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ANALYSIS OF EVOLUTIONARY MORPHOLOGIES WITH CFD: IMPROVING NATURAL VENTILATION IN CENTRAL COURTYARD HOUSING, IN SEMI-WARM AREAS OF LATIN AMERICA

ANÁLISIS DE MORFOLOGÍAS EVOLUTIVAS CON CFD: MEJORAR LA VENTILACIÓN NATURAL EN VIVIENDA DE PATIO CENTRAL, EN ZONAS SEMI CÁLIDAS DE LATINOAMÉRICA

ANÁLISE DE MORFOLOGIAS EVOLUTIVAS COM CFD: MELHORIA DA VENTILAÇÃO NATURAL EM HABITAÇÕES DE PÁTIO CENTRAL EM ÁREAS SEMI-QUENTES DA AMÉRICA LATINA

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RESUMEN

Este estudio busca reducir la demanda energética en la arquitectura mediante el uso de estrategias pasivas, específicamente enfocadas en la ventilación natural interior. Se realizaron simulaciones computacionales (CFD: Computational Fluid Dynamics) y se utilizó algoritmos paramétricos en Grasshopper, en que se aplicó una metodología basada en el diseño evolutivo. El objetivo es optimizar el diseño de viviendas unifamiliares de patio central con ventilación cruzada, al evaluar cómo la morfología de las viviendas influye en su desempeño en términos de ventilación natural. A través de procesos de morfogénesis y diseño evolutivo; se generaron más de 200 variaciones morfológicas (muestras), cuyos resultados permitieron seleccionar los modelos con mejor desempeño. Los genes más exitosos se combinaron en nuevas generaciones para repetir las evaluaciones, lográndose finalmente un modelo de vivienda que optimiza la ventilación hasta 2.5 veces más que el modelo tradicional de casa con patio central.

Palabras clave
diseño evolutivo, ventilación natural, arquitectura sustentable, CFD en vivienda de patio central.

ABSTRACT

This study aims at reducing energy demand in architecture through passive strategies, specifically focusing on natural indoor ventilation. Computational simulations (CFD: Computational Fluid Dynamics) were conducted, and parametric algorithms in Grasshopper were employed, applying a methodology based on evolutionary design. The aim is to optimize the design of single-family courtyard houses with cross-ventilation by evaluating how their morphology influences their performance in terms of natural ventilation. Through morphogenesis processes and evolutionary design, more than 200 morphological variations (samples) were generated, whose results allowed the selection of the best-performing models. The most successful genes were combined in new generations to repeat the evaluations, ultimately achieving a housing model that optimizes ventilation up to 2.5 times more than the traditional courtyard house model.

Keywords
evolutionary design, natural ventilation, sustainable architecture, CFD in courtyard housing.

RESUMO

Este estudo tem por objetivo reduzir a demanda de energia na arquitetura por meio do uso de estratégias passivas, com foco específico na ventilação natural interna. Foram utilizados a Dinâmica de Fluidos Computacional (CFD) e algoritmos paramétricos no Grasshopper, nos quais foi aplicada uma metodologia baseada em design evolutivo. O objetivo é otimizar o projeto de residências unifamiliares com pátio central e ventilação cruzada, avaliando como a morfologia das residências influencia seu desempenho em termos de ventilação natural. Por meio de processos de morfogênese e design evolutivo, foram geradas mais de 200 variações morfológicas (amostras), cujos resultados permitiram a seleção dos modelos de melhor desempenho. Os genes mais bem-sucedidos foram combinados em novas gerações para repetir as avaliações e, por fim, chegou-se a um modelo de habitação que otimiza a ventilação até 2,5 vezes mais do que o modelo tradicional de casa com pátio central.

Palavras-chave:
design evolutivo, ventilação natural, arquitetura sustentável, CFD em habitação com pátio central

INTRODUCTION

In the field of architectural analysis, according to computational simulations, the use of digital tools based on computational fluid dynamics (CFD) has enabled significant progress in design, particularly in improving natural ventilation. This analysis, which focuses on contributing to biophilic architecture (Zhong et al., 2021), is based on the design strategy of: 'the built environment morphology where it directly influences the airflow dynamics, affecting the natural ventilation distribution and the speed of currents within the space' (ASCE. 2023a, p. 107); improving the comfort conditions (El Ahmar et al., 2019), while reducing energy demand. This analysis focuses on optimizing the central courtyard housing typology with parametric methods, according to Bensalem (1996):

> The few studies on courtyards indicate that, with large sizes, a part of the air current could penetrate the empty space, raising the pressure on the courtyard's rear wall. This could increase the cross ventilation in the leeward walls. This effect was less evident in smaller courtyards (pg. 74).

Wind pressure is the ventilation mechanism that primarily affects central courtyard housing. When the wind hits a building, it creates a distribution of static pressures on the outside surface that depend on the wind direction, speed, density, orientation of the surface, surrounding conditions, and the shape of the building (ASHRAE, 2009).

The main problem is that design methods do not always optimally consider how morphological variations affect the airflow behavior inside. Consequently, approaches that integrate evolutionary methods and parametric simulations are needed to develop architectural typologies, such as housing, that maximize wind use. The objective is to start from the central courtyard house and create geometric layouts that improve natural ventilation and reduce energy demand.

STATE-OF-THE-ART

In the research of Albel Tablada de la Torre et al. (2005), where CFD is used to study 3-floor central courtyard homes, they realized that performance is optimized when ventilation is not unilateral but crossed. Similarly, the importance of having more central courtyards was also studied. It was also determined that the rooms on the upper floor of the narrow courtyard (Figure 1) have higher air velocities than the upper floors of the wider courtyard; 'since they capture most of the airflow entering the courtyard cavity, causing the rooms on the lower floors to have much lower air velocities' (Tablada de la Torre et al., 2005, p. 3)

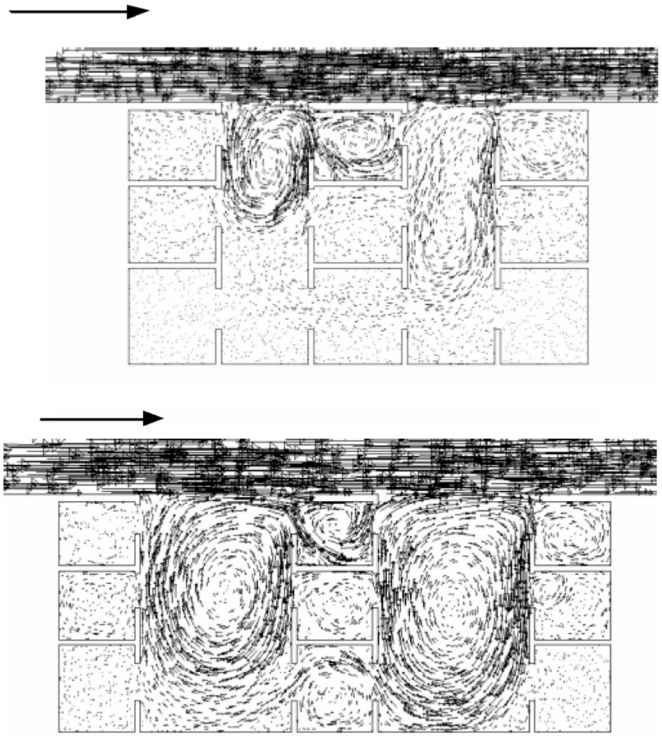

Figure 1. Airflow inside two interior courtyards and rooms with open windows. Source: Image taken from Tablada de la Torre et al. (2005)

In the investigation of Malawi. et al. (2005), a model based on genetic algorithms for the evolution of the design, using dynamic CFD to evaluate the model's performance, which generates the possibility of creating models that improve natural ventilation and previewing the results (Zheng et al., 2020), is presented. They analyze and evaluate the cross-ventilation capacity of a low-rise building with blinds to create shade, also known as louvers. Based on the coupled airflow model (similar to wind flow), the model couples indoor and outdoor airflow to perform a cross-ventilation evaluation. The greatest reduction in the ventilation rate used by louvers was up to 66.6%.

On the other hand, Rodrigues Marques Sakiyama et al. (2021) presented a CFD analysis of indoor ventilation using the wind tunnel process. They concluded that the building's orientation determines the quality of natural indoor ventilation.

Wind tower studies are also considered in this state-of-the-art as they are traditional architectural solutions that share the goal of improving natural ventilation; in addition to the hygrothermal quality, evaporative wind towers not only increase the amount of fresh air but also increase the relative humidity of the air, which generates greater thermal comfort. This happens due to the Stack Pressure ventilation mechanism, caused by the mass of an air column inside or outside a building. It can also occur inside a flow element, such as a duct or a chimney. (ASHRAE, 2009)

METHODOLOGY

A methodology based on parametric and CFD simulation was followed, integrating the following steps:

a. Base model (common ancestor): This is based on an initial central courtyard housing model, which acts as a common ancestor.
b. Morphological transformations: An algorithmic methodology is used in Grasshopper (Echeverri Montes, 2021), applying a series of transformations inspired by the Theory of Transformations to the base model's morphology.
c. CFD simulations: Each generated typology is evaluated using CFD simulations, which aim to analyze the natural ventilation behavior in each transformation.
d. Selection and crossing of genes: The 'winning' samples or best-performing ones are identified, and the areas of the house with the highest ventilation flows are recognized. These are combined with other winning samples.
e. Final selection: This second generation of samples is evaluated, and we obtain the one with the best performance (fitness[1]).
f. Analysis of window height: The best-fit wind behavior is analyzed using the results achieved regarding window heights (outlet), sill height, and lintel.
g. Comparison with the common ancestor: The air intake inclination angle in the central courtyard is compared between the two results.

THEORY OF TRANSFORMATIONS

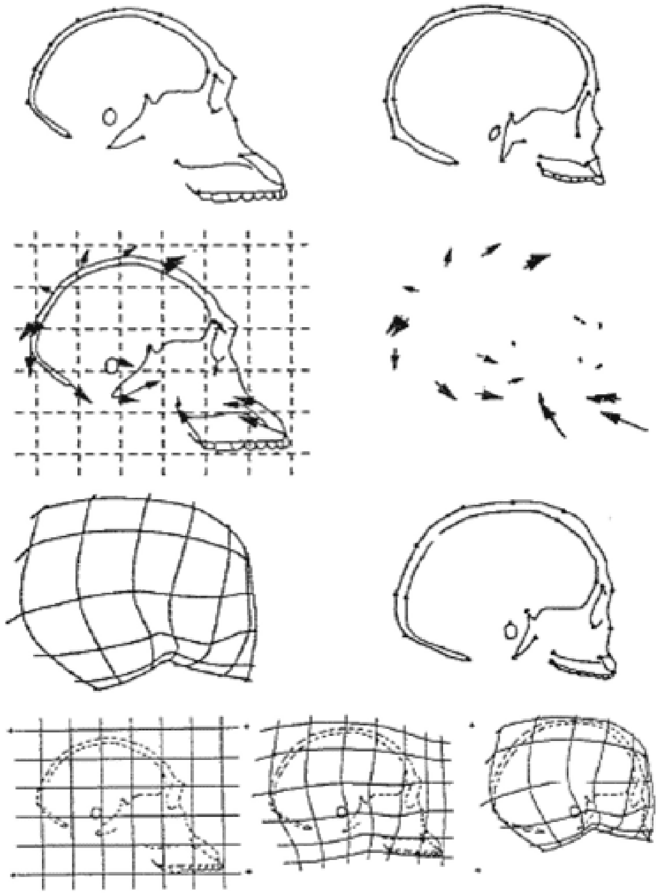

Figure 2. Theory of Transformations. Source: Image taken from Werritty (2010).

This is a morphogenesis proposal conceived by D'Arcy Thompson (1917, as cited in Werritty 2010), which examines, especially from a geometric perspective, the different types of formal transformations that could have a biological and physicochemical significance related to evolution (Figure 2) (Iurato & Igamberdiev, 2020). The homologous points and the outlines indicated are shown in the first row. The movements needed to bring the homologous points from the first image to the second are represented in the second row. Finally, the two ends of the transformation are presented in the bottom row (Werritty, 2010).

EVOLUTIONARY DESIGN

Darwin's preferred term for evolution is "descent with modification." Genetic information is transmitted by DNA between generations in most organisms (Whitlock, 2014). Usually, the population starts randomly, i.e., with randomly selected elements considered potentially useful in the given environment. Then, the fitness of each solution is evaluated, which involves a measurement or calculation to determine the relative effectiveness of each one. The results of this evaluation are used

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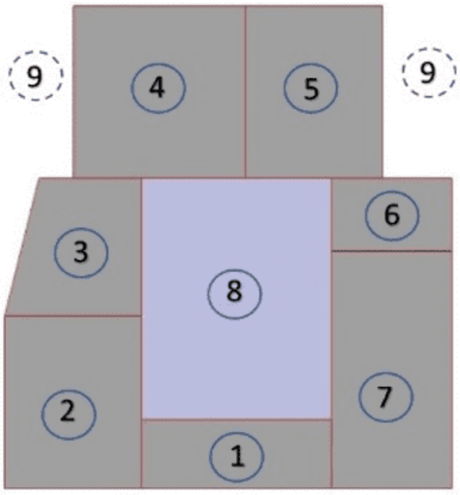
[1] Fitness involves the ability of organisms to survive and reproduce in the environment they are in. The consequence of this survival and reproduction is that organisms contribute genes to the next generation (Allen, 2009).



SIMBOLOGÍA

1. Vestíbulo
2. Cocina-desayunador
3. Comedor
4. Recámara
5. Recámara
6. Oficina
7. Sala, estar
8. Patio central
9. Baños de las recámaras

Figure 3. Design of the common ancestor. Areas 9 (bathrooms) are excluded from the analysis. Source: Preparation by the authors.

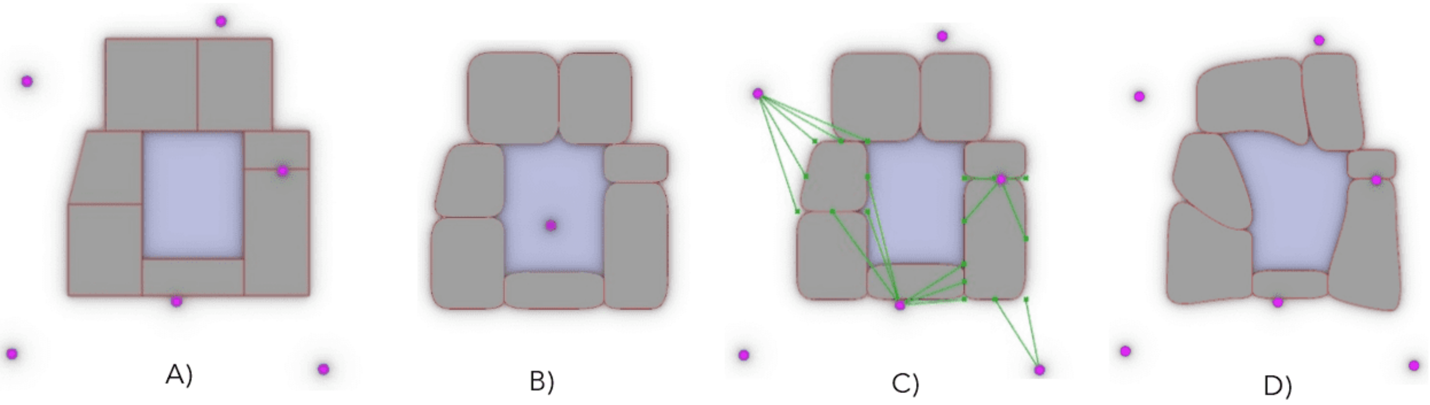


Figure 4. Transition. Source: Preparation by the authors.

at the selection stage to decide which individual solutions will continue in the competition for resources. (Banzhaf, 2013). Variations can occur due to mutation, duplication, or crossing of genes, among other reasons. According to Banzhaf, the main components of evolutionary design to create generation-by-generation sampling are as follows:

- Evaluation: As a process, adaptation describes the part of evolutionary change in a trait driven by natural selection. As a state, this refers to "adaptation features" (Futuyma, 2017).
- Reproduction: The multiplicity of species implies that evolution branches into different population lineages over time.
- Variation: In reproduction, there must be variability among descendants so that natural selection can operate effectively.
- Selection: This determines which species have the best qualities for reproduction.

RESULTS

Next, a series of steps are presented for modeling this analysis's algorithmic, evolutionary, and CFD simulation processes.

STEP 1: BASE MODEL

The common ancestor (Figure 3) on which the future morphological transformations are going to be carried out was designed based on historical architectural typologies of central courtyard housing, such as the traditional Mozabite housing (Algeria) (Zamani et al., 2012) and the Kahkeshan house, in the city of Isfahan (Iran), along with the premise that the central courtyard is directly alongside all areas of the house, the social areas are accessed through a hall, while the private areas are

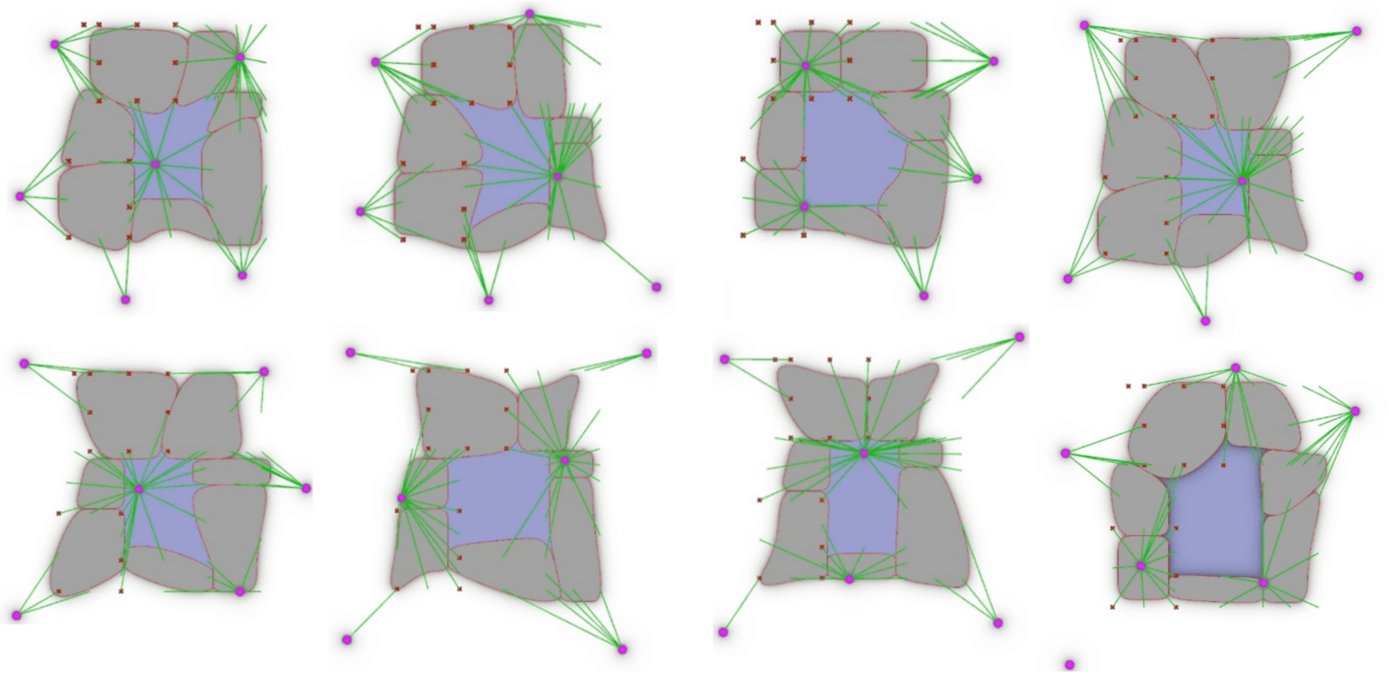


Figure 5. Some samples obtained. Source: Preparation by the authors.

at the end of the hallway. An algorithm is developed in Grasshopper that creates variations of this common ancestor; each variation is considered a sample. The algorithm must have particular parametric conditions so that each transformation's results always give a single closed surface area without lines, surfaces, or vertices crossing. In addition, all these samples have a very similar total area.

STEP 2: MORPHOLOGICAL TRANSFORMATIONS

Inspired by the theory of transformations, the vertices of each house area (kitchen, bedroom, etc.) are stretched towards the points represented with violet spheres (Figure 4). These are placed in ranges of randomness in space. The random points stretch the vertices that are closer to them. This direction's force (magnitude) is related to the distance from these points.

This begins by first converting the square areas by rounding the corners (Figure 4 B). For explanatory purposes, Figure 4(C) only measures the random points of the dining room, living room, and hall areas. The models are made from all the areas. The samples obtained are shown in Figure 5.

Similarly, to comply with an orderly and logical structuring of each house model, the partial selection of the curves alongside the central courtyard is contemplated. This is in order to select one part as a window and another as a column-type structuring element (these rules will be implemented by the algorithm based on the contour derivative of each geometry, which contemplates the alternation between contiguous figures, where the smaller curves obtained from the derivation are considered as columns) (Figure 6). In this way, the edge surfaces or boundaries are also determined, which is essential data for the calculation by CFD (Figure 8).

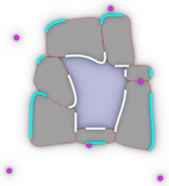


Figure 6. Structural alternation. Vertex control points in violet. Air outlet openings in light blue. Entrance openings in white. Source: Preparation by the authors.

STEP 3: CFD SIMULATIONS

The study's primary tool is Grasshopper, where the evolutionary algorithm and selection process are made. The natural ventilation simulation is done similarly using Butterfly. The latter is a Python plugin and library for creating and running advanced CFD simulations using OpenFOAM[2] (Ladybug Tools [LLC], 2022). CFD involves solving coupled partial differential equations, which must be solved successively. It can be used to solve fluid flow, heat transfer, chemical reactions, and even thermal stress problems. The main equations remain constant for all indoor airflow and heat transfer applications. However, the boundary conditions change depending on the specific problem: for example, the room layout or the supply air velocity may vary (ASHRAE, 2009).

The type of simulation used in this experiment is called "Inlet-Outlet," which simulates the flow of air driven by the wind indoors to evaluate the effectiveness of ventilation. It is the most suitable method, unlike the wind tunnel (urban-type study) and HVAC[3], among others. These calculations take grasshopper geometric surfaces as edge boundaries to distinguish the three indispensable values for this simulation: 1. Inlet: natural air inlet. 2. Outlet: natural air outlet. 3. Walls: boundary, contour, or, in this case, the house's morphology limits. The inlet is the surface representing the central courtyard at the house's highest point (Figure 8).

Since all geographical areas have different values for air velocity, temperature, and inclination due to topography, the density of buildings, vegetation, etc. (ASCE, 2023d), this process must be carried out according to the meteorological information of the geographical area where it is they are located (Figure 9). Due to these factors, the results can vary up to 200 m/s.

The inlet air velocity values are considered in randomness ranges from 0.2 to 0.8 at m/s—perception values of "calm" ventilation (Soler & Palau, 2022). In addition, there are small negative values vertically or on the z-axis of 10 degrees: this is a common practice in analyzing wind dynamics in urban environments. Although a wind tunnel was not used, the logic of applying variations at small angles is consistent with standards such as those mentioned in (ASCE, 2023c, p. 25), which recommends testing wind directions in increments of 10 degrees of azimuth, an approach designed to capture significant airflow responses.

The inlet temperature is set randomly between 22 and 35° C because it is the temperature at which it is considered that this house-room model can have the most benefit and scope to mitigate the sensation of heat without using mechanical means. The 'Wall' component defines the edge or contour limits of the entire house. The temperature for this is between 15 and 30° C, although simulations were repeated at 40° C that report few differences because it is a central courtyard housing model. The remaining parameters of this component come by default from the software; these include a non-slip condition and zero pressure gradient in the direction perpendicular to the wall, among others (OpenFOAM, 2019). The air velocity and direction generate the pressure in this type of analysis, so the pressure value is set at 0, which indicates that the pressure values start from this value.

Different sources of information, such as Wolf Dynamics (2018), were used to adapt the SnappyHexMesh[4] (SPM) component to an architecture with curved shapes. Contrary to how the 'snap' input is preset, it must be disabled. The 'additional parameter' input must be set at the lowest possible integer: 1; the lower this number, the better the component adheres to curved surfaces.

The results obtained in the simulations are the indoor ventilation flow diagram (horizontal analysis x, z) and a pressure diagram. The first consists of a field of vectors (total V) containing (N) number of cells with one vector each: each vector has direction and magnitude (or force), which represents the wind speed and direction in m/s. Each variation obtained in the evolutionary process is subjected to these tests. The magnitudes are added and divided by N to obtain an average wind speed inside the house (V interior) (Equation 1):

$$Vinterior = \frac{1}{N}\sum_{i=1}^{N} \| Vi \|.$$

(Equation 1)

Vectors with SPM cells equal to or less than $0.5m^2$ are discarded since they are empty and do not contain magnitude. In many cases, N reduces its value considerably, resulting in effective N.

ANALYSIS OF THE COMMON ANCESTOR - CFD SIMULATIONS

The first evaluation: the common ancestor (Figure 7), obtains an interior speed of 0.8367 m/s. Total V = 410 m/s. N = 490. The morphological transformations explained in Step 1 occur in the second generation of

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[2] OpenFOAM is an open-source software used for computational fluid dynamics (CFD) simulations.

[3] HVAC, or Heating, Ventilation, and Air Conditioning is a system that mechanically provides heating and cooling in residential and commercial buildings.

[4] Specifically designed to generate high-quality dominant Hexa meshes for complex geometries (Wolf Dynamics, 2018).

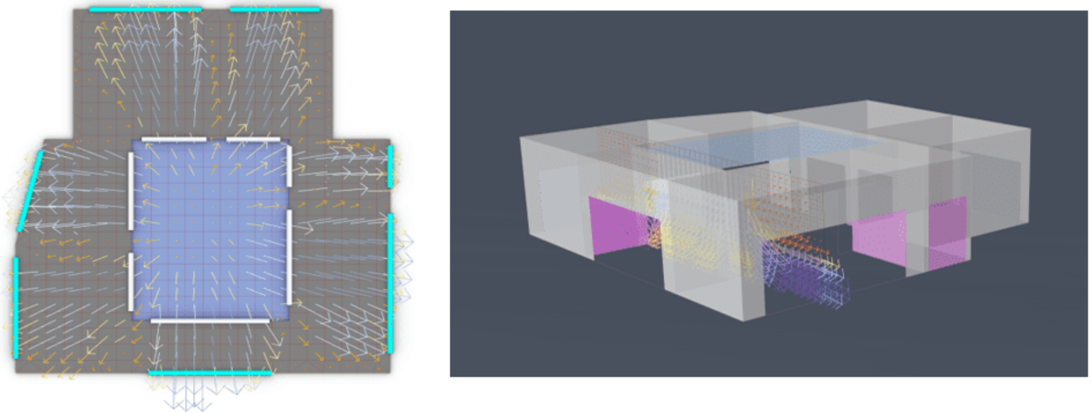

Figure 7. Simulation of the common ancestor Source: Preparation by the Authors.

Figure 8. Input data for the simulation. Source: Preparation by the authors.

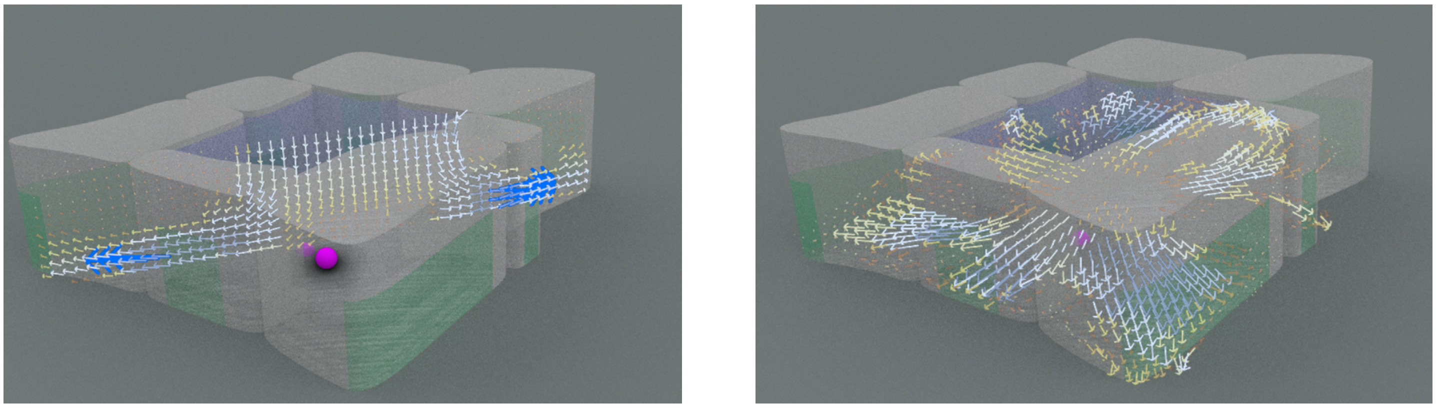

Figure 9. Analysis of the models. A) Vertical analysis: with x-coordinates. B) Horizontal analysis: x, z. Source: Preparation by the authors.

models, resulting in 75 different models being evaluated. In Figure 8, the inlet surface is blue, the outlet surface is turquoise, the normal surface is green, and the walls are white. Figure 7 (B): Snappy Hex Mesh (SHM) grid.

STEP 4: SELECTION AND CROSSING OF GENES

The higher magnitude vectors are extracted from the analysis. The random points that determine these vectors must be found to do this (Figure 9). These are the ones that are combined with those of another champion species to define the reproduction, variation, and general morphology of the third-generation models. Figure 10 shows how only 3 random points are selected from the original 6 to 8. In this way, only the most powerful genes will be detected, and new points will be added randomly

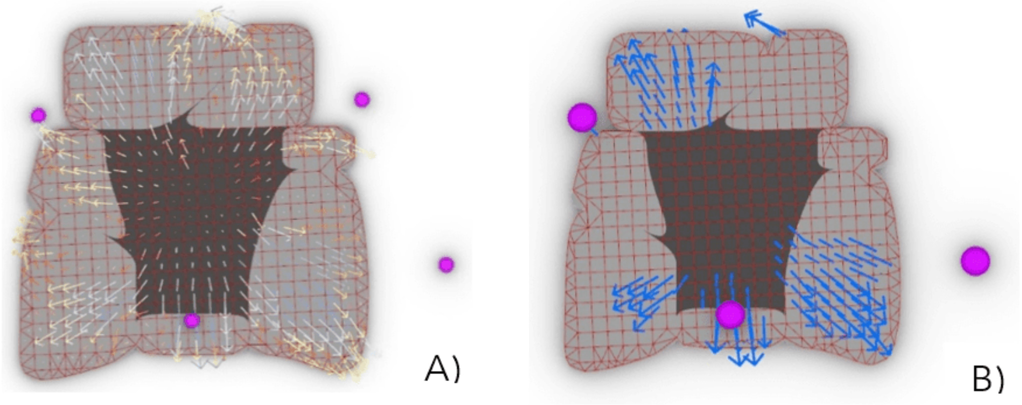

Figure 10. The process of combining winning genes. The blue color vectors (B) have a higher magnitude. Source: Preparation by the author.

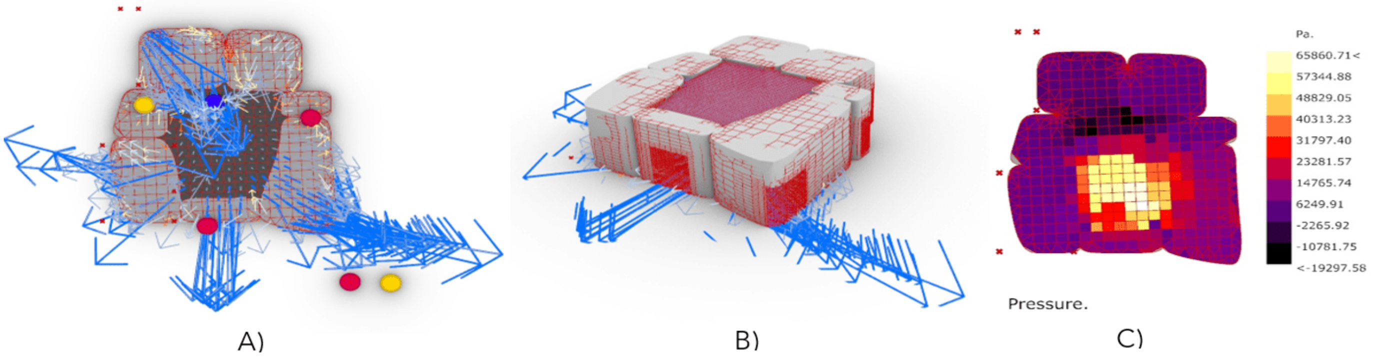

Figure 11. Winning model 09 of the third generation. Increased visualization of the vectors. Source: Preparation by the authors.

Table 1. Window height analysis of second-generation model 09. Source: Preparation by the authors.

Sim.	Type of simulation	Horizontal analysis H (m)	Sum. Total (m/s)	Interior V (m/s)	Window H (m)	Lintel H (m)	Sill H (m)
A	Vertical		925.3	1.7	0.5	2.3	1.2
B	Vertical		1398.7	2.6	0.8	2.0	1.2
C	Vertical		1471.2	2.7	1.4	0.6	2.0
D	Vertical		1474.5	2.7	2.3	0.6	1.1
E	Vertical		1439	2.7	2.3	1.6	0.1
F	Horizontal	3.2	1557.4		0.8	0.8	2.4
G	Horizontal	0.1	1620.2		0.8	0.8	2.4
H	Horizontal	0.1	1760.6		2.3	0.1	1.6

to enrich the obtained models' variation.

STEP 5: FINAL SELECTION

The model with the best fitness is model 09 of the third generation, having a Vtotal= 1,760.62 m/s. N=855v, observed in Figure 11; blue spheres are random points of the champion model of a previous generation, pink points of another champion model, and blue points that represent new possibilities for this latest generation.

STEP 6: WINDOW HEIGHT ANALYSIS (OUTLET)

Vertical (x, z) and horizontal (x, y) analyses are carried out on the two models with the best fitness regarding natural ventilation performance in terms of window height (outlet) and height variations in sill and lintel (Figure 11). The best performance is obtained when the window is located at floor level with heights of 1.4 to 2.3 meters and the lowest from below 0.80 m.

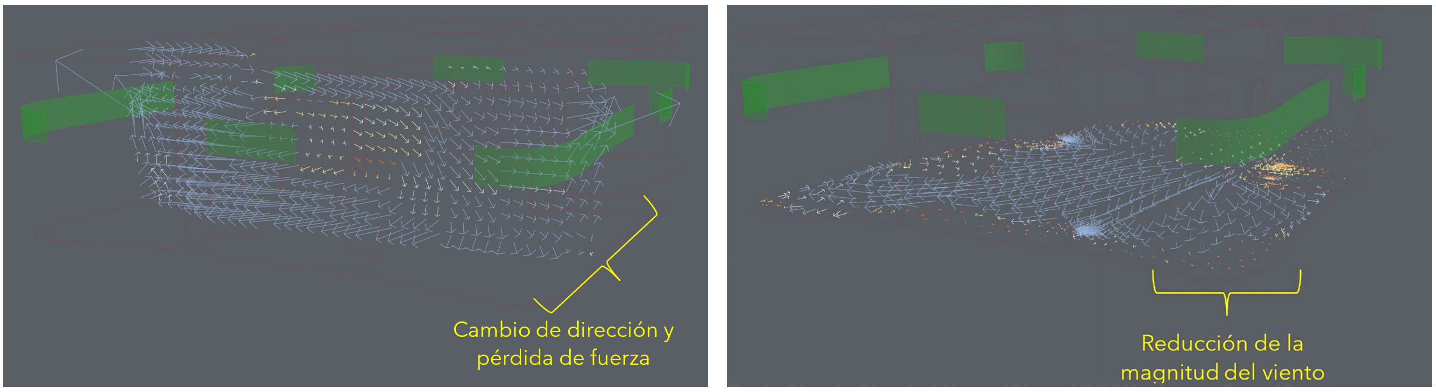

Figure 12. Outlet Analysis, simulations A, E, G, H. specified in Table 2. Source: Preparation by the authors.

Table 2. Comparison with the common ancestor. Source: Preparation by the authors.

Type of simulation	Cross-section H h (m)	(N) vector	Sum. Total (m/s)	Inlet V: Z (m/s)	V entrada: Z (m/s)	V interior (m/s)	Window H (m)
A.C.	0.1	412	160	0.8	- 0.5	0.38	2.3
M.G.		911	825.3			0.90	
A.C.		482	322		- 1.0	0.62	
M.G.		922	1253			1.32	
A.C.		482	402	0.2	-2.0	0.83	
M.G.		965	1662			1.72	

Considerable Total Vs are obtained (Table 1, F and G sim) with heights of 0.8 m. and large sills, but as can be seen: the wind direction near the sills and lintels is deviated perpendicularly to the walls or contours, which are interpreted as stagnation and turbulence zones (ASCE, 2023b), which can cause a decrease in the ventilation flow rate (Figure 12).

STEP 7: WINDOW HEIGHT ANALYSIS (OUTLET)

The results of both simulations are compared to the air intake inclination angle in the central courtyard. CA = Common ancestor, WM= Winning Model.

RESULTS AND DISCUSSION

The best fitness model obtained 1355 N, where more than 500 are empty cells; therefore, effective N is 855. Vtotal= 1,760.62 m/s. In this model 85% of the vectors are larger than 1.6 m/s. This means that in 85% of the house, not counting the central courtyard, there is a velocity greater than 1.6 m/s. This is interpreted that, with this procedure, the temperature inside the house is reduced by up to 4.2° C (Table 4) in 85% of the house (Soler & Palau, 2022). According to the Beaufort Scale, the sensation goes from having a feeling of 'calm" ventilation to "light air" (Table 3).

The winning model's natural air velocity inside the house is 2.50 times higher than the common ancestor's, as shown in Figure 13 through pre-visualization.

Table 3. Beaufort scale. Source: Information extracted from Soler & Palau (2022)

Beaufort Scale	Wind name	Speed (m/s)
0	Calm	0.5
1	Light air	1.5
2	Light breeze	3
3	Gentle breeze	6

CONCLUSIONS

These results show that it is possible to analyze and obtain a better performance of natural indoor ventilation in a house through the evolutionary design

Table 4. Effect on the human body. Source: Information extracted from Soler & Palau (2022)

Air velocity on people (m/s)	Feeling that the ambient temperature has been lowered by (°C)
0.1	0
0.3	1
0.7	2
1.0	3
1.6	4
2.2	5

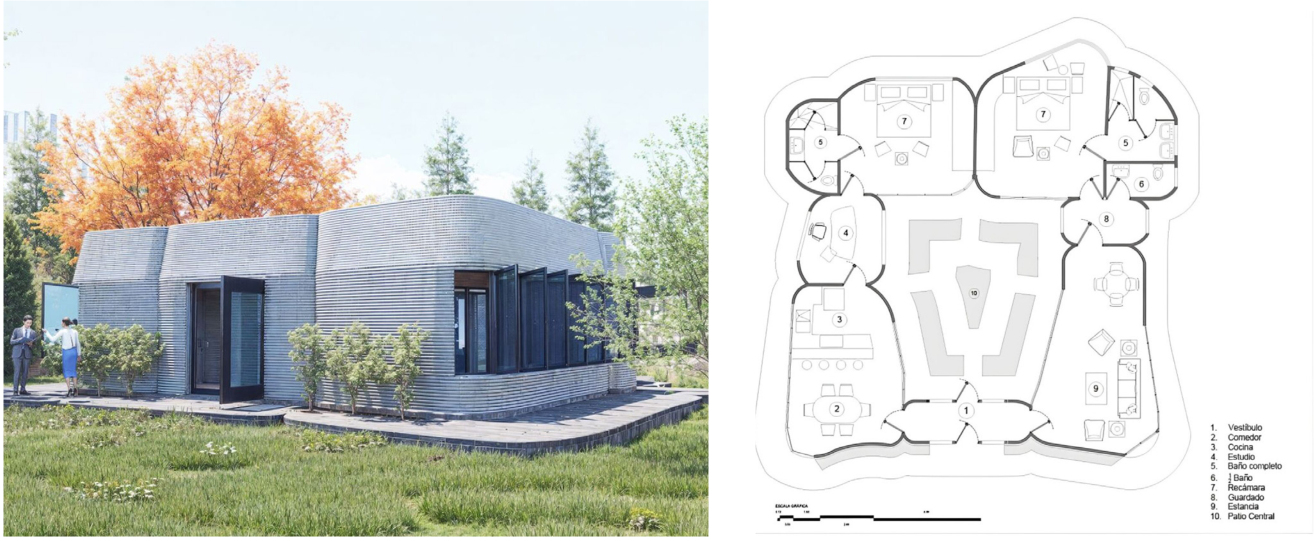

Figure 13. Application and visualization of the results of second-generation Model 03. Source: Preparation by the authors.

process presented in this article. This is appropriate in the context of biophilic architecture for its sustainability and incorporation of natural patterns in its morphology.

This process should be considered in an architectural design context since the methodology allows for analyzing natural ventilation performance in central courtyard housing through evolutionary design and CFD. This shows how evolutionary design can be an effective tool for exploring morphological variations. Moreover, this method is proposed to add value to work with existing sustainable architecture methods and techniques such as the garden slab and earthship, among others. This method is also proposed to contemplate using contemporary construction techniques, such as 3D printing.

The results could be developed further if more species are evaluated. This would include the growth of the housing area, new areas, uses, and layouts, among others, as well as the improvement of the algorithm, such as increasing the gene or DNA values and starting from a common ancestor of a different nature, up to the exploration of the ventilation behavior in different types of housing with different air inlets and outlets. The search and experimentation in other phenomena cause a relevant research hypothesis, such as the 'funnel' effect, 'the spiral,' and 'biomimetics,' among others. It also analyzes the hygrothermal properties of natural ventilation, such as air humidity.

CONTRIBUTION OF AUTHORS CRediT

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