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The use of building performance simulation to support architectural design: a case study

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Abstract

Considering the complex interaction between energy performance, lighting, acoustic and thermal comfort in contemporary design, building performance simulation [BPS] shall play a key role in addressing decision making process and technical choices towards optimized configuration during the whole design phase.
The paper reports the outcomes of a case study – performed in the framework of Ma Final Design Lab at the Department of Architecture, University of Bologna – where BPS was adopted from the very beginning as a tool to support the design process from the concept validation to the final architectural configuration to fit with passive house standards.

Keywords: CFD; Energy efficiency; Sustainable design; Middle-East architecture; Design process; Building Simulation; Iteratively process; Solar Decathlon Middle East

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1. Introduction

Architectural forms are typically defined by a number of different aspects including typological, technological, functional, environmental features that are managed according to a hierarchical organization according to the designers' ability and the context the object is related with. When high energy performance standards are expected, the interaction between these features is often increased in complexity and multiple effects can influence the result. In order to optimize the thermal and energy behavior, designers need to achieve a balance between the physical-geometrical features of the building itself and the adopted technological solutions and equipment.

In conventional design processes the building energy performance is commonly assessed when most of the key architectural features of a building are fixed. Software for Building Performance Simulation (BPS) offers the chance to achieve more precise evaluations applying Computer Fluid Dynamic (CFD) principles, typically used in the automotive design, in the building sector. The tool is typically adopted to assess the system performances when a specific design is fixed using feedback to correct technical features and details with no significant impacts on the architectural shaping phase. New design scenario could be preliminary evaluated instead if CFD is used from early stage to properly consider the dynamic behavior of the building embedded in its environment including an effective visualization of indoor ventilation fluxes, air temperature variation, etc.

2. Objectives

The paper reports the outcome of a design process where CFD was adopted from the very beginning to drive the project in optimizing architectural and technological response to quite extreme climate conditions. The potential of the computational software is used as an operative tool to support environmental control while optimizing architectural forms. The research work was developed according to three main steps: 1) definition of the passive solutions (natural ventilation, evaporative cooling, stack effect and cross-ventilation) fitting with the project purpose according to environmental and climate conditions of the assigned site; 2) review of traditional and more recent solutions belonging to the specific region to be used as references for the project; 3) definition of design concepts to be validated and further developed. Once each single concept was defined, it was entered into an iterative validation process using BPS: the architectural concept was translated into a model reproducing all the specific features and tested especially for what concerned natural ventilation using computational fluid dynamics (CFD). The simulations' feedback was used to correct and calibrate the model (and re-configure the concept) to increase the overall performance. The process was iterated until the results matched with the expected performance level.

The purpose was on one side to test BPS as a design tool (and not simply as a way to assess the behavior deriving from a pre-defined technical solution) and on the other to experiment an innovative training process at academic level. A relevant result was indeed the capacity to reduce the gap between the expected performance level fixed at the beginning and the real achievable level once the final configuration was definitely shaped.

The process was also aimed to combine the instinctive and creative side of the design process with a more conscious knowledge of the related environmental effects while varying the architectural configuration.

3. Context and case study

The study was developed as a Master Degree Final Thesis, recently discussed at University of Bologna, Department of Architecture [DA]. The project assumes as initial brief the rules of Solar Decathlon Middle East [1] competition that will take place in Dubai during 2018. The initiative is a contest open to University teams from all over the world with the aim to design (and finally build) a highly performing prototype for a single house according to the passive standards. The study represents the preliminary project in the case DA would concretely join the competition.

The project must fulfill ten key evaluation criteria dealing with solar energy, architecture, engineering and construction, energy management, comfort condition, house functioning, sustainability, vegetation and hardscaping (hard landscape materials in the built environment structures that are incorporated into a landscape), communication and innovation. Several constraints have to be considered including site dimensions (that are 20 m length and 20 m width, with a maximum height allowed fixed in 6 m), construction process (only assembled solutions are permitted), time and logistic.

Originally born in Washington D.C., Solar Decathlon Competition [2] gradually increased its educational role as a program that motivates designers and engineers into research and optimization of technical and architectonical response. It then moved in Europe and other locations to boost the sustainable paradigm in architecture. For the first time, the location is set in the Middle East with a radical shift of climate parameters compared to previous editions: the need for cooling rather than heating the building is indeed the key challenge of the competition.

3.1. Climatic Context

With reference to climate analysis and thermal simulation, Dubai climatic data were taken from the Energy Plus Weather Database that uses annual hourly IWEC data, collected for WMO Station 412170, OMAA Abu Dhabi International Airport, which is the nearest site to Dubai.

Dubai is situated on the Persian Gulf coast of the United Arab Emirates at an altitude of 16 m, at 25.2697°N 55.3095°E. Dubai's climate is classified type "BWh" (Köppen classification [3]) and type "4B" [4], that means it is considered an arid subtropical hot desert.

Summer is potentially most dominant with a temperature that reaches 47°C and a very significant solar radiation on roofs (2150 kWh/m² per year). The relative humidity depends on the impact of prevailing winds that bring hot humid air over the Persian Gulf from the northwest, and hot, dry air at higher speed (typically 4.2 m/s) from desert on the east side. Rainfall is typically below 100mm on yearly basis.

Climatic analysis is necessary to define boundary conditions but it is also useful to achieve an understanding of the key features of traditional/vernacular architecture in the Middle East [5,6,7]. Indeed, the most important characteristic of the Arabic traditional architecture is the integration of different building elements that contribute to control indoor conditions. A typical example is the so called bādgīr (literally "wind catcher") [8,9,10], a traditional structure used to achieve passive air-conditioning of the building. The air trapped in the vents of the tower is cooled as it descends and turn in to refresh the rooms below by convection and evaporation [11,12,13].

3.2. Computation Fluid Dynamics

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to provides a qualitative prediction of fluid flows [14]. Throughout computer simulation, CFD enables scientists, engineers and designers to perform numerical experiments in a virtual laboratory [15,16].

The approach to the CFD simulation is based on a procedure characterized by three main step:

- First one is focused on the definition of the geometry and physical boundary using computer aided design, the definition of the physical modelling and the definition of boundary conditions;
- Second one deals with the simulation start and the iteratively solution of equations;
- Third one is the post-processing phase, where the resulting solution can be visualized.

A steady state model was used for simulations, with the following characteristics:

- Building envelope is approximated to a geometric element. No specific material was associated, being the simulation processed at a very early stage. No thermal features (i.e. conductivity and thermal inertia), that can influence the simulation, were assigned to the building envelope. Only architectural configuration was investigated.
- To define the inlet of the air volume, 4,5 m/s wind speed from North-West was induced as "Velocity" boundary condition (in the diagrams, from top left).
- To define the outlet of the air volume, Static Gage Pressure = 0 was assigned.
- No boundary conditions were assigned to windows and doors. Air flows in and out of the building were based on the effects of wind and buoyancy.
- Mesh was automatically sized by the software and refined with a size adjustment factor equal to 0.4.
- Simulation run times were always set to 500 iterations.

4. Methodology

The adopted methodology is carried out through an iterative process that, starting from a first concept, assesses it, collects the results and critically reviews them to repeat the sequence with a refined configuration.

In order to adequately set the input and properly communicate with the software, a deep research dealing with natural ventilation issues and context condition was performed. Once measures and date were collected from indirect sources, a first rough model of architectural shape of the building was set up. At the very beginning it looked simply as the aggregation of some boxes, fitting with the concept but mostly aimed at exploring the main way to cool down the building by using natural ventilation. Once the size and the configuration of the boxes were set, CFD was used to verify a number of scenarios coming from different openings layouts. All the hypothesis came from variation of the same concept giving a different declination to those elements that coming from the traditional Arabic architecture were translated into contemporary features.

The goal was to understand how ventilation phenomena were influenced by a specific shape for each configuration simulating Dubai climatic conditions and especially considering temperature, wind speed and direction, pressure. The process was run for five main design configurations.

The building was defined as a squared volume that, moving from a configuration to another, provided a better response in moving air inside the building, dragging it along controlled paths in order to expel hot air out of the building. In order to consciously monitor all of these aspects using the simulation software, the shape of the prototype was varied operating on the mutual aggregation of the volumes, on the openings and on the height of any single box. Each configuration has been designed and inserted in the simulated environment and assessed in terms of ventilation: working in a three dimensional virtual realm made possible to visualize the air-flows throughout the volume as a whole.

Figure 1.a provides a graphic representation of how air flows work in the configuration which is assumed as a double skin box where openings are placed on opposite sides in order to drive the air flux into a main channel, increase the pressure of the air entering through small holes and increase air speed while maximizing the path within the building and obtaining a widespread benefit.

Figure 1.b provides a graphic representation of what happens when the volume is split in two boxes: air flows in through the small openings in the podium (oriented according to the main wind direction); the mutual shift of the boxes creates a low pressure near the openings that favorite the rising hot air extraction.

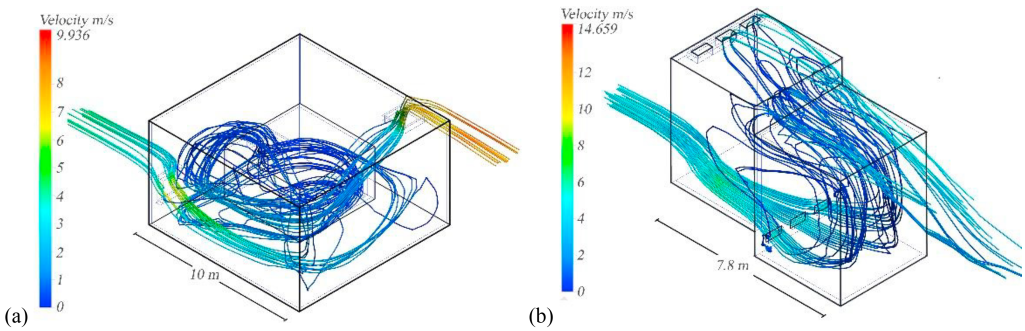

Fig. 1. (a) first model configuration with two openings on opposite sides; (b) second model configuration, the volume is split in two boxes, with bottom and top openings

In order to embed a further architectural element aimed at creating a ventilation effect on the roof, the model was refined and simulation performed again. Figure 2.a provides a graphic representation of the consequences of adding a horizontal surface above the boxes: air speed in between is increased due to Venturi’s effect leading to a more efficient extraction of hot air from the building. Figure 2.b shows a forth configuration where boxes are varied in height and aggregated in a more complex way: both the main volumes receive air from a further box placed as podium, facing its openings toward the main direction of the wind. Air flows into the main volume, crossing it and following the extraction effect triggered by the higher volume acting as wind tower. In the upper part of this tower, openings are placed in order to maximize the extraction of rising hot air. Furthermore, the roofing surface suspended over the boxes helps to cool down the flat roof thanks to the air movement in between.

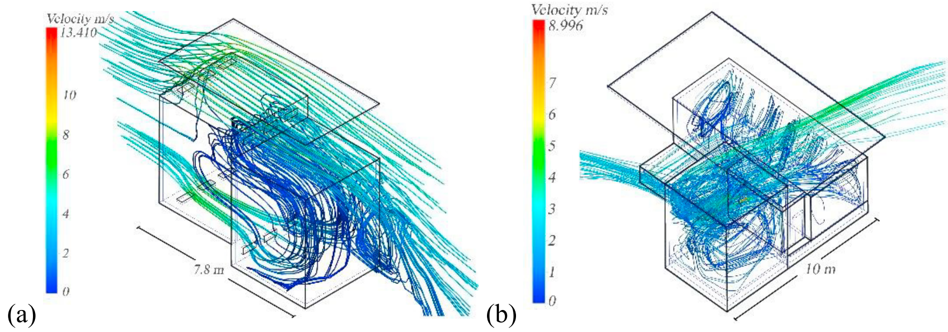

Fig. 2. (a) third model configuration: the volume is split in two boxes, with bottom and top openings and horizontal ventilation under the suspended roof; (b) fourth model configuration: volumes aggregation is varied and the tallest box operate as a wind tower.

5. Results: final configuration as architectural concept

The iterative approach of the methodology led to revise the model layout several times refining details in order to best fit it with the architectural concept. Figure 3 provides a graphic representation of the final configuration which turned out to be the coherent result of the whole process, able to fulfill most of the brief requirements in terms of natural ventilation that were set up during the concept definition phase. The use of CFD allowed to refine and re-arrange the most appropriate architectural shape to improve natural ventilation and achieve the pre-defined objectives. The final configuration is based on three boxes of different sizes (5.25x3.50m; 4.80x2.40m; 6.50x4.70m; h=3.50m) aggregated around a taller element (2.00x2.00x6.00m) that operates as a wind tower. All of them are laid over a podium and – except for the tower – are all covered by a suspended roof that shields from the solar radiation and increase the horizontal ventilation over the flat roofs. The ventilation flows inside the boxes are optimized according to the simulated environment taking into account daily variations and assigned functions to each box.

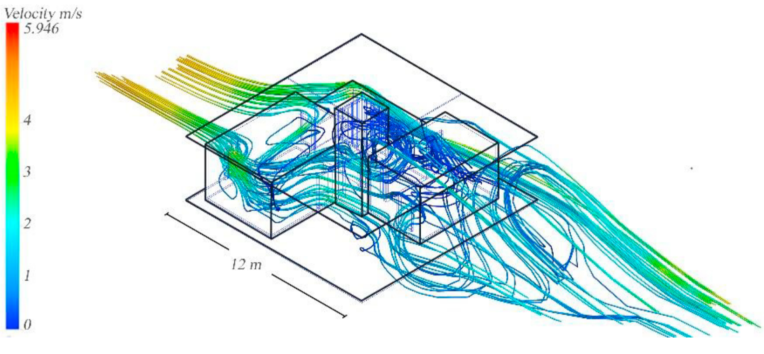

Fig. 3. final configuration of the model.

As Figures 1, 2, 3 show, CFD supported the design process step by step instead of being conventionally used simply to validate a layout driven mostly by formal decision. Indeed, CFD does not give answers on architectural language – that is still in the hands of designers' creativity – but offers a reliable tool to define which kind of natural ventilation phenomena create the best benefit in terms of natural ventilation improvement inside the boxes.

Analyzing the outcomes, it's possible to identify the main characteristics that makes the architecture effective:

- Primarily sufficient inlet flow is guaranteed by more openings of a reduced size dislocated in different positions rather than limited opening of a largest size;
- Secondly the stack effect in the building is enhanced by the highest box in the center of the configuration that helps in driving the natural ventilation and hot air extraction;
- Finally, a configuration obtained by aggregating several boxes allows to increase the volume and the fluid dynamic effect compared to a single volume configuration.

Furthermore, this step-by-step approach allows to obtain an original design concept embedding an effective natural ventilation strategy as a starting point to further define architectural shape, materials, technologies, etc.

6. Conclusion

The design approach described in this paper started from the assumption that Building Performance Simulation tools offer the potential to support architectural design from early stage. BPS and CFD simulation allowed to think (to create and to verify) an architectural concept while having feedback on its behavior, adequate to refine and improve the design solution according to pre-defined objectives. This means that the impact of the use of these tools on the design process would be greatly increased if adopted from the very beginning in design optimization instead of being limited to the final analysis. Virtual simulation can be used as a “predictive tool” to support the decision making process during the design stage.

Despite the complexity of the tools – that required to be adequately trained – the outcomes of this study encourage the application of the same methodology to other projects aiming at maximizing the benefits derived by use of natural phenomena and passive strategies as well as the achievement of high levels in terms of energy performance.

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