Façade apertures optimization: Integrating cross-ventilation performance analysis in fluid dynamics simulation.

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Abstract

Performance-oriented design has as a primary aim to introduce spaces that achieve acceptable levels of human comfort. Wind-induced airflow plays a significant role in the improving occupants' comfort in a building. This paper explores the extent to which simulation of natural airflow can potentially be a contributing parameter in the conception of performance-aware designs.

Testing the natural ventilation performance of a pavilion, the study employs Fast Fluid Dynamics simulation. A performance analysis is conducted, whereby an array of automated feedback loops carried out by a genetic algorithm can produce a number of acceptable solutions as regards the optimization of facades' openings. The experimentation conducted proves the ability of the model to yield design instances that fulfill a number of environmental criteria related to airflow and human comfort. In this light, the paper suggests that the aforementioned method can be used as an experimentation platform to influence the direction a designer may take when considering a design proposal.

1. INTRODUCTION

Performance analysis in the field of architecture allows the designers to become aware of the buildings' behavior as regards their relationship with the environment. Researchers focus on different ways to predict the interaction of a designed proposal with natural elements, towards a more comfortable built environment that achieves, in parallel, low levels of energy consumption. Moreover, building engineering aims to solve everyday problems, such as providing sufficient day lighting and indoor air circulation. As a result, a great amount of knowledge in the territory of natural elements, such as sun and wind, is now available. It is on the designers' remit to integrate this knowledge into their plans, but as a common practice it is not until the last phases of the design process that they engage with such issues.

This study focuses on wind, which is a dynamic phenomenon that can exhibit very complex behavior in relation to built forms. Therefore the question arises of how the building skin may respond to it. In this study an exploration is carried out regarding the shaping of façade openings as they get informed about the state of wind around them.

In recent years, mechanical ventilation has been preferred to natural ventilation as it can provide stable air conditions and resolve airflow problems triggered by inadequacies in design (Cowell 2012). Nevertheless, heating, ventilation and air conditioning systems (HVAC) are complex and need a large number of components to operate. In addition, this kind of technology consumes a great amount of energy, whilst not always managing to deliver the desired indoor climate (Kleiven 2003).

Consequently, architects propose the integration of natural ventilation techniques in order to create functional buildings (Mendez 2012). In this case, computational achievements like Computational Fluid Dynamics (CFD) and evolutionary algorithms which were investigated during the development of this paper can be proved as potentially useful techniques to design, taking into account performance analysis.

Natural phenomena simulated in computer models require a skilful expert user. Wind engineers are employed for the interpretation and operation of such complex simulations (Malkawi 2004). Moreover, powerful computer processors and a great amount of time are needed until the simulation model converges in an accurate result. Recently, in the field of fluid dynamics a less accurate but adequately informative model was presented. This model is Fast Fluid Dynamics (FFD), firstly presented by Stam (1999), and this has been the model used for the tests conducted in this research.

The main objectives of this paper are to highlight the architectural consequences and possibilities as these are formed by the integration of wind analysis in the design process. The goal of the simulation model presented, is to provide optimum airflow rate and distribution in the building's interior. How can we design a façade that allows the appropriate amount of air to circulate through the internal space? In addition the study presents an exploration of natural ventilation in combination with the forced opening and closing of façade components that imply random movement of people through the building envelope.

2. BACKGROUND

Hensel and Menges (2008) argue that considering the performance of a design during early stages, both the morphology of the structure and its environmental performance is important. In this light, form generation and environmental analysis become equal factors to the decision-making process. Thus, performance-driven design can take place even from the phase of conception. The scope of such a strategy is not to gather specific and accurate information about energy performance but rather observe and manipulate the "*tendencies or patterns*" of the design's behavior in accordance to natural forces (Hensel and Menges 2008).

2.1. Natural ventilation principles and comfort levels

Utilisation of the natural driving forces for the purpose of ventilation has for several decades provided the desired thermal comfort and air quality for people. In traditional architecture of south eastern countries porous structures (i.e. screenwalls) were widespread as a way of providing good comfort levels for the inhabitants (Hensel et al 2008; Hensel 2008). The performance analysis of these structures can prove their efficiency to achieve high rates of air exchange due to the availability of air, passing through the perforated building envelope (RIBA 2011).

Natural ventilation is a method to deliver air into buildings and replace the existing aged air with fresh air, using the force of wind (Cheung and Liu 2011; RIBA 2011). The most common types of this method is the stack effect, enabled by wind towers and cross-ventilation, enabled by openings on opposite sides of the buildings (RIBA 2011). The second is the case examined in this study. The wind is the driving force of the whole system. The way to allow this force to move through indoor spaces and also control its distribution is to design openings that affect the circulation of air and channel it to specific directions. The parameters that define the requirements of airflow depend on the comfort level standards (ASHRAE-55 2010; ISO 2005).

It has been studied and estimated that the way people perceive their satisfaction comfort levels depend on parameters such as the air temperature, the mean radiant temperature, the air velocity and the relative humidity of the space they live in. Apart from the comfort level parameters, one should also consider the local climate so as to draw some conclusions as regards the applicability of natural ventilation in each case. The above parameters should be considered before implementing the model presented in this paper.

2.2. Simulations of Fluid Dynamics

Computational Fluid Dynamics are models used to predict air distribution using mathematical equations to solve the flow of air in spaces (Awibi 1989). Carillho de Graca et al (2002) have implemented CFD simulation to assess the air circulation performance in indoor spaces in specific countries. Suga et al (2010), focused on the design of windows, taking into account wind-flow. Also, Cheng and Liu (2011) examined the patterns created by air around buildings, with the objective to optimize the void space among them. These studies used the CFD model as an evaluation analysis only for orthogonal rooms or buildings and typical rectangular windows.

Stam proposed a different way to approach the simulation of fluids. The FFD model, which he proposed, was initially introduced for the game industry (Stam 2003). Chen and Zuo (2007) validated the model for several situations, among which indoor ventilation can be found. In a more recent study of them, the conclusions that are drawn apart from the accuracy of the model also prove that it is a much faster solution in comparison to conventional CFD models (Chen and Zuo 2009). Computing time is considered an important factor when trying to implement a methodology during the conceptual phase of design.

To date there is a limited number of studies that aim to prove the applicability of this model in building engineering. Such an approach has been proposed by Chronis (2010) and Chronis et al (2011) as a form-finding method. His regard was not environmental but an effort to find forms which are informed by the wind load. Hence, this model has not yet been used for wind-induced indoor ventilation that can provide human comfort investigating the transformations of the apertures of a façade, as the case presented in this paper.

In the studies discussed above, it is a usual practice to couple fluid simulations with genetic algorithms. This model has been used extensively by Malkawi, who have also noted the importance of visualization during the optimization process(Malkawi et al. 2005). This enables the designer to visually evaluate the good solutions carried out by the algorithmic process, providing him with an opportunity to select from a number of good solutions as regards air simulation (Malkawi et al 2005). His studies focus on mechanically ventilated systems. The coupling of FFD and GA have also been recently realized and proved to be an effective strategy (Chronis 2010).

The space tested in this research exhibits similarities with previous studies. These similarities include the fluid simulation and main principles of the genetic algorithm (Chronis 2010), as well as the setting of the space and the placement of openings on windward and leeward side (Malkawi et al 2005; Cheung and Liu 2011). In the contrary, a different approach is suggested as regards the geometry of the façade's openings, which is non-orthogonal, and the optimization for natural ventilation using FFD as the evaluation method.

3. METHODOLOGY

This paper proposes a simulation model that aims to give the designer an insight about the natural ventilation performance of a built form. Such a methodology can be considered useful for architectural projects located in countries with climate that exhibits high temperature and moderate or high humidity. Although there is not a specific brief to be fulfilled, an assumption for the parameters that would appear in such a case was made.

3.1. General setup and simulation environment

As an initial step to set up the context for the experimentation, specific assumptions were made in respect to human related and environmental parameters. The calculation are made for an unfurnished room and the use of space is considered to be a communal space. Hence, the metabolic rate of the occupants is 1.2 which implies sedentary activity (ISO 2005). The clothing insulation that influences the human comfort levels is 0.7. Using the above values it is possible to have as an output the desired air velocity which in this case is in a range between 0.4ms^{-1} and 0.8ms^{-1} (ASHRAE-55 2010).

When cross-ventilation is the objective, it is a common practice to place openings on the windward and leeward side of the building. Using a wind rose from Rome as a reference, the apertures are placed accordingly (figure 1). Due to the hot climate in this city, it is considered a suitable case study for a natural ventilation system.

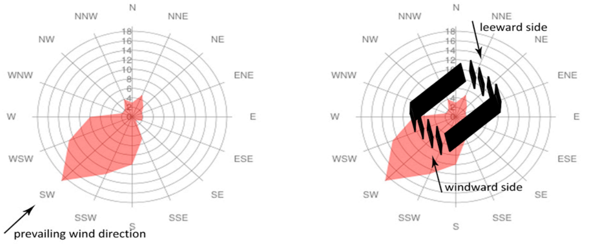

Figure 1. The space tested placed on the wind rose diagram.

As for the rest of the structure, ie meaning the remaining walls, the ceiling and the floor, all have a flat shape, creating an orthogonal volume of fixed area, in order to eliminate the complexity of the system. Moreover, the objective of the investigation is to optimize the apertures' form and not the overall shape of the building envelope.

This paper engages with curved openings optimization for natural airflow as they are formed by a series of louvres. In order to evaluate the performance of the model, testing was implemented on an existing type of louvres' geometry. In specific, the properties of the louvres were based on the façade of the Thematic pavilion at Expo 2012 in Yeosu, Korea. For this project Soma architects and Knippers Helbig developed a series of elastic fins that can perform complex deformations (Knippers and Speck 2011). The building shell of Nebuta house in Japan, realised by Molo, was also taken as reference for the form of the louvres. In both cases an array of fins creates variations in the sizing of the openings due to the ability to bear torsion.

The model is implemented in Processing language and allows three-dimensional free-form geometries to be presented. The whole configuration of space is divided in two categories: the static elements and the moving elements. The static elements consist of the ceiling the floor and two lateral walls while moving elements are proposed for the two remaining sides of the space which are also the windward and leeward side (figure 2). In the above described design it is suggested that the moving elements will replace the role of doors and windows, if it is thought as a real building. The overall volume occupied by the simulated model is characterized by its width (4.8m), length (6.15m), and height (3.9m).

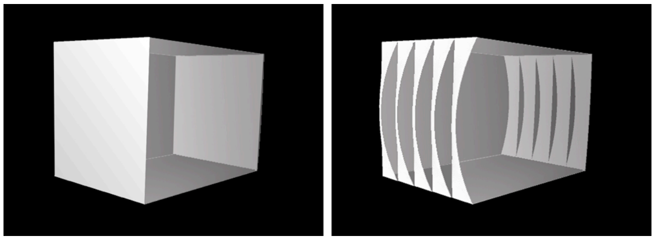

Figure 2. The louvres closed (left) and open (right).

Each louvre in the simulation environment, is a non uniform b-spline surface (NURBS). Trying to simulate the behavior of the elements found on the facades mentioned (Soma pavilion, Nebuta house), the louvres should perform a certain range of movements. In both projects the property of twisting is prevalent. For this to be achieved, a Gaussian distribution was incorporated in the NURBS algorithm. Creating a Gaussian function is a simple way to achieve the expected type of relation between the adjacent control points (figure 3).

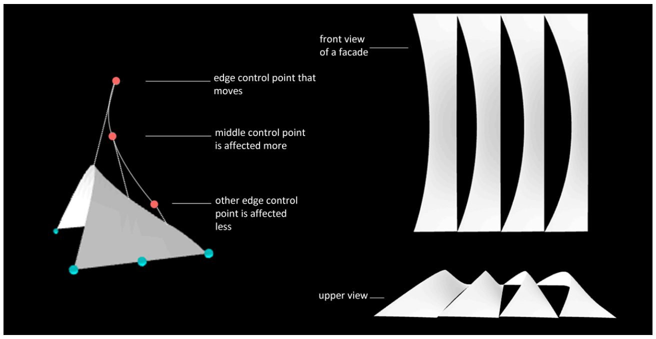

Figure 3. The louvres simulated as NURBS surfaces.

3.2. Implementation of Fast Fluid Dynamics

FFD has already been used in a number of studies, where a detailed explanation of the scheme can be found (Stam 1999; Chen and Zuo 2007; Chronis 2010). The algorithmic model used is based on an implementation, in three-dimensional space, of Stam's model (1999) by Ash (2006), which was later on coded in Processing by Chronis (2010).

The fluid solver runs iteratively to define the fluid movement that will take place in every time step. The model is grid based which in three-dimensional space consists of uniform voxels. The visualization of the whole scheme is exclusively based on a range of colours that represent the value of velocity in each voxel, using a mapping function. Furthermore, the behavior of the system relies on the initial velocity forced into the system to stimulate the fluid. While the research focuses on natural ventilation this velocity represents the wind. Throughout the simulation, the first row of voxels on y direction is prescribed to have a specific velocity.This implies that the wind is blowing continuously with a specific direction and velocity.

As a further step, a three-dimensional vorticity confinement function was incorporated into the algorithm. This was based on a two-dimensional scheme encoded in Java by Mckenzie (2004). The specific extension aims to reduce the numerical dissipation that exhibits the FFD model. Creating small swirling flows commonly found in smoke simulation the velocity field is influenced (Fedkiw et al 2001).

It is also worth mentioning that a visual representation of the information that the fluid simulation can provide was created. Trying to visualize the indoors condition of the airflow, a function in Matlab was used to create a three-dimensional graph from the given velocities (Matlab website 2012). For every test a memory structure was created where the velocity value of each cell located at height equal to 1.5m was kept. These values were later on parsed by a Matlab function and a three dimensional graph was created where the velocity component specified the colour and the height of each part of the surface (figure 4).

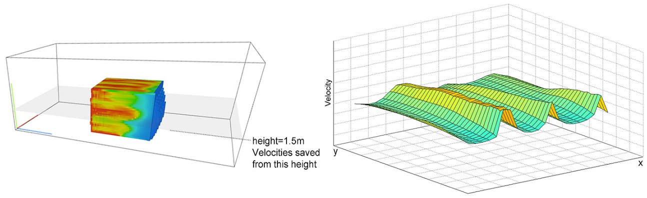

Figure 4. From left to right: FFD domain, Visualization of velocities in 3d space using the surface function in Matlab.

The fluid solver, as the majority of CFD programs, is voxel-based. The NURBS surfaces and the remaining elements that confine the room, were incorporated into the fluid solver using a parametrization technique which subdivides each surface into discrete voxels. The voxels that depend on the shape of the NURBS are enabled to change their state, according to the displacement of the surface, while the remaining voxels are static, and unaltered for each test. These voxels represent the internal boundaries of the fluid solver, redefined in every time step . The size of the fluid domain for all the tests on the x, y and z axis was set to 76, 150 and 50 respectively. In total 57 x10^5 voxels were simulated and their size was uniform. Size values between 2 and 5 were tested and 3 was chosen as the voxel size that would be used in the final tests (figure 5).

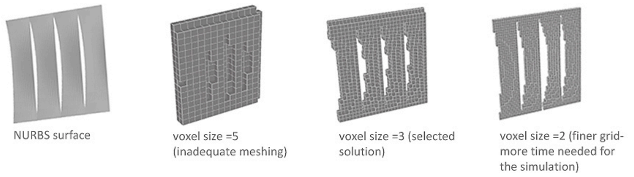

Figure 5. The meshing of the surfaces as it occurs due to different voxel size.

The simulated room occupies 34x10^3 voxels. Numerically the space that can possibly be occupied by people is taken in a distance of 0.6cm from the lateral walls and 1m of the ceiling. This region was used for the calculations that took place, in order to evaluate the performance of the room for natural ventilation. This is a common practice, since in the periphery of a room the condition of air does not affect considerably the human comfort (ASHRAE-55 2010; Malkawi et al 2005).

3.3. Genetic algorithm

An evolutionary method was implemented along with the FFD scheme to enable an automated evaluation of a large group of possible design solutions. The algorithm implemented relies on an example created by Turner (2010). In specific, the genetic algorithm (GA) is based on a standard number of population members that are evaluated by a fitness function. Each member consists of a possible instance of the design. The differentiation between each instance depends on the genes, as they are encoded. In the case presented, the genes determine the displacement of the control points for each louvre on the x and z direction. These genes, random initially, are assigned with a range of values, and the pace according to which these values can be incremented. The possible values are discrete from 0 to 5. The lower limit of this range means that the louvre is completely closed and the displacement is 0°, while the upper limit means that the louvre, at the height of 1.5m, is open at 50°. The pace of the inclination is 10° (figure 6).

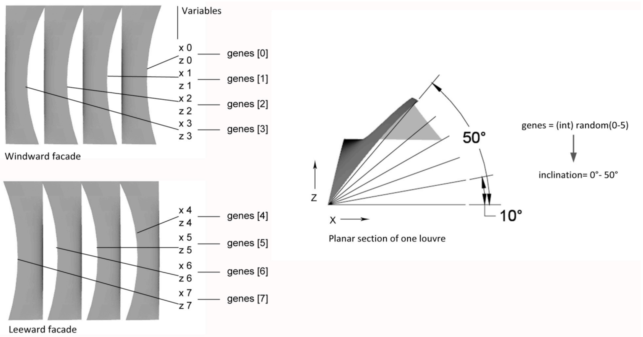

Figure 6. Representation of the GA scheme and the possible values of the genes.

A fitness function, related to natural ventilation, determines the effectiveness of each solution. Afterwards the whole population is sorted from the less to the most fulfilling option. The next step is the mutation and crossover of the possible values of the genes. Two instances are selected and a percentage of their genetic elements is passed to a new instance, while there is also a probability of new solutions to occur. The resultant solution is then evaluated replacing the less effective member of the existing population (figure 7).

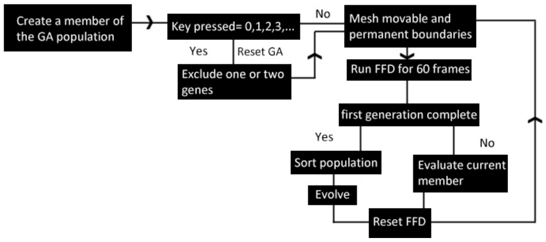

Figure 7. Flowchart of the GA scheme.

3.4. Multiple criteria fitness function

The fitness function elaborates the objectives of the problem into an algorithmic process. In the case presented, the airflow is adjusted due to the transformations of the facades elements, until an appropriate airflow pattern is met. The main parameter that influences the airflow is the velocity of air in the occupied space. In this light, velocity is used to recognise the behavior of the wind indoors.

Although the velocity component was the only key element used for the evaluation scheme, it was used in a number of ways that could provide adequate information concerning the indoor conditions. Four different functions were incorporated into the fitness function creating multiple criteria for the evaluation process. These required the calculation of the average velocity, the air exchange rate, the standard deviation and the maximum velocity.

The average velocity of the values found in the occupied space, should fall into a range so as the fitness to increment. The upper limit for the average velocity was 0.8ms^{-1} and the lower 0.4ms^{-1}. If the values did not fall into this range the fitness would be influenced negatively.

Furthermore, since the aim is to achieve a great degree of air exchange, to replace the aged air with fresh, the calculation of volumetric range exchange was adapted. Examining the voxels located in the interior side next to inlet openings, the area they occupy was multiplied by the average velocity found in their centres. This equation is commonly found in environmental studies as regards air (Autodesk 2011). The higher value of the volumetric rate the better the resulting fitness.

Additionally, in order to achieve a uniform distribution of air indoors one more function was introduced. This function was formulated for eliminating the deviation from the mean velocity. Standard deviation increments in a high degree when a great difference from the average value is found and respectively the fitness decreases. As stated in previous studies, it is considered as an effective way to achieve a better distribution of uniform air velocities (Malkawi et al 2005).

Moreover, the maximum velocity found indoors was also integrated in the fitness function. A high value for maximum velocity affects inversely proportional the fitness value. As this function also influences the evaluation part of the GA, the solution space was further constrained.

The above values are considered integral parameters that affect the effectiveness of a natural ventilation system. Thus, it was decided to elaborate them in a way that they could equally affect the fitness of a solution. In this respect all the values as they are computed by each function were mapped to numbers raised to the power of -1.

4. TESTS AND RESULTS

The first test consisted the ventilation performance analysis of a room with orthogonal openings so as to provide a set of measurements. These values provide the study with a performance benchmark in order to compare the effectiveness of the proposed façade that consists of louvres, to a convetional type of façade, that consists of common windows and doors (figure 8). The second test examined the possible transformations of 8 louvres, so as to provide sufficient wind-induced ventilation. For the rest of the tests one or two louvres, of the windward façade, were left open throughout the simulation as if people were allowed to pass from the open louvres.

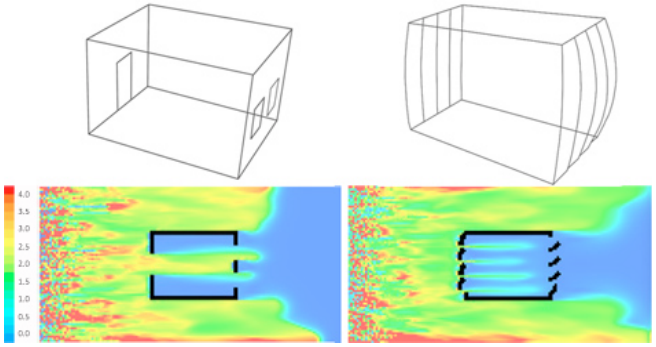

Figure 8. Diagrammatic representation of the rooms tested and respectively planar sections, across the x and y axis, for z=1.5m during the fluid simulation.

The most effective way to introduce sufficient airflow indoors is the creation of inlets that are slightly smaller than the outlets (RIBA 2011). This design principle for cross-ventilation appeared in the solutions presented in this study, proving that the solution follows the general guidelines of designing for natural ventilation. In addition, the coupling of FFD and the optimization method is effective and sufficiently creates solutions that can be considered acceptable, as we can also visually evaluate from the 3d representation of the air velocity distribution found in the room (figure 9). Thus, the model generates solutions that could provide informative insight during the process of decision making, even for complex façade configurations as the one implemented in the present experimentation.

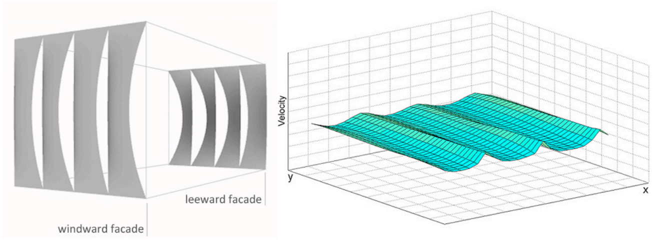

Figure 9. The optimized form of the openings and 3d representation of the velocity values found indoors that exhibit good distribution.

Moreover, the tests that factor in human circulation, where a number of louvres have openings with inclination set at 50°, enabling the remaining louvres to be optimized, achieved to converge in acceptable solutions in regard to human comfort levels. Among the successful tests, a specific pattern of the configuration of louvres came up in the solutions. Firstly, once more the sizing of inlets and outlets roughly matched. Secondly, the pattern that emerged indicated an interaction between the louvres of the windward and the leeward façade. As a general overview, the louvres placed in opposite positions between the two sides exhibited inversely proportional inclination creating a better distribution of air (figure 10). This shows a trend towards the solution of the addressed problem, converging in an optimal form of the two opposite façades.

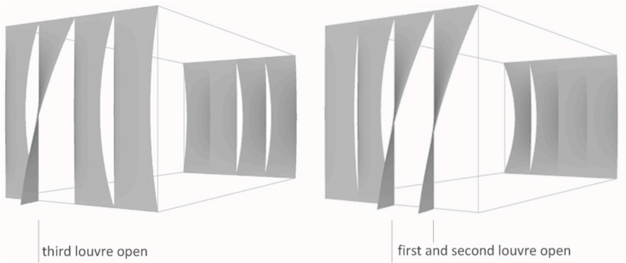

Figure 10. Two examples that depict the trend appears between the windward and leeward facades in the optimized solutions.

As presented in this paper the method of computing the fitness, combined four different functions. In this light, a system of multiple layers was created for the evaluation process. This method provided the study with a complete set of criteria with the aim to create a robust methodology that allows an accurate evaluation method. However, this method added extra complexity to the optimization problem resulting in a high level of difficulty towards the convergence in one solution. The four calculations taken into account were conflicting. For example, throughout the optimization process a satisfactory result should exhibit average velocity that falls in a specific range of low values and low maximum velocity but high volumetric rate exchange, which are contradictory attributes. Although the problem was complex throughout the majority of the tests the genetic algorithm managed to converge in solutions that achieve the required standard conditions.

The coupling of FFD and GA is a computational demanding scheme, however. For every design instance to be evaluated the fluid simulation should run across the whole domain creating a time consuming performance analysis method where approximately 6 hours needed until a the GA converges in a solution. The complexity appears visually in the fitness graph of the tests where two louvres in a row should remain open and thus a great amount of air was introduced indoors. In these cases the optimization process remained steady in local optima, for about 100-200 generation, until a better solution was found (figure 11). Hence, a refinement of the optimization algorithm so as to integrate a hybrid-heuristic model is proposed for further investigation.

Figure 11. Improvement over generations of three population members (optimization process).

5. CONCLUSION

The paper presented the extent to which simulation of natural airflow can potentially be a contributing parameter in the conception of performance aware designs. A specific case study, where two facades consisting of elastically deformable vertical louvres, was implemented to enable experimentation. A set of fulfilling design instances that have been analysed for their ventilation performance have been generated. The coupling of fluid dynamics simulation and genetic algorithm have proved an effective way to design taking into account wind-induced ventilation. The aftermath of integrating such a methodology could be the choice of passive cooling systems instead of mechanically air conditioning systems, which are more popular in architectural concepts to date. Providing a platform for experimentation, this paper aims to stimulate a reciprocal conversation between performance and shape. As a general overview, this paper underlines that the form of a structure can be enriched by the information provided from its performance attributes. This way a structure will be able to exhibit inherent performative qualities from the initial stages of its creation.

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References

ASHRAE-55 (AMERICAN SOCIETY OF HEATING). 2010. Refrigerating and Air-Conditioning Engineers. ANSI/ASHRAE Standard 55-2010 Thermal Environmental Conditions for Human Occupancy. Atlanta: ASHRAE.

ASH, M. 2006. Fluid Simulation for Dummies, [online] Available at: <http://mikeash.com/pyblog/fluidsimulation-for-dummies.html> [Accessed 1 June 2012].

AUTODESK (Autodesk Education Community). 2011. Sustainability Workshop: Wind ventilation. [online] Available at:<http://sustainabilityworkshop.autodesk.com/fundamentals/wind-ventilation> [Accessed 15 June 2012].

AWIBI, H., D. 1989. Application of Computational fluid Dynamics in Room Ventilation, Building and Environment, 24(1), pp. 73-84.

CHEN, Q. AND ZUO, W. 2009. Real time or faster-than-real-time simulation of airflow in buildings, Indoor Air, 19 (1), pp. 33-44.

CHEN, Q. AND ZUO, W. 2007. Validation of fast fluid dynamics for room airflow, Proceedings of the 10th International IBPSA Conference Building Simulation, pp. 980-983, Beijing, China.

CHEUNG, J., AND LIU, C. 2011. CFD simulations of natural ventilation behaviour in high-rise buildings in regular and staggered arrangements at various spacings, Energy and Buildings, 43, pp. 1149-1158.

CHRONIS, A. 2010**.** Generative Fluid dynamics, Integration of fast fluid dynamics and genetic algorithms for wind loading optimization of a free form surface. Diploma thesis. MSc AAC. UCL.

CHRONIS, A., TURNER, A., TSIGKARI, M. 2011. Generative Fluid Dynamics: Integration of Fast Fluid Dynamics and Genetic Algorithms for Wind-Loading Optimisation of a Free Form Surface, Proceedings of the Symposium on Simulation for Architecture and Urban Design at the 2011 Spring Simulation Multi-conference, Boston, USA, pp. 79-86.

COWELL, R. 2012. Seminar Review: The Natural Ventilation of UK School Classrooms, UCL, October 2011. Natural Ventilation News, 5, CIBSE Natural Ventilation Group Management Committee, London, pp.7-8.

FEDKIW, R., STAM, J., AND JENSEN, H., W. 2001. Visual Simulation of Smoke. In SIGGRAPH 2001 Conference Proceedings, Annual Conference Series , pp. 15-22.

GARRILHO DA GRACA G., CHEN Q., GLICKSMAN L. R., NORFORD L. K. 2002. Simulation of wind-driven ventilative cooling systems for an apartment building in Bejing and Shangai. Energy and Buildings, 34. pp.1-11.

HENSEL, M. 2008. Performance oriented design, precursors and potentials. Architectural design, (78) 2, Wiley Academy, London. pp.48-51.

HENSEL M. AND MENGES A. 2008. Inclusive performance: Efficiency versus effectiveness. towards a morpho-ecological approach for design. Architectural Design, 78 (2), Wiley Academy, London. pp. 54-63.

HENSEL, M., HENSEL, D., S., GHARLEGHI, M., AND CRAIG, S. 2008. Towards an architectural history of performance. Architectural Design, 78 (2), Wiley Academy, London. pp. 25-37.

ISO (INTERNATIONAL STANDARDS OFFICE). 2005. ISO 7730-2 Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Geneva: ISO.

KATO, S. AND MURAKAMI, S. 1985. Three-dimensional numerical simulation of turbulent air flow in ventilated room by means of 2-equation model. International Symposium Computation Fluid Dynamics, Tokyo.

KLEIVEN, T. 2003. Natural ventilation in buildings. Architectural concepts, consequences and possibilities. Phd Thesis. Norwegian University of Science and Technology.

KNIPPERS J. AND SPECK T. 2011. Design and construction principles in nature and architecture. Bioinspiration and Biomimetics, 7.

MALKAWI A. M. 2004. Developments in environmental performance simulation. Automation in Construction, 13(4). pp.437-445.

MALKAWI A. M., SRINIVASAN R. S., YI Y. K., AND CHOUDHARY R. 2005. Decision support and design evolution: integrating genetic algorithms, CFD and visualization. Automation in construction, 14. pp.33-44.

MATLAB (WEBSITE). 2012. Surface and mesh creation. [online] Available at: <http://www.mathworks.com/help/matlab/ref/surf.html > [Accessed 30 July 2012].

MENDEZ, G. 2012, Barriers for natural ventilation in the UK. Natural Ventilation News, 5, CIBSE Natural Ventilation Group Management Committee, London, pp.3-5.

RIBA (ROYAL INSTITUTE OF BRITISH ARCHITECTS). 2011. Sustainability Hub. Natural ventilation stuck ventilation. [online] Available at:< http://www.architecture.com/SustainabilityHub/Designstrategies/Air/Air.aspx >, London: RIBA. [Accessed 9 June 2012].

STAM J. 2003. Real-fluid dynamics for Games. In Proceedings of the Game Developer Conference, March 2003.

STAM, J. 1999. Stable Fluids, In SIGGRAPH 99 Conference Proceedings, Annual Conference Series, pp.121-128.

SUGA, K., KATO, S., HIYAMA, K. 2010. Structural analysis of Pareto-optimal solution ets for multi-objective optimization: An application to outer window problems using Multiple Objective Genetic Algorithms, Building and Environment, 45, pp. 1114-1152.

TURNER, A. 2010. Genetic Algorithm. [online] Available at:< http://www.openprocessing.org/sketch/3101>. [Accessed 5 July 2012].