A parametric approach to design a wooden climatic responsive village in Atacama Desert (Chile)

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Abstract

The typical architecture of countries in a hot arid climate is a valuable source of principles that today we call bioclimatic and sustainable. Ancient people knew very well how to avoid the harshness of the desert and their knowledge came from centuries of experience and attempts. Among these principles, we can remember the typical narrow winding alleys, the courtyard houses, the domes and the large thermal mass of the walls. It was decided to combine this knowledge with computer techniques to try to parameterize these aspects in order to optimize and make them as effective as possible, allowing us to add something to what had been handed down. The project was born from a practical need, creating new settlements in places far from civilization, but close to important human activities. The first aim of the project is to design self-sufficient houses, using the sustainable desert principles, and the second aim is to use the concept of folding architecture to build a village as soon as possible. From an energetic point of view, the patio has a crucial role to enhance the inner environment: producing shade, it supports natural ventilation. Starting from a "zero organism", through generative algorithms made in *Rhino/Grasshopper*, this effect is optimized by maximizing the area of the shadow produced by the roof inside the patio, during the hottest hours. By classifying the various organisms obtained, through structural (i.e.: length, compressive stress) and energetic parameters (i.e.: radiation analysis, cooling loads), a ranking open to various solutions has come out.

1. Introduction

The research described in this paper explores the potential of using digital technologies in architecture, particularly for developing more sustainable buildings. The argument is that technology, in general, and computation in particular, allows architecture to respond to geographical and individual requirements. The use of technology to develop responsive and customized buildings represents a change and an opportunity for a more ecological approach. A clear understanding of the main problems and site surrounding conditions, which influence building design, increases the possibility of adopting environmentally friendly strategies in the early stages of design, even before a building form exists. Meaningful data visualization can assist designers in making better design judgments. The proposed houses system uses digital tools to find a solution that could adapt to different locations and weather conditions. In particular, this project was born from a practical need (Mattoccia, 2014): creating new settlements in places far from civilization but at the same time close to important human activities, as a mining activity in Atacama Desert could be. The first aim of the project is to design Self-Sufficient Houses, able to create a comfortable environment in this extreme climate, using the desert sustainable principles (see Sec.1.3). At first, we solved the problem to build the village as quickly as possible using the concept of Folding Architecture (see Sec. 2.1). Then, to reproduce the traditional urban fabric of a desert city, characterized by a natural growing, we used the idea of Cellular Automata (see Sec. 2.2). All these concepts converge in Desert Architecture as shown in Fig. 1. The settlement is characterized by a folding base module that can be aggregated in an independent way. The research is based on the optimization and the design of this module.

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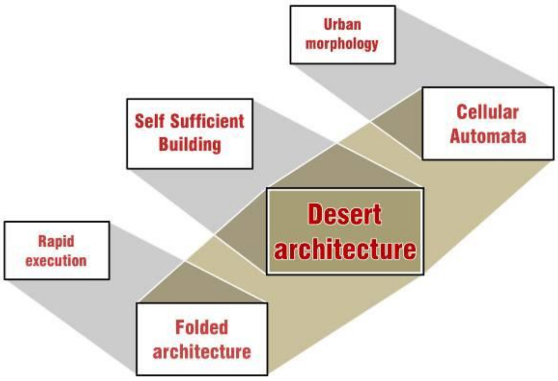

Fig. 1 – Desert Architecture: scheme of design aims.

1.1 Parametric Architecture

Coding in architectural design can be understood as representation of algorithmic processes that express architectural concepts or solve architectural problems, as generative tools for the shape design which follows well-defined criteria, such as sun, wind, environment or other considerations. To apply computational methods, first of all we have to translate the thought process into a computer program by a programming language. In a Textual Programming Language (TPL), the codes are linear sequences of characters, while, in a Visual Programming Language (VPL), the codes consist of iconic elements that can be interactively manipulated according to some spatial grammar. *Grasshopper*, a plug-in of *Rhinoceros*, is a VPL; it increases a large set of primitive components, mathematical functions and modifiers, allowing an effective reduction in the implementation effort and a significant advantage in working in visual scheme.

In a parametric model, the schema is the collection of relationships between functions and parameters, where the form is a function of the latter. The connections allow dataflow from primitive to primitive, until it reaches the end of the graph that creates geometric models.

While algorithms assist the examination of complex strategies, human reasoning still governs the selection of appropriate input parameters to take in consideration. Choices are born from human capacity, so the real advantage of a parametric approach is the rapidity with which it can carry out certain operations, such as optimization, which would have been impossible to develop by hand. The role of the architect is crucial, both from a technical point of view, for instance by setting the range of the input, and for the design strategy, choosing the most effective one.

1.2 Climate

The climate of the Atacama Desert is characterized by wide daily thermal fluctuations, with a high temperature difference between night and day. In summer, daily temperatures range from under 14 °C to over 32 °C, and in winter from 0 °C to 22 °C, with an average temperature difference of 20 °C during the year. These conditions are accompanied by low daytime relative humidity, intense solar radiation (Fig. 2) and strong hot dusty winds, predominantly from the south-east. During the year, there is very little rainfall, which causes a very low vegetation cover and limited water supplies.

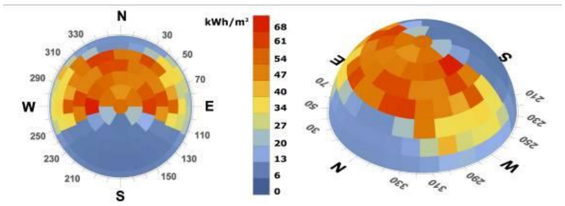

Fig. 2 – Solar radiation analysis: Sky Dome *(Grasshopper, Ladybug)*.

1.3 Desert architecture

Nowadays to obtain a comfortable environment we consume a lot of energy to heat or cool buildings. In a more or less remote past, when energy was not so easily available, architects had to resort to other, often clever systems to provide maximum comfort to the indoor environment. Briefly, Desert Architectural principles of hot arid climate are the following (Maleki, 2011): Town planning, Courtyard house, Dome and Thermal inertia.

Town planning. An important strategy against the extreme climate is the agglomeration of the buildings, which limits the total surface exposed to solar radiation, reducing therefore also the heat absorption overall, and diminishing the penetration of dusty wind within the village. The urban form of a traditional city is highly centralized and inward looking, with a continuous pattern of courtyard houses (Fig. 3a). density (Fig. 3d).

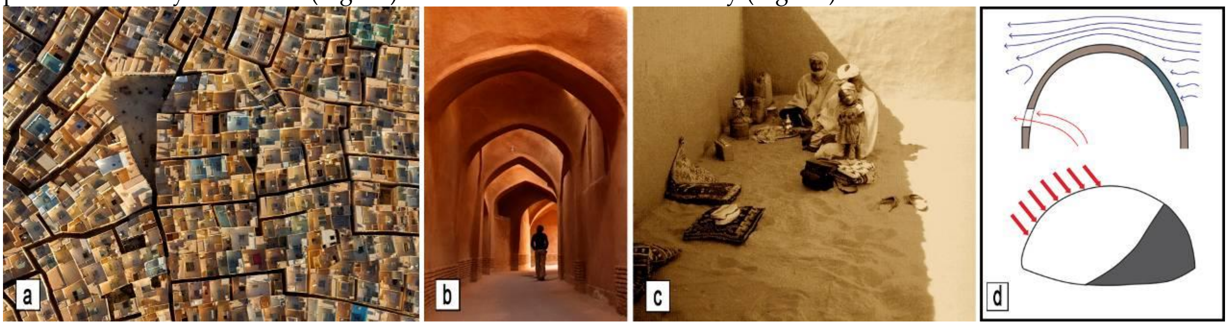

Fig. 3 – Desert Architecture: a) A typical desert pattern; b) Covered alleys; c) The shadow casts by a courtyard; d) The dome's advantages.

Each building is joined together by common walls and connected by a very diffuse network of narrow alleys (Fig. 3b) departing from the main road system. The directions of this pattern are conceived to avoid wind and to produce as much shade as possible.

Courtyard house. This shape is a microclimate modifier, which may improve thermal comfort conditions in the inner enclosed space. The building shades the courtyard (Fig. 3c) and the streets as well; this shading effect lowers the overall cooling load (Scudo, 1988). A well-designed courtyard house is cool during the day, when ambient temperature is high and warm at night when it is low. During the night, the cool air is stored until the mid-hours of the next day, and during the day the courtyard acts as an air shaft: cool air begins to rise and also leaks out of the surrounding rooms. It is a simple design strategy for bringing both air-movement and natural light into the entire house.

The dome. The roof is the most critical component of the whole building: it receives the greatest amount of solar radiation during the day, and emits the greatest quantity of heat by night radiation to the sky. The dome, compared with equivalent flat covers, ensures thermal performance considerably more effective. A dome has a greater area of assignment of heat by convection and transfers heat more efficiently than a flat roof. Furthermore, when the dome is exposed to not zenith sunlight, it always has a part in the shade and a part in the sunlight. This means that there should be a difference of temperature between the two parts and a corresponding movement of air, due to the difference in air

Thermal inertia. When outdoor conditions are very extreme, the system has to resist thermal gains, minimizing hot air infiltration, solar radiation and heat conduction. Thick walls of brick or stone have been traditionally used in construction of buildings. These walls perform the dual function of isolating the internal environment from outside and of storing the absorbed heat during the day. Thus, heat flow from outside to inside is delayed, while in the cooler hours the heat, stored in the walls, partially heats the indoor environment. The consequence is a leveling of the curve of the temperature changes inside the building.

2. Simulation

2.1 Tectonic system

The necessity of having a foldable structure arises from the need to build our houses as quickly as possible given the extreme climate in which our project takes place. One answer to this problem is given by *origami*. An origami form is constituted by patterns that are the repetition of similar geometric shapes, which will form a deployable surface: this means it is possible to fold this pattern to a compact-package state. We have chosen the famous "Miura pattern" (Fig. 4) to design the complete structure that arrives folded on site and that can easily be opened. This pattern can be obtained by a repetition of reverse folds in lines producing symmetric trapezoids that form a herringbone tessellation, in which, in each corner, we have 3 mountains and 1 valley or 1 mountain and 3 valleys. The folded pattern has a characteristic *zigzag* corrugation that allows extending and retracting in both directions. As you can see in Fig. 4, we have chosen this pattern inspired by the use of the dome in the desert whose purpose is to always have a shady and a light area that allow convective motions within the building. The Miura pattern works in the same way, for each little module, red in Fig 4.

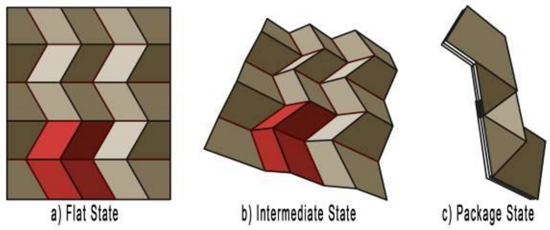

Fig. 4 – Miura Pattern, in red a single module: a) Flat State, b) Intermediate State, c) Compact-Package State.

For the optimization, we need something that can assume all possible shapes, not necessarily regular and symmetric, demanded by the environment. To generalize the Miura pattern, we used the relationships presented by Tachi (Tachi, 2009). A vertex (Fig. 5) with 4 fold lines, and thus with 4 sector angles θ_i (i=0,1,2,3), produces a one degree of freedom mechanism.

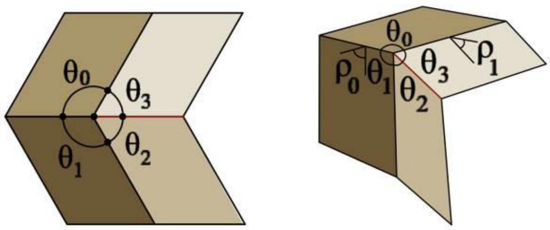

Fig. 5 – The relation between angles.

To obtain a flat-foldable and developable surface, these angles have to respond to the following conditions:

$$\sum_{i=0}^{3} \vartheta_i = 2\pi \qquad (1)$$

$$\sum_{i=0}^{3} (-1)^i \vartheta_i = 0 \qquad (2)$$

Thus the sector angles satisfy the equations:

$$\vartheta_0 = \pi - \vartheta_2 \qquad (3)$$

$$\vartheta_1 = \pi - \vartheta_3 \qquad (4)$$

The fold angles ρ_i and ρ_j incident to the vertex are related as follows (Tachi, 2009):

$$\tan\left(\frac{\rho_i}{2}\right) = \begin{cases} A_{i,j}\tan\left(\frac{\rho_j}{2}\right) & (i-j=1 or 3) \\ \pm\tan\left(\frac{\rho_j}{2}\right) & (i-j=2) \end{cases} \qquad (5)$$

where the latter represents that pairs of opposite fold lines having an equal absolute folding angles. $A_{i,j}$ is a coefficient between these two equivalent pairs determined by θ_0 ...θ_3 for instance intrinsic measure in the crease pattern independent from the folding angles. If $|\rho_0|=|\rho_2|>|\rho_1|=|\rho_3|$, we obtained (Tachi 2009):

$$|A_{0,1}| = \sqrt{\frac{1+\cos(\vartheta_0-\vartheta_1)}{1+\cos(\vartheta_0+\vartheta_1)}} \qquad (6)$$

Now we have something that can communicate with the genetic solver that will work on the angles θ_i and ρ_i (in) to obtain an optimized surface (out).
Moreover, with this system, from a structural point of view, we can use the modern technology X-Lam, a panel made of different wood crossed fiber layers with excellent mechanical and thermo-hygrometric properties (Buri and Weinand, 2010).

2.2 Cellular Automata

Desert agglomerations are villages that grow spontaneously and without a plan, imposed by the administration. Cellular Automata (CA) gives a very realistic prediction of urban structural evolution, and in particular, it is able to replicate the various fractal dimensionalities and self-organizing structures of a desert cities pattern.
A CA may be defined as a discrete Cell Space, with a set of possible Cell States and a set of Transition Rules that determine the state as a function of the states of all cells within a defined Cell-Space Neighborhood. Time is discrete and all cell states are updated simultaneously at each iteration (White, 1997). From an urban modelling point of view, we have a Cell Space of 3.5x3.5x3 meters for two storeys, using the typical Cell State of computer language, 0 and 1, to represent land use. In bi-dimensional CA, the most used neighborhoods are the Von Neumann (4-cell) and the Moore (8-cell). In one-dimensional CA (here used preliminarily) we studied left and right cells, so we have 256 possible patterns and the cell changes according to the state of its neighborhood in each level. All these

parameters are controlled inside *Rabbit*, a set of components within *Grasshopper*. Using this approach, we can choose the position of patios and loggias in our module, in order to obtain something more spontaneous. In Fig. 6 we show the four steps of how the cells grow and we added a set of random point in which the cells have a default state; but this solution is only one of many possibilities, making every module of the agglomeration unpredictable and different from the next.

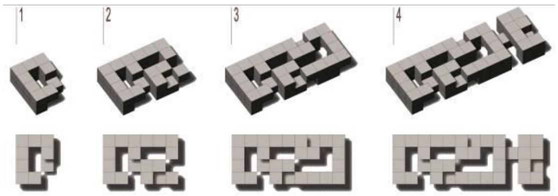

Fig. 6 – The steps of a Cellular Automata generation *(Grasshopper, Rabbit).*

2.3 Generative design algorithm

Now we can start to optimize our "zero organism" for 25 people of two storeys, which is obtained joining the concept of the *origami* and the Cellular Automata (Fig. 7).

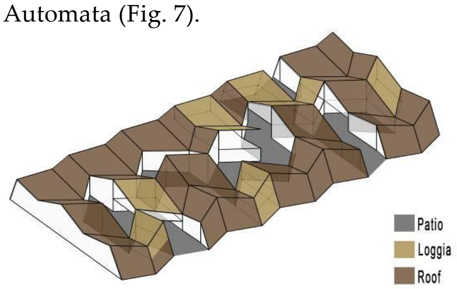

Fig. 7 – Zero organism.

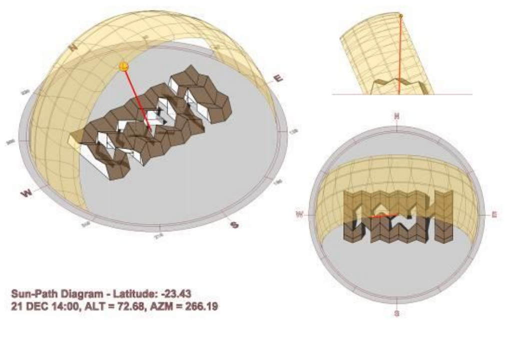

Fig. 8 – Solar path with the worth solar radiation *(Grasshopper-Ladybug).*

Among all the parameters we can optimize, we chose the ventilation. The patios are crucial for the working of internal ventilation, as mentioned in Sec. 1.3. They work with the wind, but in the desert it is hot and dusty, or with a difference of pressure due to different temperatures between the shady and the light parts. Therefore, we decided to optimize the shadow that the roof casts inside the patios in order to have a large area where people can stay and to improve the ventilation during the day reducing the cooling load. Thus we need a specific solar radiation and we considered the worst one during the worst day of the worst month of the year: for the Atacama Desert it is 21 December at 2:00pm (Fig. 8). On this day, the sun is high, so the shade is very small and by optimizing this situation, we are sure to reach a comfortable condition throughout the day. To reach this aim, we selected three criteria (Caruso et al, 2013):

- maximize the shadow cast from the roof;
- minimize the difference between the patio's area and the shade area;
- minimize the ratio between the previous quantities.

To start, we picked an organism facing south and using the first criterion we saw the organism was inclined to open itself independently from the patio's shape. Therefore, we introduced the second criterion using the patio's area, but in this case the body tended to close regardless the shadows produced inside the patio. To balance both the effects we launched the third criteria. To set this process inside *Grasshopper*, we needed to fix the range of all the parameters, in order to get a structure that is possible to build and in which we have living spaces. Both for structural reasons concerning the resistance of the material and for the transportability of the folded structure, all the data ranges are set in order to have shorter lengths than eight meters. The algorithm can change the angles and the length of each panel with the constraint of obtaining a deployable roof at the end, so all the quantities are linked together with the relation explained in Sec. 2.1. To optimize the shape, we used *Galapagos*, which is a genetic and evolutionary solver. It applies the principles of evolution found in nature to the problem of finding an optimal solution. It starts by generating a population of random solutions, evaluating their fitness (objective function), and subsequently applying the basic genetic operators of reproduction, crossover and mutation.

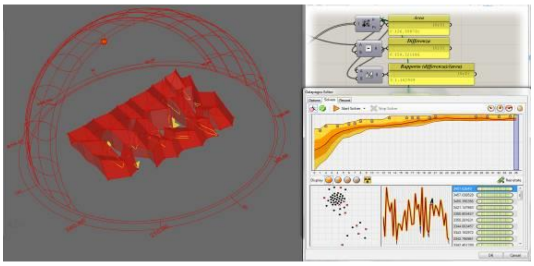

Fig. 9 – A screenshot of Galapagos during the optimization.

This generates a new population with higher average fitness than the previous one, which will in turn be evaluated as shown in Fig. 9.
Summarizing, the input of the algorithm comprises the angles and the length of the *origami*, the output is the shape of the module. The algorithm calculates the shade inside the patios using a specific solar radiation with *Ladybug* (Roudsari et al, 2013), a set of components for environmental analysis, and the genetic solver tries to reach the objective function modifying all the input parameters until the fitness is appropriate.

3. Results, a set of solution

After the simulation, a different population of surfaces was obtained, exactly 25 organisms, because we used different criteria and above all because the genetic solver is not a deterministic process. Each time we ran an optimization, we obtained a different result, with a different shape, even though only in the details, as shown in Fig. 10. This set of solutions is related to the orientation: if we had chosen a different orientation at the beginning, we would have obtained different solutions, one for each direction. After the optimization, we had different types of sections (Fig. 11), because the roof tried to rise as much as possible with various configurations to achieve the most efficient shape.

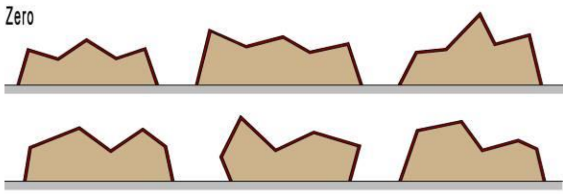

Fig. 11 – Typological sections of the organisms.

Before choosing the best organism, we analyzed the solar radiation of all the organisms in order to decide on the best strategy. We have classified all the elements relying on each criteria: from the best to the worst, we assigned a score based on the standings at each element and at the end we produced a ranking by adding the scores obtained by each organism. Among the criteria in addition to energetic principles (the shade), structural criterion was introduced (the maximum length of each panel) as shown in Table 1. With this ranking, we are open to different solutions depending on the design strategy. For instance, for a hot climate, by analyzing the solar radiation incident on any surface, we can choose the organism with the least amount for having less heat transmitted within the building. If we want to maximize the functioning of the solar panels (DHW productions or electricity generation), we can choose the shape with the best incident solar radiation. In our case, we chose the second strategy, in order to have a self-sufficient building, and the organism has obtained the highest score between solar and structural criteria. In Fig. 12 and in Table 1 we show how improved the shade produced by the roof is and how decreased the area's percentage exposed to direct solar radiation within the courtyards is.

3.1 The building

The plan of the building is completely free because the roof is self-supporting, so we could choose different solutions.

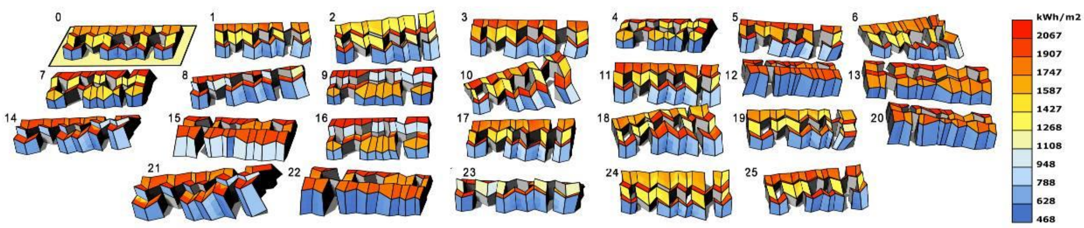

Fig. 10 – A set of solution, different 25 organisms with incident solar radiation values on the envelope (kWh/m^2).

Table 1 – Energetic and structural ranking of the first twenty organisms.

Rank	area shadow (m^2)	%	area patio (m^2)	Difference (m^2)	%	Ratio	%	max length (m)	energy ratings	structural ratings	total ratings	total radiation (kWh/year)
Zero	**60,00**		**167,6**	**107,6**		**1,79**		**5,00**				**1008417**
1	**71,5**	**19,2**	**116,4**	**44,9**	**-58,2**	**0,63**	**-64,9**	**7,50**	**75**	**19**	**94**	**1189514**
2	83,7	39,5	142,2	58,4	-45,6	0,70	-61,0	6,75	65	28	93	1217178
3	80,1	33,5	138,2	58,2	-45,9	0,73	-59,5	7,42	62	22	84	1045507
4	66,1	10,2	112,4	46,2	-56,9	0,70	-60,9	7,85	67	10	77	773916
5	62,7	4,57	115,4	52,7	-51,0	0,84	-53,2	6,95	50	25	75	962300
6	65,1	8,63	107,3	42,1	-60,8	0,65	-63,9	8,45	69	3	72	1013998
7	64,9	8,30	115,2	50,2	-53,3	0,77	-56,9	7,53	56	16	72	1139801
8	67,4	12,4	121,9	54,4	-49,4	0,81	-55,0	7,60	56	14	70	974846
9	90,8	51,3	170,9	80,2	-25,5	0,88	-50,7	7,51	52	18	70	1197409
10	79,4	32,4	161,0	81,5	-24,2	1,03	-42,7	6,94	42	26	68	1023435
11	72,8	21,3	125,4	52,6	-51,1	0,72	-59,6	9,75	66	1	67	1305800
12	87,5	45,9	162,3	74,7	-30,5	0,85	-52,4	6,88	54	11	65	1314111
13	44,0	-26,6	90,6	46,6	-56,7	1,06	-40,9	6,97	37	24	61	922216
14	59,9	-0,12	117,2	57,3	-46,7	0,96	-46,7	7,49	38	20	58	944317
15	62,4	4,08	118,5	56,1	-47,8	0,90	-49,9	7,61	43	13	56	881543
16	60,1	0,10	136,4	76,3	-29,0	1,27	-29,1	7,48	26	21	47	1097412
17	65,1	8,42	136,4	71,3	-33,6	1,10	-38,8	7,88	35	9	44	982568
18	92,8	54,6	198,9	106,1	-1,38	1,14	-36,2	8,76	39	2	41	1097354
19	55,7	-7,13	120,8	65,1	-39,4	1,17	-34,8	7,54	26	15	41	823836
20	77,6	29,3	177,5	99,9	-7,10	1,29	-28,1	7,99	31	8	39	1260171

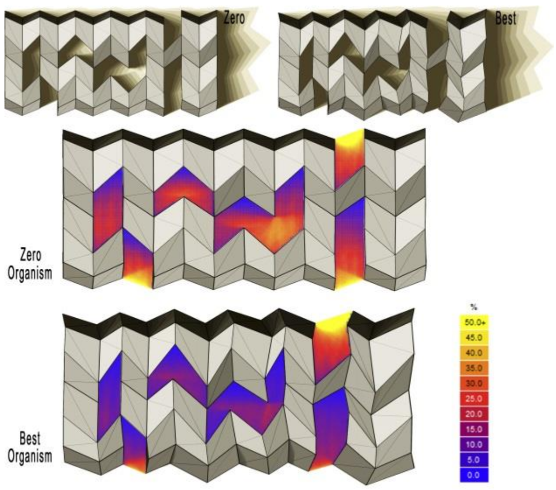

Fig. 12 – Zero and best organism, with the shadow and the percentage exposed (*Ecotect*).

For instance, we can accommodate eight families: we have two flats for two people, four flats for three people and two flats for four people.

The entrances are arranged inside the courtyards, thus a protected road system and a public space are created (Fig. 14a). The second element to be designed is the skin. All the package wall is prefabricated, the stratigraphy consists from inside to outside in (Fig. 15): a X-lam bearing layer of 12 cm, a vapor barrier, an insulating layer of mineral wool of 10 cm, a waterproofing layer and a wooden covering of 3 cm, obtaining 0,25 m thick wall, with a thermal transmittance of 0,25 W/m^2K, a surface mass of 94 kg/m^2, an attenuation factor of 0,15 with a time lag of 12h 37'.We can notice the ratio S/V (S is the external surface, V is the volume) of the zero and optimized building (best organism) is improved, going from 1,14 m^{-1} to 0,93 m^{-1}.

With regard to the interior lighting, we have placed double skin glass facades all around the courtyards, avoiding the outside, to prevent direct solar radiation. Instead, for the cross ventilation, we have placed well protected openings on the outside skin (Fig. 14b). Now having determined the number of people and the characteristics of the skin, we can place the photovoltaic panels. Considering the appliances and the requirements for lighting, we need an average production of electricity equal to 24000 kWh per year, for all the families. We selected the roof panel with the best solar radiation for square meters; to produce the electricity demand stored in a battery, we need the first eighteen roof panels. To keep the logic of constructing our building in the shortest possible time, we took the amorphous silicon panels that allow a fast assembly and a freedom of forms to the detriment of a reduced efficiency equal to 6%.

4. Conclusions

In this paper an evolutionary algorithm is developed in *Grasshopper*, whose main feature is the automatic integration within the energy simulation. The program was employed to obtain a self-sufficient building starting to decrease the thermal loads due to solar radiation and maximizing natural ventilation. After the optimization of the foldable module, we analyzed the building in *Ecotect*, choosing all the internal environment parameters (i.e. air temperature, relative humidity, air change rate).

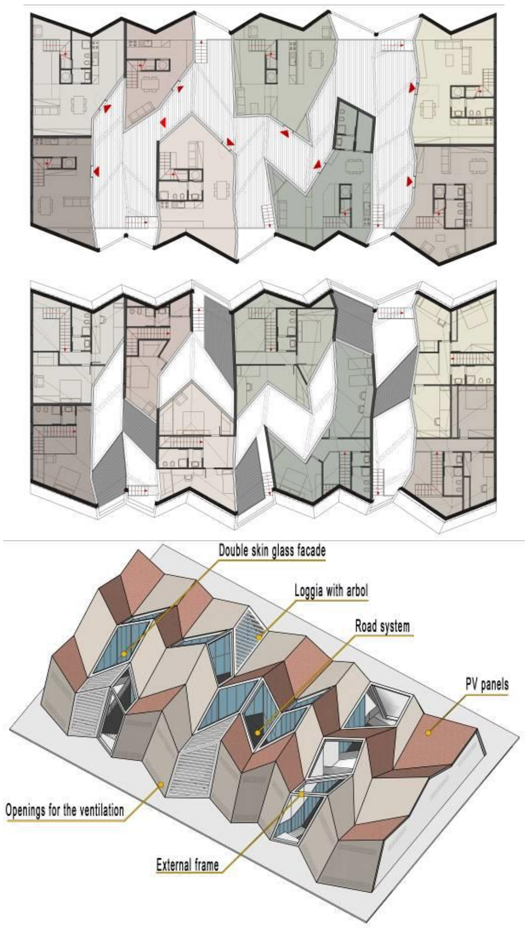

Fig. 14 – (up) Ground floor; (middle) First floor; (down) Axonometric view.

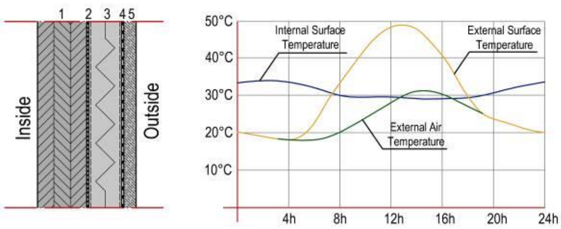

Fig. 15 – Skin stratigraphy (Layer 1: X-Lam, 2: vapor barrier, 3: thermal insulation, 4: waterproofing layer, 5: wooden covering).

Increasing the ratio between the shade and courtyard area of 65% (Table 1), the cooling load decreased by 38% (Table 2). Even though the building has not changed substantially in shape, the advantages are recognizable. The whole study is placed in a specific site and climate, but with the parametric approach, we can change the environmental initial parameters, maintaining the same process, we can achieve the same purpose. The optimization can be a valuable instrument in the early design stages; it provides a high number of solutions to be presented to the decision makers for the ultimate choice.

Table 2 – Cooling load (kWh) during summer (*Ecotect*).

Month	Zero	Winner	%
Jan	3440	2919	15
Feb	3023	1930	36
Mar	2145	622	71
May	124	20	84
Nov	572	274	52
Dec	1340	837	38
Total	**10647**	**6604**	**38**

5. Acknowledgement

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