Generation and Integration of an Aerodynamic Performance Data-Base within the Concept Design Phase of Tall Buildings

David Menicovich, PhD Student at Center for Architecture, Science and Ecology
Daniele Gallardo, PhD Student at ADAMUS lab
Riccardo Bevilaqua, Assistant Professor at ADAMUS lab
Jason O. Vollen, Associate Director at Center for Architecture, Science and Ecology
Institute: Rensselaer Polytechnic Institute

1 Abstract

Despite the fact that tall buildings are the most wind affected of architectural typologies, testing for aerodynamic performance is typically conducted during the later design phases, well after the overall geometry has been developed. In this context, aerodynamic performance studies are limited to evaluating an existing design rather than a systematic performance study of design options driving form generation. Beyond constrains of time and cost of wind tunnel testing, which is still more reliable than Computational Fluid Dynamics (CFD) simulations for wind conditions around buildings, aerodynamic performance criteria lack an immediate interface with parametric design tools. This study details a framework for empirical data collection through wind tunnel testing in a uniform airflow of mechatronic dynamic models (MDM) and the expansion of the collected dataset by determining a mathematical interpolating model using an Artificial Neural Network (ANN) algorithm developing an Aerodynamic Performance Data-Base (APDB).

The philosophical provocation for our research is found in the early 20th century when Frederick Keisler proclaimed the interacting of forces CO-REALITY, which he defined as The Science of Relationships. In the same article Keisler proclaims that the Form Follows Function is an outmoded understanding that design must demonstrate continuous variability in response to interactions of competing forces. This topographic space is both constant and fleeting where form is developed through the broadcasting of conflict and divergence as a system seeks balance and where one state of matter is passing by another; a decidedly fluid system.

However, in spite of the fact that most of our environment consists of fluids or fluid reactions, instantaneous and geologic, natural and engineered, we have restricted ourselves to approaching the design of buildings and their interactions with the environment through solids, their properties and geometry. The research described herein explores alternative relations between the object and the flows around it as an iterative process, suggesting an additional layer to the traditional approach of *Form Follows Function* by proposing *Form Follows Flow*.

2 Introduction

According to the United Nations, virtually all the expected population growth during the next 30 years will be concentrated in urban areas, situating the development of sustainable urbanization as one of the crucial challenges to our future [UN 2002, UN

HABITAT 2006]. Globalization, growing population, and increasing urbanization caused tall building typologies to become widely used for stimulating urban regeneration in the last two decades of the 20th century [Watts, Kalita and Maclean, 2007]. Successively, the magnitude of investment in the construction of tall buildings in rapidly growing urban areas in the first years of the 21st century has no precedents [Ali and Aksamija, 2008, Goncalves and Umakoshi, 2010]. Further, the vast majority of developments during this period did not utilize the well established principles of environmental or sustainable design [Goncalves et al, 2010].

Wind plays a large role in the design of tall buildings and greatly affects lateral structure, cladding and ventilation strategies. The specific concern for wind-induced effects has prompted investigations into the relationship between geometrically driven aerodynamic characteristics of a structure and the resulting wind-induced excitation level.

Kwok, Wilhelm and Wilkie investigated the effect of various edge configurations on the wind-induced response of tall buildings with rectangular plan [Kwok et al, 1988]. Their research found that slotted and chamfered corners, and their combinations, caused significant reductions in the along-wind and crosswind forces. Kareem & Tamura investigated slotted and chamfered corners, fins, setbacks, buttresses, through-building openings, sculptured building tops, tapering, and drop-off corners [Kareem and Tamura, 1995]. Further initiatives to explore the effects of building shape on aerodynamic forces have confirmed the benefits of adjusting tall building configurations and corner morphology in significantly reducing the along-wind and crosswind responses [Hayashida & Iwasa, 2004, Miyashita et al. 2004].

Far less attention has been given to the relationship between the implications of geometry based aerodynamic modifications on other building parameters. Tse conducted parametric studies on building financial returns (i.e., the impact and value of aerodynamic modifications) based on wind engineering considerations in the economics of tall buildings. This study showed that conflicts arise between aerodynamically efficient plan shapes, effectively suppressing wind-induced loads and hence reducing construction cost, and simpler floor plan geometries that maximize the size and value of saleable/rentable floor area. The researchers concluded that intangible benefits, such as the functional, emotional and aesthetic user needs, are difficult to link to an economic value in a direct quantification [Tse et al., 2009].

In their study, Gane and Haymaker observed that the current inability to efficiently conduct multidisciplinary model-based analysis is in part because design and analysis tools are not well integrated and require substantial time investment in structuring the information for discipline-specific needs. There is a lack of engineered-based analyses of concept design options because engineers are normally engaged after architects have already chosen a preferred design. Gane and Haymaker concluded that deficiencies in the current conceptual design process lead directly and indirectly to solutions with mediocre day lighting and excessive thermal loads with associated increased energy demands, making the cost of operating tall buildings unattractive as a long term economic model [Gane & Haymaker, 2008].

The following work details the generation and integration of aerodynamic performance data-base in the concept design phase in order to address design process deficiencies as shown in Figure 1.

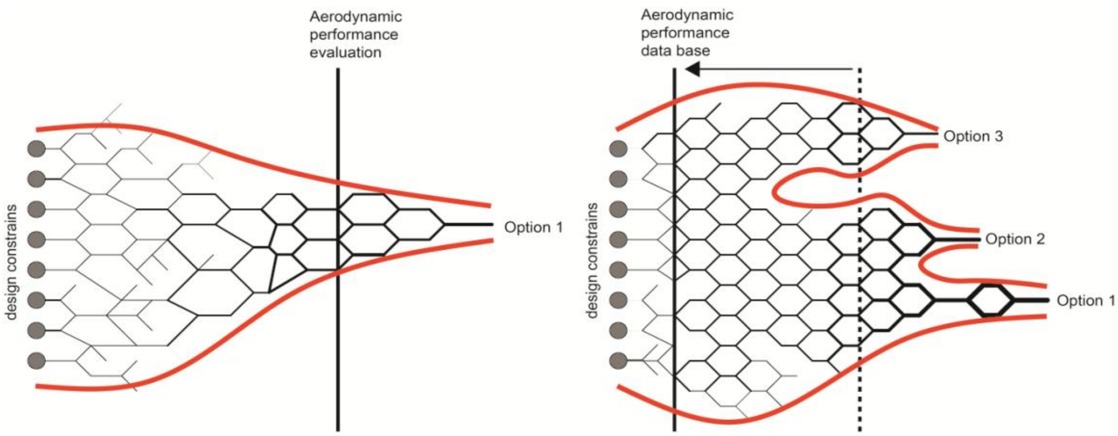

Figure 1. Schematic showing current and proposed design processes. Integrating the APDB early in the process would expand the design space by enabling more data driven design options and support communication between architects and engineers.

The objective of providing performance driven data through the use of APDB is to enable a multidisciplinary model-based communication between stakeholders in order to expand the design space in which they operate. Despite the fact that some techniques included within the proposed workflow have been used previously for architectural and building related applications, as in the case of ANN [Krauss et al., 1997; Jingfeng, 2005; Stavrakakis et al., 2010; Gavalda et al.,2011], or are common in other fields, as the use of MDMs (meaning models capable of dynamically change their shape according to command received by a microprocessor) in aerodynamic research and practice [Abdulrahim et al., 2004], the novelty of our approach lies in its application and integration into the design process of tall buildings, specifically within the early stages of design.

The remainder of the paper is organized as follow. In Section 3, the proposed workflow is described, with a detailed explanation of the MDM design in subsection 3.1. Subsection 3.2 illustrates the experimental setup used to collect wind response data-base, and its processing is described in subsection 3.3. Subsection 3.4 shows how the empirical data-base has been used to train and validate an ANN, in order to get a mathematical model capable of interpolating the empirical database. Section 4 contains a summary of the work and related conclusions while section 5 describes future work.

3 Workflow Process

The workflow process described in Figure 2 includes the following steps:

1.Design Criteria and Constrains Definition.

2.MDM Design and Fabrication (section 3.1): the primary geometric parameter (the geometrical feature to be explored in the design process) was chosen as the basis for model performance.

3.Data Acquisition (section 3.2): 3 MDM were tested in the wind tunnel according to the experiment matrix described in Figure 8. Vibration and pressure data were collected.

4.APDB Generation (sections 3.3 and 3.4): The limited dataset collected through experiments was used to train an ANN for interpolation purposes, allowing the generation of an effectively continuous dataset.

5.Validation (section 3.4): the APDB was validated against a tested configuration not included in the ANN training process.

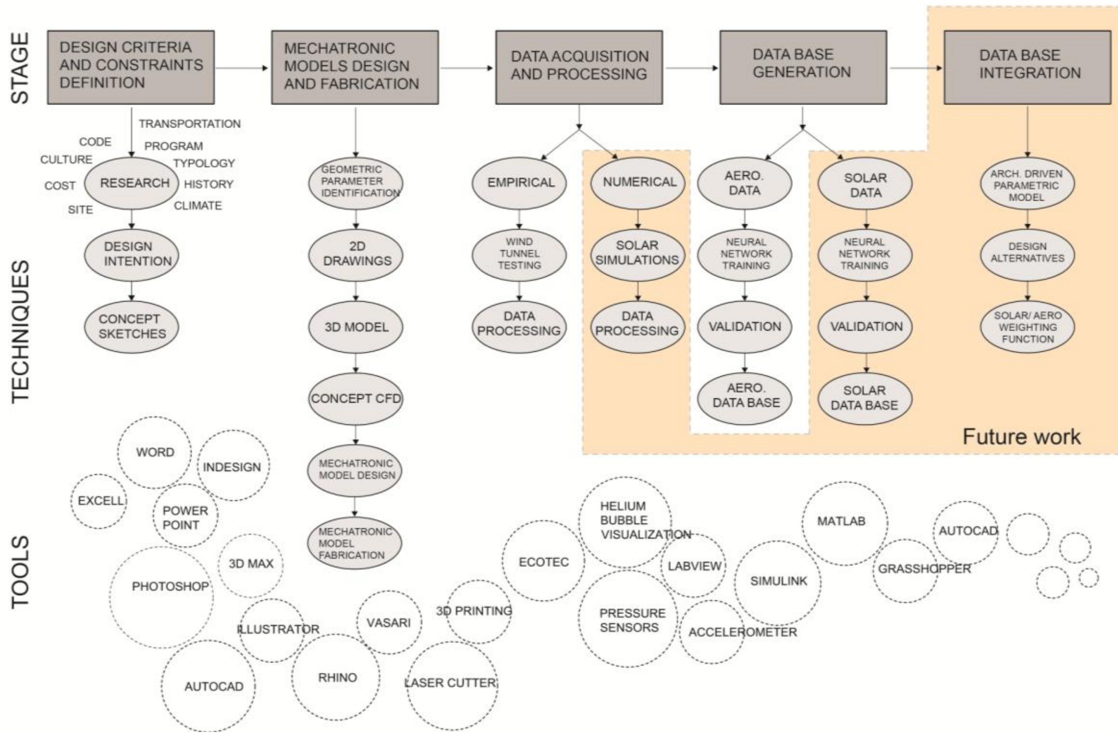

Figure 2. Workflow Diagram

3.1 The Mechatronic Dynamic Model (MDM): A Way to Span the Concept Space

The Concept Space is defined as all the possible combinations of the configurations that the geometrical parameters can assume. Understanding the Concept Space is key factor in defining the MDM, which is required to span the entire space.

The study explored only one parameter: differing 3-d texture patterns, since the main goal was to develop a framework, rather than concentrating on specific applications. These patterns, present on two sides of the MDM, were tested in five configurations protruding out of the facade baseline (ranging from 0mm to 4mm). Three models with three different patterns were analyzed as shown in Figure 3.

A 3-axis accelerometer was mounted to the unsupported end and seven pressure ports were integrated on the leeward façade. The 3-d pattern protrusion was controlled by a piston manipulated by a set of cams connected to a motor and microcontroller. Figure 4 shows the basswood armature and the same model covered with spandex for impeding air flow into the model. The microcontroller was connected to a potentiometer where the value of resistance determined the position of the servo-motor and thus the protrusion of pattern from the surface.

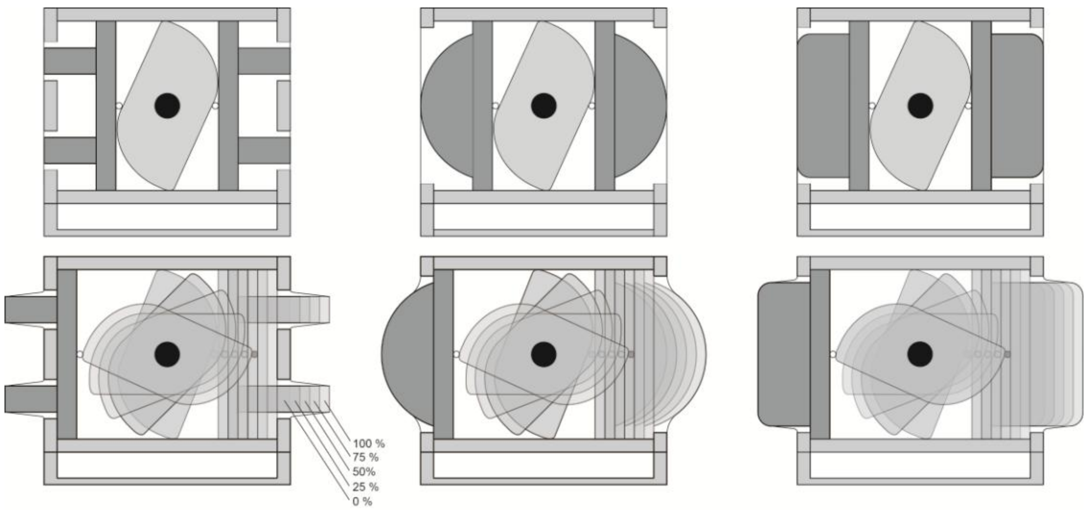

Figure 3. Plan view of three MDMs in their different testing configurations. From left, Model 1, 2, 3.

The MDMs gave qualitative information for the values of acceleration only, as they were made of basswood and presented different dynamical properties compared to real buildings. However, having a common baseline, the recorded values of accelerations were useful in terms of behaviors observed as trends and performances, and were used to compare design options. Figure 5 is an exploded axonometric view of Model 3.

Figure 4. Model 3 basswood armature (left) and covered with Spandex (right)

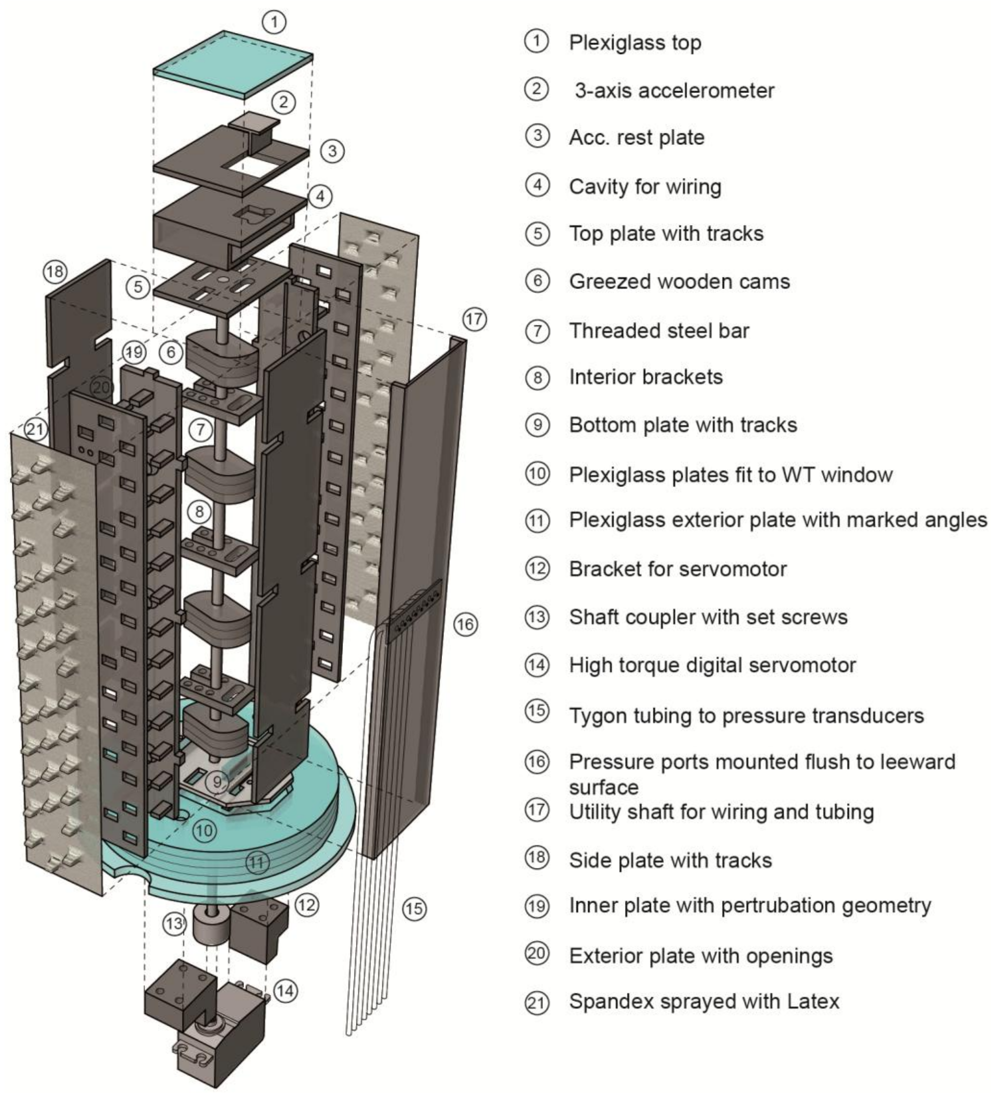

Figure 5. Exploded axonometric view of the MDM

3.2 Wind Tunnel Experimental Setup

Experiments were conducted in a re-circulating subsonic wind tunnel. The testing section is 24”x24”x96” reaching wind speeds up to 300 fps. The wind tunnel is equipped with a flow visualization device generating helium filled bubbles allowing qualitative interpretation of the flow around the studied object. Figure 6 shows the test section of the wind tunnel while using the helium bubbles visualization tool.

Figure 6. The test section of the wind tunnel with the helium bubble visualization device on. A wide-angle image showing the flow from right to left (top). The building is placed in the middle of the test section. Downstream it is possible to see the trajectories of the helium bubbles mapping the flow and the vortexes generated by the building interference. A close-up of the model with the patterns completely out (bottom).

The MDM was fixed to one of the vertical walls of the wind tunnel. For simulating a change in wind conditions, the MDM was rotated for several angles of attack and the wind speed was changed. The accelerometer presented the axes x and y on the plane representing the top of the building and the z axis along the building span. Only the vibrations along the x and y axes have been considered, since they can be related to the crosswind and along-wind responses.

Figure 7 shows the connections of the experimental setup. As previously noted, the MDM was equipped with a servo-motor which allowed changes in the pattern protrusion. The servo-motor was controlled by a dedicated servo microcontroller (an Arduino UNO board) (SA), and powered by an AC-DC converter, which supplied 7.4V. The SA was used to send the motor a command signal proportional to the resistance value across a potentiometer. The potentiometer was connected to the SA power output of 3.3V and to one of the SA analog inputs. Each angular position corresponded to a specific perturbation.

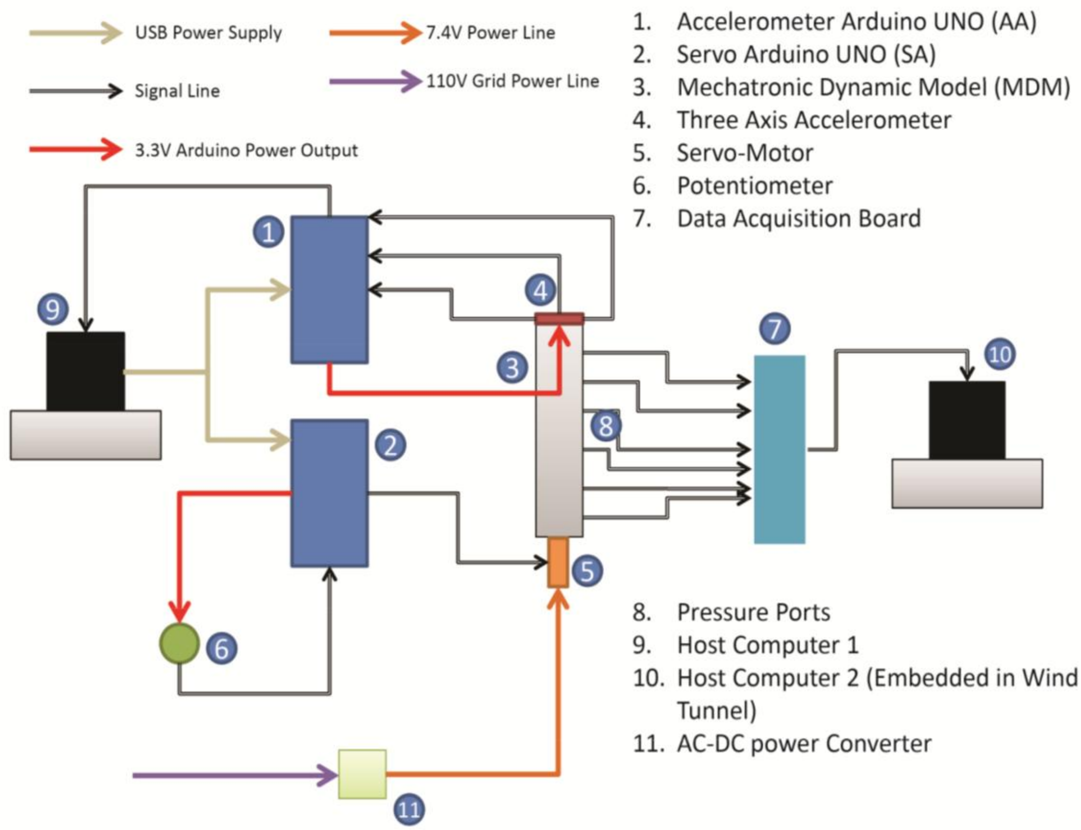

Figure 7. Schematic of the power and signal connection of the experimental setup

The accelerometer mounted on the MDM's top was connected to a second microcontroller (an Arduino UNO board) (AA). The accelerometer was a 3-axis accelerometer powered by the AA 3.3V power output pin. It had one signal line per axis and all three went to separate analog input ports of the AA. The signals were read by the AA, and sent to the host computer. The host computer dialoged with the AA through a serial port. Each pressure port on the MDM was connected to the wind tunnel embedded pressure analysis device. Pressure sensors were connected to a secondary host computer for processing.

All the tests performed in the wind tunnel have been done in a uniform airflow. In reality, tall buildings face different wind conditions, depending on height, due to the presence of an atmospheric boundary layer (ABL). Although real flow conditions are more complex in reality, it is very likely for a tall building to encounter uniform flow conditions from a certain height. The higher the tall building, the more uniform will likely be the flow. As for the complexity of the lower regions, this study can be seen as a preliminary step towards a more complete modeling that can be achieved introducing layers of complexity in the experimental setup.

Moreover, since this work aims to establish a methodology for producing comparative data which would allow to choose between different design configurations, more importance has been given to have similar airflow conditions throughout all the experiments performed, rather than concentrating on the actual profile of the airflow.

Using the data for any other purpose different from comparison of performances would be an error, since in order to relate the wind tunnel results to a full scale building, it is necessary to introduce an ABL as well as produce models with similar dynamic properties to the ones of real buildings.

3.3 Data Collection and Processing

Each MDM was tested with 5 different pattern configurations. Each configuration was tested for a wind angle of 0°, 30°, 60°, 75° and 90° and for a wind speed of 10 fps, 20 fps, 30 fps, 40 fps, 50 fps, 60 fps and 70 fps.

The configurations chosen for wind tunnel testing were the result the characterization of typical wind condition around buildings and the minimum amount of data required to properly train the ANN.

The number of data points for acquisition for each MDM was 175. The procedure to test the models in each configuration is detailed below:

1. Insert the model in the wind tunnel with a specific angle.

2.Regulate the protrusion of the pattern on one configuration.

3.Set the wind speed.

4.Record vibration and pressure data for 2 minutes.

Steps 3 and 4 were repeated until all velocities were cycled, and after that, the protrusion was changed to the new values and the wind velocity cycled again. Once all the protrusions/wind speed combinations were tested, the model angle was changed and the cycle was repeated in full again. Figure 8 shows a schematic diagram of the experimental matrix.

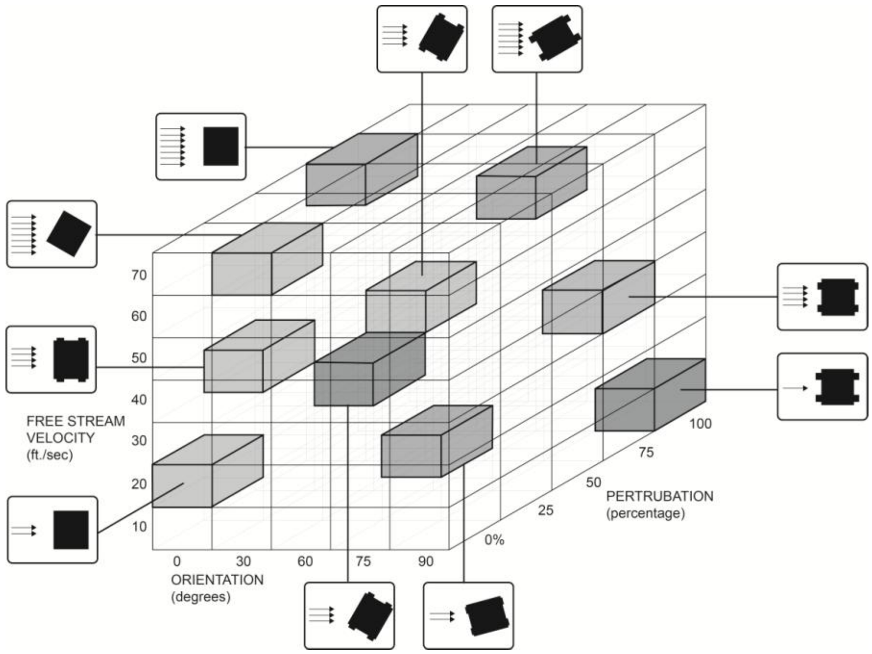

Figure 8. Schematic of the experimental matrix with highlighted cases for illustration.

The vibration data related to x and y axes was successively analyzed to determine the maximum amplitude of the oscillations. For each case, two values of maximum acceleration amplitude have been determined, one for each axis. Finally, pressure values were recorded.

3.4 Artificial Neural Network: Training and Validation

An Artificial Neural Network (ANN) is a mathematical tool that can be used for interpolating data and modeling systems whose dynamics is not easily understood or is too complex to model efficiently.

An ANN can be seen as a mathematical model that adapts its structures in order to match the actual output values to its own predicted values, given a set of input conditions (see Figure 9). ANNs have the capacity to filter out the noise present in both input and output signals.

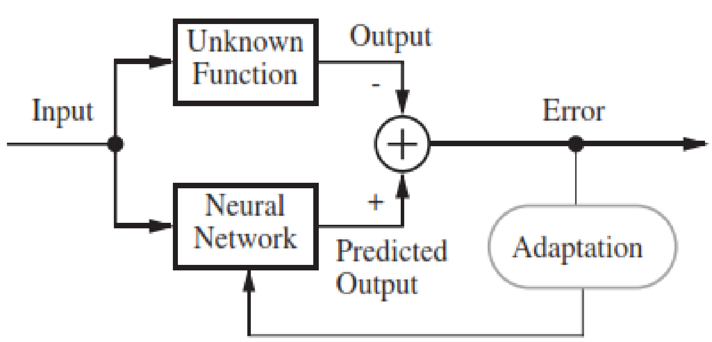

Figure 9. Schematic of how an ANN performs training, comparing the predicted output with the target values in the training dataset

The finite experimental dataset generated through wind tunnel experiments was used to train an ANN. The mathematical model generated through training was able to interpolate the initial finite dataset and generate an effectively infinite data-base (any combination of configurations), considering a certain degree of approximation.

The training dataset for each MDM was represented by the whole experimental dataset but the data related to the wind angle of 65°, which was used to validate the ANN predictions. The input data was represented by the wind conditions (direction and speed) and by the protrusion level, while the target/output data was represented by the vibrations along x and y axes.

The chosen ANN had one hidden layer made of 11 neurons (a neuron is the basic element on which the ANN are built. Each neuron gets the input values and processes them. A typical ANN is made of groups of neurons organized in layers). The structure of the ANN was chosen after trying different configurations and evaluating its predicting performances. One hidden layer and 11 neurons represented the trade-off between computation time and accuracy of prediction. The output layer was made of two neurons, to match the number of outputs (see Figure 10). The network was trained with a Levenberg-Marquardt method, which proved to be more effective for the generation of interpolating mathematical models and a Mean Square Error method was used to measure the training performance.

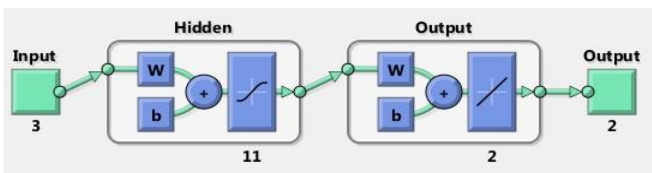

Figure 10. Schematic of the ANN used to model the aerodynamic performances of Model 3

The ANN model was used to generate a predicted output data-base, given the same set of input condition of the experiments and experimental and predicted data was compared, as shown in Figure 11.

It was observed that there is a good correspondence between predicted and collected data. The predictions related to the x axis present a root mean square error (RMSE) equal to 0.2074 while the data related to the y axis present an RMSE of 0.3025. Nonetheless, it is always advisable to check the predicting capabilities of a neural network using a set of data that has not been used to train it. For this reason, the experimental data related to a wind angle of 75° has been used to test the predicting performance of the ANN. The RMSE for the predictions related to the x axis in the validation dataset is equal to 0.2057 while for the y axis the RMSE is equal to 0.2323. Since the RMSE on the validation dataset did not increase but is actually lower, it means that the ANN was not over-trained and that it maintains good generalization properties. Figure 12 shows the predicted and collected vibration data for x and y axes given a set of different input conditions.

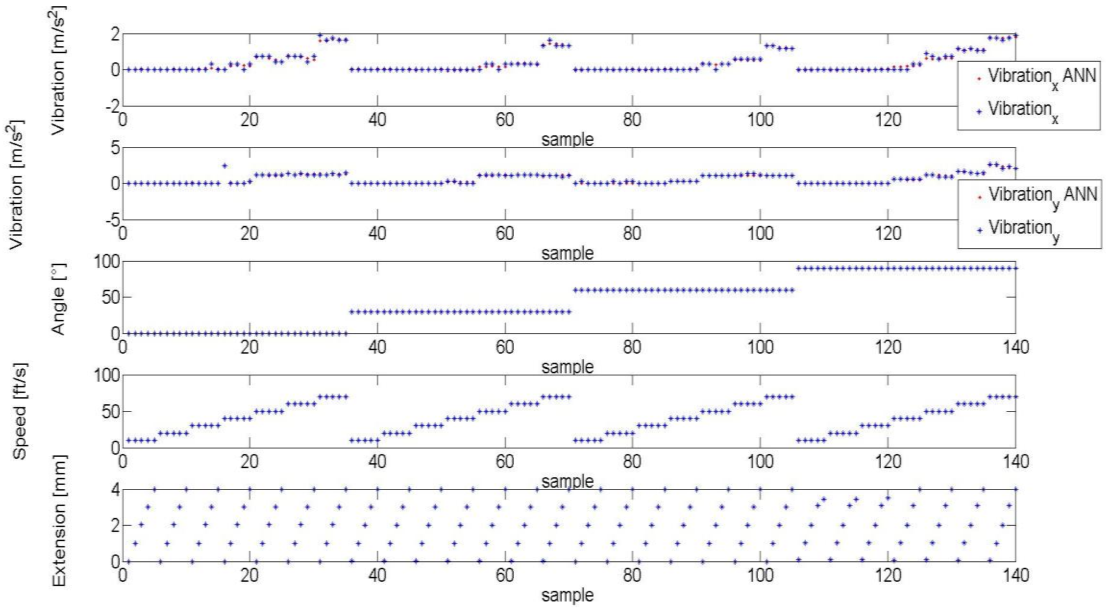

Figure 11. Top to bottom: the predicted and collected data for vibration along x, the predicted and collected data for vibration along y, the wind angle at which the sample has been tested, the wind speed at which the sample has been tested, the value of extension (protrusion) in mm at which the sample has been tested.

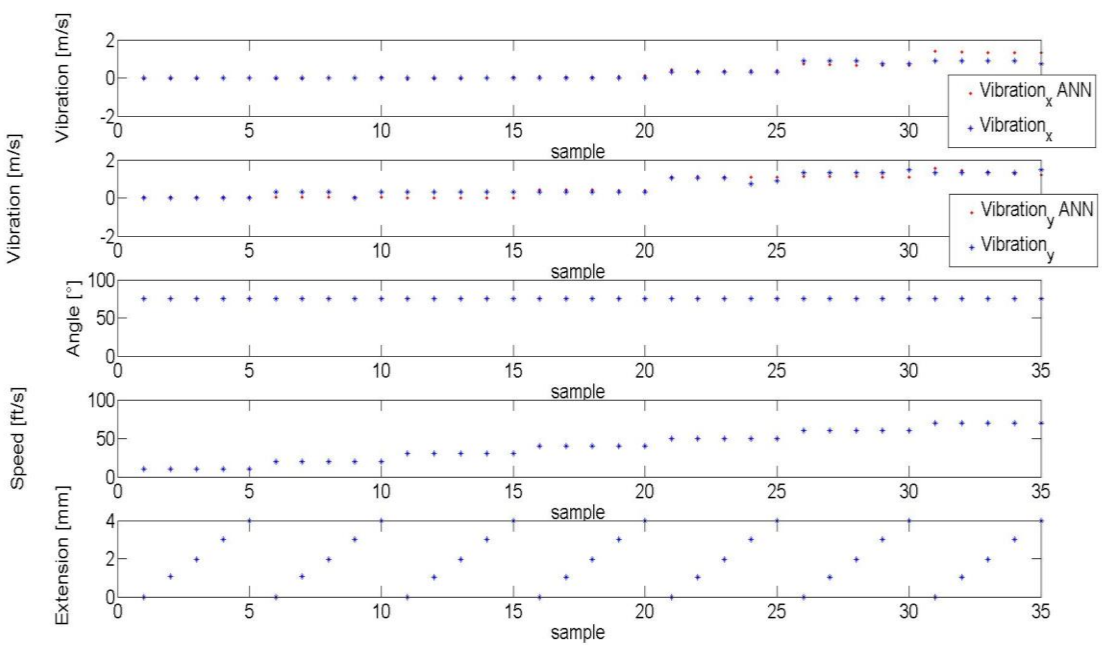

Figure 12. Top to bottom: collected and predicted vibration data along the x axis for a wind angle of 75°, collected and predicted vibration data along the y axis for a wind angle of 75°, the wind angle at which the model has been tested, the wind velocity at which the model has been tested and the Extension (protrusion) level at which the model has been regulated.

4 Summary, Conclusions and Discussion

This paper presents the development and validation of a work flow process to integrate performance based design criteria during the concept design phase, in this case, aerodynamic performance criteria. MDMs have been tested in different configurations in the wind tunnel, simulating different wind conditions (speed and direction) in order to generate an empirical database of aerodynamic performances.

The empirical database has been used to train and validate an ANN, needed to expand the empirical database through interpolations.

The aerodynamic performance predicted by the ANN proved to be consistent with the empirical data. The proposed framework successfully allowed inquiring on the aerodynamic performances of a building, starting from a limited empirical dataset obtained through experiments in wind tunnel. The interpolated aerodynamic performance can be used, coupled with other parameters like building costs and energy-driven parameters like self-shading, to drive the design of buildings during the concept design phase.

Performance driven design will require a radical shifting of process and workflow to deliver buildings with accountability through an integrated interdisciplinary approach and a greater design space. Our research shows promise as a step towards the generation and integration of aerodynamic performance data-base within the framework of the design practice of tall buildings.

5 Future Work

The natural progression of the work is the generation of other data-bases, such as solar performance, for a set of similar configurations, and their integration with the APDB. Combining performance data-bases and integrating them into the framework constraints of a parametric design approach will enable the new design process workflow, as shown in Figure 13.

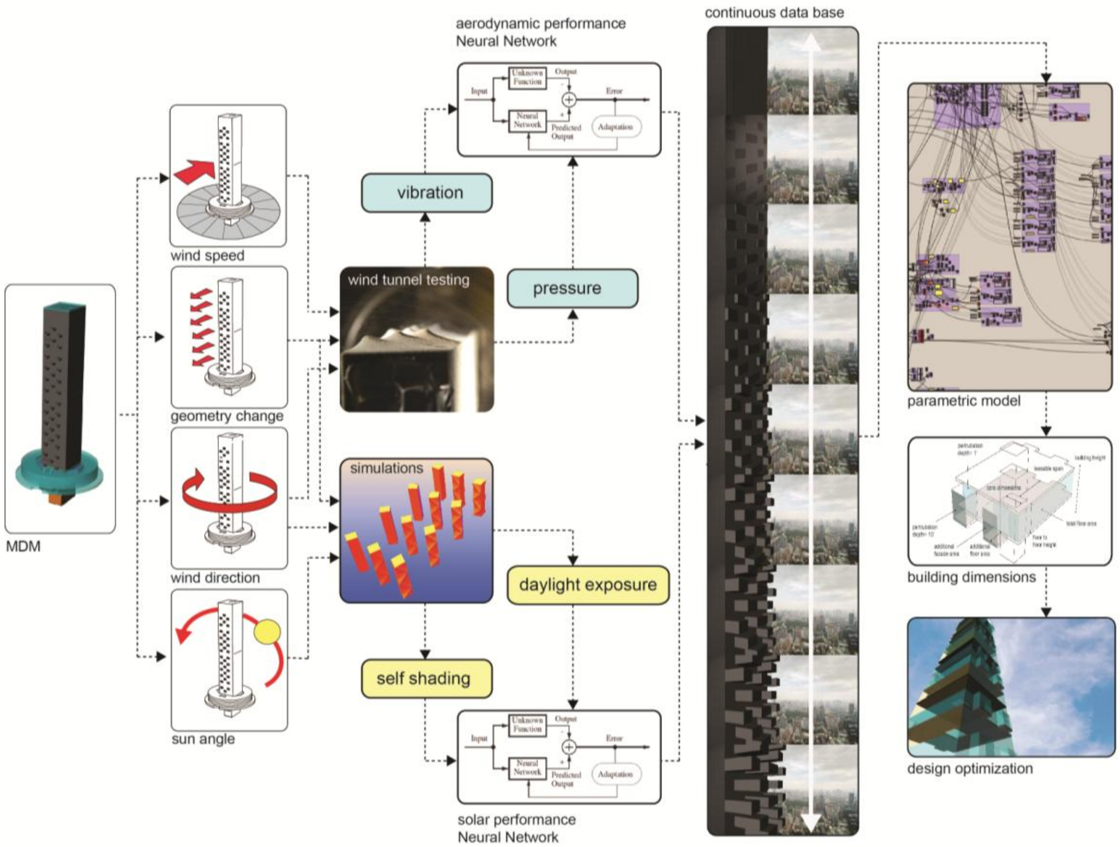

Figure 13. The integration of the proposed workflow into a framework of early design phase of tall buildings.

Future models should include more parameters so more complex interdependencies could be related to full-scale conditions. Furthermore, future models should be tested under simulated ABL both for performance of individual buildings as well as for tall buildings immersed in a built context. Finally, advancing the resolution and type of the models' sensing capabilities will enable the inclusion of other important parameters such as temperature and heat transference, and the prediction of building performance at other scales.

6 Acknowledgements

The authors wish to thank Professors Dyson, Letchford and Amitay at Rensselaer Polytechnic Institute for their knowledge and support.

7 References

Abdulrahim, M., Garcia, H., Ivey, G.F., Lind, R., (2004). Flight Testing A Micro Air Vehicle Using Morphing For Aeroservoelastic Control, 45 AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 19-22 April 2004, Palm Springs, CA, USA.

Ali, M., Aksamija, A. (2008). Towards a Better Urban Life: integration of cities and tall buildings. Invited Keynote Paper. The 4th Architectural Conference on High Rise Buildings , June 2008, Amman – Jordan.

Gane, V. and Haymaker, J. (2008). Benchmarking conceptual high rise design processes, CIFE report #TR174, Stanford University, 2008.

Gavalda, X., Ferrer-Gener, J., Kopp, Gregory A., and Giralt, Francesc (2011). Interpolation of pressure coefficients for low-rise buildings of different plan dimensions and roof slopes using artificial neural networks. Journal of wind engineering and industrial aerodynamics, V: 99(5):658-664.

Goncalves, J.C.S. and Umakoshi, E.M. (2010). The environmental performance of tall buildings. Washington DC: Earthscan.

Hayashida, H., Iwasa, Y. (1990). Aerodynamic Shape Effects on Tall Building for Vortex Induced Vibration, Journal of Wind Engineering and Industrial Aerodynamics, V.33 (1-2): 237-242.

Jingfeng, X., (2005). An artificial neural network approach for predicting architectural speech security. The Journal of the Acoustical Society of America, V.117 (4):1709-1712

Kareem, A., Tamura, Y. (1996). "Mitigation of wind-induced motions of tall buildings, tall building structures: A world view", Council on Tall Buildings and Urban Habitat, Lehigh University.

Keisler, F., (1939). "On Correalism and Biotechnique: A Definition and Test of a New Approach to Building Design". The Architectural Record, Sept 1939: 60-75.

Krauss, G., Kindangen, JI. Depecker, P. (1997). Using artificial neural networks to predict interior velocity coefficients. Building and Environment, V. 32 (4):295-303.

Kwinter, S., (1992). "Landscapes of Change: Boccioni's *Stati d'animo* as General Theory of Models". Assemblage V.19:50-65.

Kwok, K.C.S., Wilhelm, P.A. and Wilkie, B.G. (1988). Effect of edge configuration on wind-induced response of tall buildings. Engineering structures. V.10 (2): 135-140.

Miyashita, K., Ohkuma, T., Tamura, Y., Itoh, M.(1993). Wind-Induced Response of High-Rise Buildings: Effects of Corner Cuts or Openings in Square Buildings. Journal of Wind Engineering and Industrial Aerodynamics, V.50: 319-328.

Stavrakakis, G.M., Zervas, P. L., Sarimveis, H. and Markatos, N. C. (2010). Development of a computational tool to quantify architectural-design effects on thermal comfort in naturally ventilated rural houses. Building and Environment, V.50 (1): 65-80.

Tse, K.T., Hitchcock, P.A., Kwok, K.C.S., Thepmongkorn S., Chen C.M., (2009). Economic Perspectives of Aerodynamic Treatments of Square Tall Building, Journal of Wind Engineering and Industrial Aerodynamics, V.97: 455-467.

UN HABITAT, (2006) Annual report.

United Nations, (2002). "Future World Population Growth to be concentrated in Urban Areas", United Nations Population Division Report, New York, NY: United

Nations.

Watts, S., Kalita, N., Maclean, M., (2007). The economics of super tall towers, the structural design of tall and special buildings.V.16 (4): 457-470. John Wiley and Sons, Ltd.