions) demonstrated greater indoor temperature differences than ordinary homes, warming quickly during the sunshine apex hours and cooling off rapidly at night due to large heat losses through the windows. To reduce temperature fluctuations and to transfer the thermal load to a later time in the day, the solution is to employ thermal mass in the constructive elements.[3]

Thermal mass is achieved by any material that can absorb and store heat. The thermal mass can be divided into two categories:

- *free thermal mass* - furniture elements, gypsum boards, doors, etc. (such elements provide more protection by shading than heat storage);
- *intentional thermal mass* – structural elements made of brick, concrete, clay-based materials, gravel, etc. (these components must have a certain consistency / thickness, precisely to ensure the storage of heat). Trombe walls and solar water walls also employ ingenious passive storage systems to achieve energy savings in buildings [4].

Another passive design strategy, in addition to harnessing solar energy, represents **natural ventilation exploitation**. The main objectives of using a ventilation system are ensuring energy efficiency, indoor thermal comfort, indoor air quality and avoiding excessive humidity (condensation, moisture infiltration). The natural ventilation is considered to be a simpler and more sustainable approach in comparison to the use of mechanical ventilation. [5]. The benefits of choosing a natural ventilation system versus a mechanical one include: low investment costs, acoustic comfort, ensuring desired air flow rates, no malfunctions occurrence. Among the disadvantages of natural ventilation systems can be underlined the following: variable air flows depending on weather conditions, difficulty of implementing such a system in polluted and noisy environments, the emergence of stagnant air zones.

Natural ventilation can be achieved through several methods, such as: air infiltration (occurs when the building envelope is not airtight), mobile windows and self-adjusting air inlets and outlets grilles.

The natural ventilation exploitation includes several techniques (figure 2):

- *cross ventilation*, most effective in summer (glazing and ventilation openings on opposite facades – wind pressure differences);
- *air recirculation* in winter time (including air purification and moisture assurance with the help of green areas);
- *cooling through evaporation* (a rooftop pool or a water mirror);
- *geothermal cooling* (air can be cooled by passing it through underground pipes or underground air space).

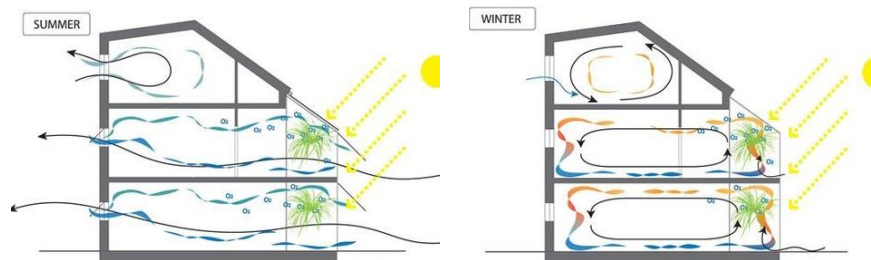


Figure 2. Ventilation strategies during the warm and cold seasons. [Image source: <http://www.pipetracks.co.uk>]

3. Contemporary house design integrating passive principles

The main concept of the single family house presented in this study is integration of passive solar design principles along with novel digital possibilities for structure modeling. In order to satisfy passive design principles, great attention was given to the orientation of internal spaces, as well as the optimum glazing ratio on the facades. From a functional point of view, the living room area, as well as the dining room and the kitchen, all on the ground floor, are oriented towards South (figure 3), while technical spaces, annexes and the main entrance, all face North. A pool is designed to regulate the outdoor and indoor humidity through evaporative cooling effect.

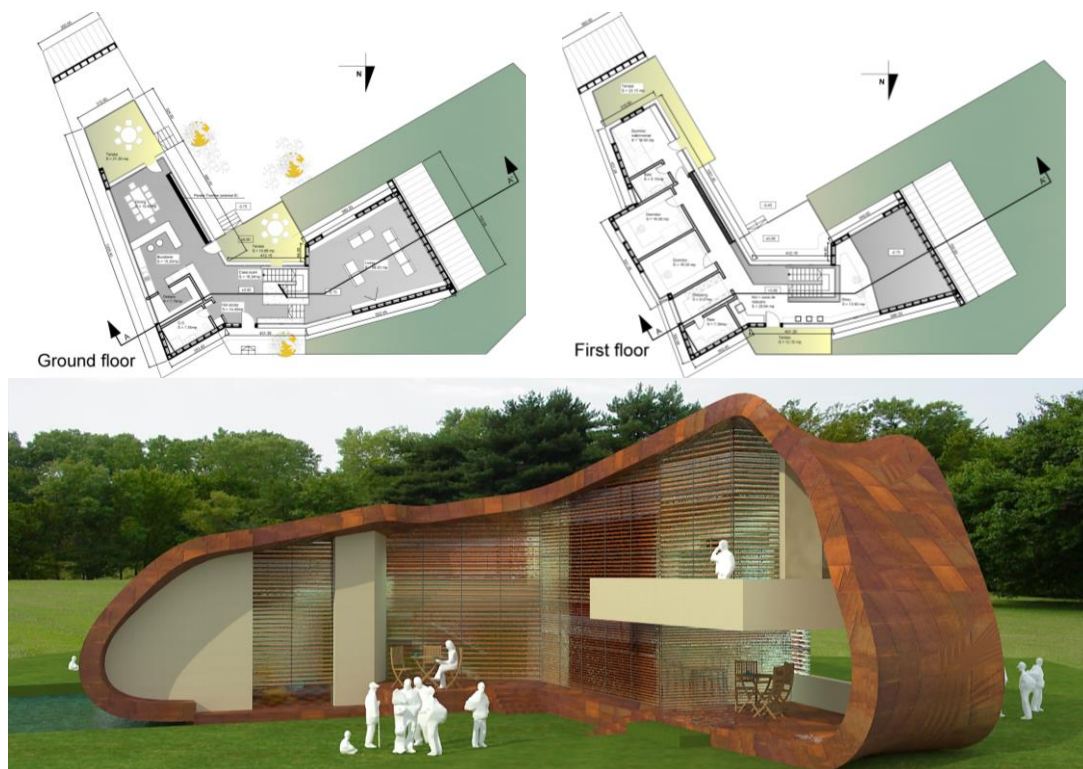


Figure 3. Ground floor and first floor plans; Rendered perspective from the southern direction.

The night area is developed exclusively on the first floor, with the bedrooms oriented towards East. In order to ensure a high level of indoor comfort, and to exploit thermal mass, a Trombe wall was proposed on the South façade (figure 4).

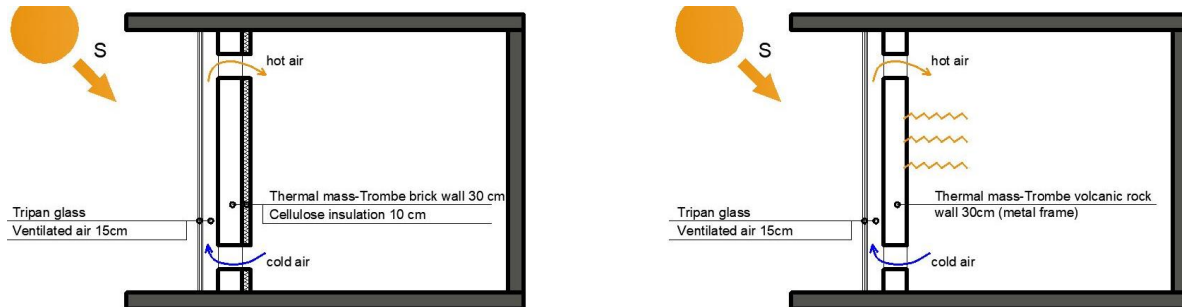


Figure 4. Proposed Trombe wall detail (Southern facade) – 2 thermal mass types.

The South oriented Trombe wall heats the internal spaces during winter, by making use of solar energy gain, allowing through its thermal mass differential heat restitution. Hence, the Trombe wall accumulates heat throughout the day and releases it during the night, when the internal temperature descends under the wall's surface temperature. In order to avoid overheating during summer, the curtain walls are fitted with an integrated sun shading system.

The outer skin is conceived as a two layer system, with an inner structural membrane and an outer envelope. The wooden laminated structure of the roof is parametrically generated, comprised of a 3D array of 35 cm high studs (waffle structure – figure 5).

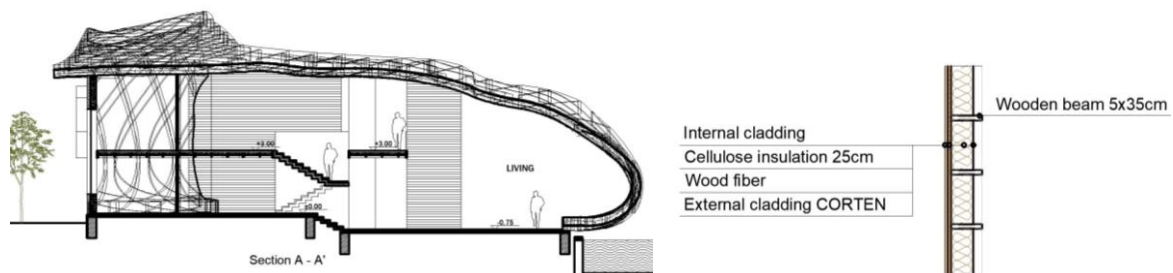


Figure 5. Section; Structural detail.

4. Waffle structure optimization

Laminar structures are generally characterized by a high degree of industrialization, by the simplicity and speed of execution, and by the possibility of fixing the roofing directly on the network. As a result of the many advantages they offer, from both technical and economic perspectives, laminar structures are currently among the most efficient wooden structural solutions, especially in the case of large openings [6].

In the past decade, digital processes enabling a spatial geometry definition based on simulations have influenced the architectural design [7]. This was almost universally true for structural and environmental tests through which the contribution of architects and engineers in the conceptual phase has become both a defining characteristic of digital aided design and a customary element of all complex passive or active strategies.

Information technologies come to the aid of increasing the quality of the process and of the design result through new CAD programs, new CAM technologies, intelligent materials and, not least, through facilitating access to information.

The wooden structure proposed for the analyzed model house has been generated and optimized using Rhinoceros software with Grasshopper plugin (figure 6). The involvement of mathematics in the design process is found at both macro and micro scale. For the design of a free shaped curved surface

(NURBS), one of the preferred techniques becomes approximation with a series of panels that allows it to be built. In selecting the method of obtaining the panels, a number of factors must be considered, among which the most important are:

- the costs associated with a certain type of panel;
- the complexity of the connecting nodes;
- the structural implications.

The method of obtaining the final panels results in the extraction of a basic model of the construction (due to the use of a primary geometric form for surface coverage).

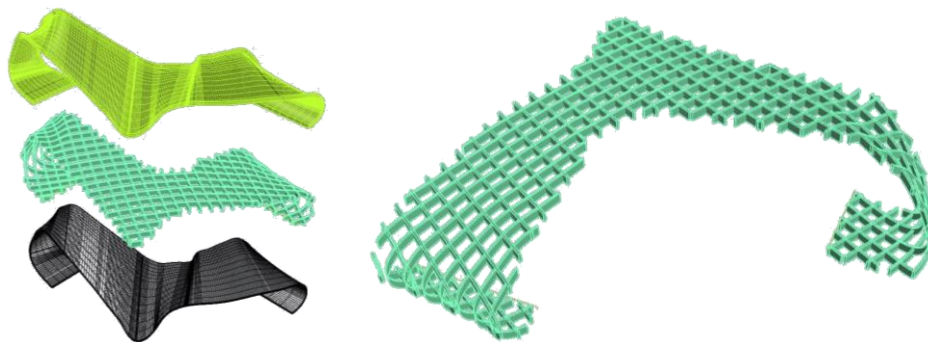


Figure 6. Waffle structure (3D array of 35 cm high studs) optimized with Rhinoceros and Grasshopper software.

Using quadrilaterals patterns to cover a surface eliminates some of the triangulation drawbacks, but introduces an additional set of problems. Decreasing the complexity of the nodes and obtaining symmetrically arranged sides in the nodes allows for the structural torsion to disappear and ensures a reduction in material consumption, providing a surface with a lower weight [8].

5. Thermo-energetic analysis

The thermo-energetic analysis for the proposed house model was simulated with the ArchiCAD Eco Design Software (figure 7).

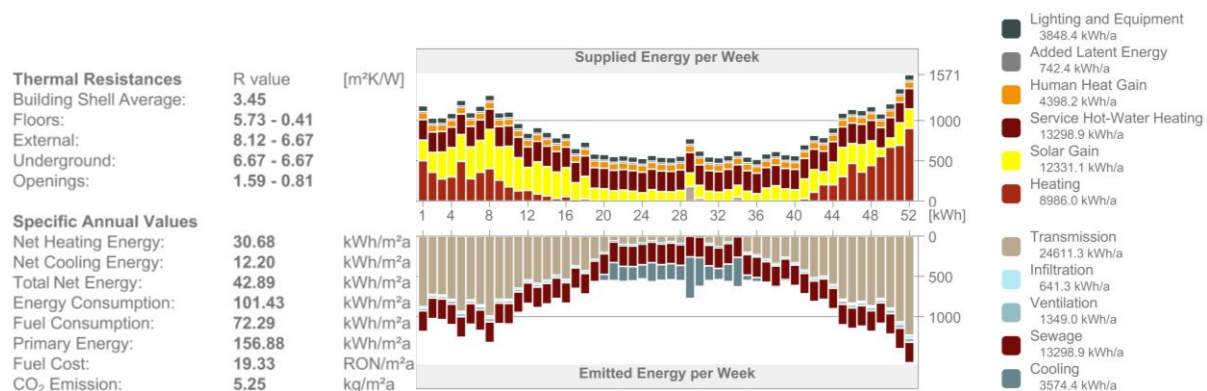


Figure 7. Energy balance and environmental performance.

The indoor comfort parameters were evaluated taking into account the air quality, indoor temperature during the cold and warm seasons and the carbon footprint.

It has been noted that the indoor air temperature ranges among the average values of 20 °C and 26 °C all year long (figure 8). The simulations were made for the months of March, June, September and December. The indoor thermal comfort for the summer months could be improved by proper cross ventilation and by implementation of an earth tubes cooling system.

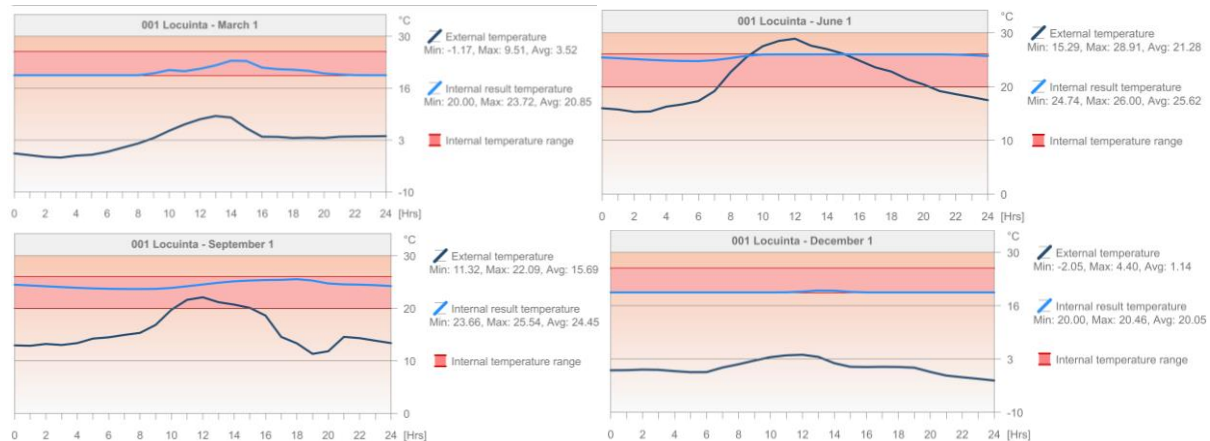


Figure 8. Daily temperature profile.

The carbon footprint can be better assessed through the CO₂ emission rate (1536 kg/a), as illustrated in the figure 9.

Source Type	Source Name	Primary Energy MWh/a	CO ₂ emission kg/a
Renewable	Solar (Thermal & PV)	6	0
	External Air	4	0
	Pellet	19	397
Secondary	Electricity	15	1139
Total:		44	1536

Figure 9. Environmental impact.

The environmental modeling was performed during several simulations and the output results were used to improve the spatial geometry of the roof's parametric components. Also, it was an ongoing process of optimizing the façade's glazing ratio, thermal insulation and overall energy scheme in order to obtain a better performance-based design of the studied house model.

From the thermo-energetic analysis we conclude that the annual heat energy demand is 30.68 kWh/m²a, a relatively low value for a house with a considerable air volume. The tabel shown below summarizes the values that can serve as criteria for assessing indoor comfort during the warm and cold seasons (table 1).

Table 1. Thermo - energetic analysis for the proposed house model – specific annual values.

	Values
Building geometry data	A/V [m ⁻¹]
	0.24
Energy performance	Glazing ratio [%]
	24 %
	Net heating energy (q _{heating}) [kWh/m ² a]
Indoor comfort during summer	Net cooling energy (q _{cooling}) [kWh/m ² a]
	12.20 kWh/m ² a
Thermal resistance R value [m ² K/W]	Exceeding Tcomfort [°]
Environmental impact	5 °C
	Building Shell
	3.45 m ² k/W
	CO ₂ emission [kg/m ² a]
	5.25 kg/m ² a

Considering that standard annual temperature value is 21 °C, the studied house model's indoor temperature during the month of June is exceeded only by up to 5 °C, a more than acceptable value, considering that cooling energy demand is very low, just 12.20 kWh/m²a, due to minimizing active energy sources for cooling. The energy performance simulations show that the indoor air temperature during summer could be decreased by implementation of passive cooling systems (evaporative cooling or earth tubes cooling).

6. Conclusions

Implementation of passive solar design principles in an architectural project determines a significant reduction in energy consumption throughout the whole life cycle of a building, without a major impact on initial investment or maintenance costs. At the same time, the specific strategies of passive design can be easily integrated in a contemporary architectural solution.

Contemporary digital design, and in particular its generative geometric patterns, are especially focused on satisfying efficiency and performance demands. The performance levels derived from the thermo-energetic analysis position the studied house model in the category of high efficient houses, with a heating/cooling demand of under 50 kWh/m²a; able to ensure a healthy and comfortable environment, with a low level of CO₂ emissions, as a result of passive systems integration collaborated with spatial geometry optimization and a high level of thermal insulation.

7. References

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