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A Bioclimatic Comfort Design Toolkit For High-Rise Buildings

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Jeroen Janssen is an associate within p.art®, the Parametric Applied Research Team at AKT II, a structural engineering consultancy based in London. He is responsible for the Bioclimatic Design Services the firm is offering to architects and developers. He and the team developed an in-house custom digital toolkit to enhance the workflow of these numerical simulations, working in close collaboration with architects and engineers. Janssen received an MSc degree in Architecture and Engineering from Eindhoven University of Technology and holds an MArch from the Architectural Association School of Architecture in London.

Abstract

Building in an ever more urbanized world, with high-rise buildings increasing in both height and number, makes it essential to ensure we create comfortable urban spaces, as the urban microclimate in and around towers is affected dramatically. This paper proposes a new method of computational design that creates a continuous workflow, one that synthesizes the interaction of dynamic structural behavior, climate, and thermal comfort directly into the digital design process. The author's team has developed a custom software interface that connects different aspects of the design (geometry, BIM, structural analysis, and computational fluid dynamics) in one workflow, allowing different members of the design team to interact simultaneously and inform the design in real time.

Keywords: MEP Engineering, Thermal Comfort, Environmental Engineering, Computational Fluid Dynamics (CFD)

Introduction

The essence of architectural design comes down to the question of providing shelter and well-being for the occupants of a space. It follows that we should be able to ask ourselves the simple question of whether we are comfortable in a space, whether it is inside or outside. But the answers to this seemingly simple question are difficult to quantify. We need tools and measurements to assess and decide if the design is successful for the intended use of a space.

The efficacy of the toolkit developed by the author's team can be shown through the example of three real-world projects in London (see Figures 1, 2, and 3). An initial speculative test case around the Centre Point Tower will illustrate the use of an hour-by-hour thermal simulation and show how this can be utilized to assess and mitigate

Figure 1. Centre Point Tower, London. © (cc-by-sa) Paul Farmer.

Figure 2. Millbank Tower, London. Source: Millbank Tower Proposal.

Figure 3. South Bank Tower, London. © John Parkin

potential urban heat island effects. The redevelopment of the Millbank Tower will be presented as a second case study of how the toolkit has been used to determine pedestrian wind comfort levels around the complex and its influence on the design. A third test case shows how the toolkit determined load patterns on the façade of the South Bank Tower and established a direct link to the dynamic structural analysis software. The toolkit allows the design engineer to utilize these advanced computational tools to inform the design in the earliest stages of the process and therefore enable a new generation of high-rise buildings in the megacities of the future.

Design Challenges

Current design practice shows a myriad of ways to deal with the problems ahead. Where some designers use rules of thumb and define the impacts of the built environment to the microclimate in a very generic way, others might use sophisticated digital tools to model and simulate the environment in great detail. In basic conditions, these rules of thumb might be sufficient and serve the design quite well. However, urban environments are becoming ever more complex, influencing the effects of natural forces on buildings, and amplifying buildings' effects on their surroundings. The current language of architectural design is taking on more complex shapes, while at the same time public awareness of the environment is growing together with the desire (and increasingly the ability) to control or change it. These rules of thumb might then prove not elaborate enough, and therefore a detailed simulation is required.

Modeling and simulating climatic phenomena, and subsequently wind or thermal comfort assessments, is still considered state-of-the-art technology that can only be dealt with by a specific field of experts within practice and academia. These models are not only highly complex and extremely time-consuming to set up, but are also data-hungry, requiring extensive computational power to execute the simulations and subsequently read out and understand the results.

The author's team, consisting of AKT II, together with Tyréns UK and Gas Dynamics, took on the challenge to inform and shape architectural design by using the urban microclimate as a design input. In order to do this, the researchers needed to gain an understanding of the full aspects and influences that go into modeling and simulating the microclimate. The objective, then, was to find bioclimatic design solutions and develop a toolbox of repeatable methods for designing with them. These methods would then be assessed and compared through classified and well-known comfort criteria in order to make a valuable contribution to the early design phases.

Currently, there is a fragmented array of tools and a patchwork of software on the market that serves to answer questions regarding climatic comfort. Many of these work in isolation on one aspect, be it solar radiation, wind flow, or humidity. Other climatic inputs, and the summary results of their interaction, are not intrinsically taken into account. Furthermore, most of these tools are geared to the *internal* comfort of built spaces, whereas the aim of this research is to develop the potential for influencing pedestrian comfort in the *external* urban realm.

In order to accurately model the full range of urban climatic response, the team felt the need to combine these aspects together into one comprehensive toolkit, which not only allows for a full year-round simulation, but also provides an efficient link to the urban geometry and a user-friendly interface.

What is Comfort?

Before continuing to the technical aspects of the simulation, the design space needed to be defined. What do we mean by pedestrian thermal and wind comfort?

Thermal comfort is described as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." Standards for internal thermal comfort are well defined within local building regulations (ASHRAE 2013). Maintaining this standard of thermal comfort for occupants of spaces is one of the important goals for design engineers.

> "The team's goal was to develop a novel digital design toolkit that could simulate and assess the external thermal comfort of pedestrians in an urban space."

Internal thermal comfort is a well-established field of practice for the services engineer. The team's goal was to develop a novel digital design toolkit that could simulate and assess the external thermal comfort of pedestrians in an urban space. This toolkit would allow creating a well-informed design for the microclimate of external spaces in complex climatic conditions. With this toolkit, the role that the proposed geometry and material properties will play to influence the perceived comfort of a space can easily be assessed.

Within the research community, there is strong interest in the quality of open urban spaces and a continuing search for methods to design with climatic effects. A number of research projects have been undertaken to determine comfort indices to meaningfully assess and compare external spaces. One of the most extensive works of research evaluates people in an urban space in any climatic region according to its Actual Sensation Vote (ASV) (Nikolopoulou, Lykoudis & Kikira 2004). The ASV finds an empirical comfort assessment of a space, corrected for different climatic zones, largely based on field surveys with nearly 10,000 interviews across

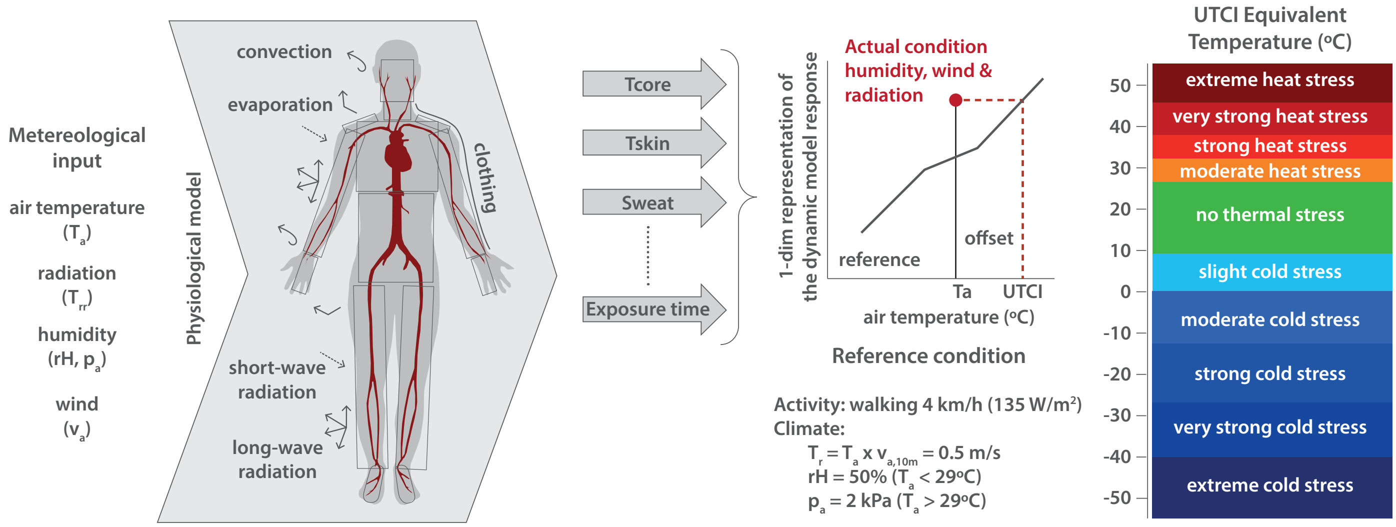

Figure 4. The Universal Thermal Comfort Index (UTCI) Equivalent Temperature identifies comfort in an urban space via a relative temperature scale.

Europe. Other models, such as the Predicted Mean Vote (PMV), form a mathematical view on thermal comfort and were originally developed for internal thermal comfort problems; however, their use nowadays is being extended for external applications (Fanger 1970).

This team decided to implement the Universal Thermal Comfort Index (UTCI) within the Bioclimatic Design Toolkit (Bröde et al. 2009). The research establishing this index was initiated to fill the gap in available assessments in order to produce a satisfactory result, considering thermal-physiology and heat-exchange theory. The index is specifically geared towards thermal comfort in the urban space. The research set out to define a model of thermo-physiological significance in the whole range of heat exchange conditions of existing thermal environments, which would be valid in all climates, seasons, and scales, as well as be useful for key applications in human biometeorology. The project was funded under EU Cooperation in Science and Technology (COST) Action 730, and built up over several years of research by a number of highly respected research institutes across Europe. The methods were verified and validated using 65 independent experiments, revealing good agreement with measured data for regulatory responses.

The UTCI Index adopts the Fiala body model, which is a complex multi-node model that accurately simulates phenomena of human heat transfer inside the body and at its surface, taking into account the anatomical, thermal, and physiological properties of the human body (Fiala et al. 2011). Heat losses from different body parts to the environment are modeled in detail, considering the inhomogeneous distribution of temperature and thermoregulatory responses over the body surface. Within the model, people's clothing behavior was considered based on the air temperature, in a non-linear way.

The atmospheric variables determining the complex heat exchange conditions are air temperature, wind velocity, water vapor pressure, short-wave (solar) radiation, and long-wave (infrared) radiant fluxes emitted by the surroundings, including the sky. All these inputs are taken into account in determining the UTCI Index (see Figure 4).

While the UTCI is a very powerful and comprehensive comfort index, often there is still the need to look at some climatic phenomena in isolation. This is specifically the case for the wind environment around a site, and when pedestrian wind comfort is considered an issue. With a Computational Fluid Dynamics (CFD) simulation, we can evaluate the wind regime around a development in a numerical wind tunnel. When the full spectrum of wind directions is being evaluated, the results can be related statistically to the probability of occurrence of wind blowing from a certain direction with a certain velocity. Typically, measured data of a 30- to 50-year period would be used and compiled to a model year (Troen & Petersen 1989). This can then be expressed into a comfort value, relating both wind speed and gustiness to the proposed activities of a space. On the whole, they are based on threshold exceedence criteria, i.e., "if a mean hourly wind speed of 5 m/s is exceeded for more than 5% of the year, the space will be unsuitable for sitting." This team often used the widely known and respected Lawson comfort criteria, considered best practice guidance and widely used in the established field of wind research within the United Kingdom; or the

> "What happens when the dynamic behavior between structure and wind start to influence each other, and therefore determine the structural properties of a supertall building?"

Dutch wind nuisance criteria, which is a codified method in the Dutch building regulations (see Figure 5) (Blocken, Janssen & van Hoof 2012; Lawson 2001; NEN 2006).

Bioclimatic Design Toolkit

Having established the requirements for a comprehensive assessment of the thermal comfort of an urban space, the radiant effects due to the climatic inputs need to be modeled and simulated, together with the effect of materials and geometry and subsequently the simulation results connected to the intended use of a space.

An hour-by-hour simulation needs to be built to assess air temperature, solar radiation, relative humidity, wind direction and velocity, and their effects on latent heat and surface temperatures (see Figure 6). Bioclimatic Design Toolkit starts by reading the climatic inputs from an external weather file, which is generally derived from 30 to 50 years of measured data compiled into a typical "model year," with data for every hour in the year. The geometric properties are modeled in the 3D CAD environment and material properties are assigned. Façades are automatically subdivided into small, discrete elements in order to capture all variations over the geometry. This modeling and set-up happens within McNeel's Rhinoceros software, directly linked into the toolkit. This allows for efficient handling of models, control over the simulation and the ability to quickly assess multiple options early in the design phase. When all these climatic effects are simulated by the toolkit engine, the results can then be visualized directly into the 3D CAD environment and thus fully embedded within the design models of the wider design team. Following the physical simulation of thermal effects on the façades, the urban domain can then be interrogated for the climate indices mentioned above, by means of cutting a horizontal plane and visualizing the thermal comfort for every point on this plane.

The simulation of the toolkit starts by establishing three initial sets of data that will be used during the hour-by-hour thermal simulation. The first one is a shadow map for the full geometry under investigation for every hour of the year (see Figure 7). The second data set is the shape factor, which entails the geometric relationship or ratio of how much each panel "sees" of all the other panels, and is used for the long-wave panel-to-panel reflections during the subsequent simulation. The final data set to compute before starting the simulation is the sky-view factor, which determines how much of the sky is visible for every data point on the façade.

Thermal Comfort at Centre Point Tower

For the area around the Centre Point Tower in London, a speculative test case was built to assess the thermal comfort of the new public spaces in front of the tower. The tower, an iconic London landmark, was originally built in the 1960s and is currently under redevelopment, including a redesign of the public spaces surrounding the complex. The team used this well-known urban environment as a test case during the development of the toolkit and as a validation to check the accuracy of the calculations.

After establishing the global inputs into the toolkit, the hour-by-hour simulation commenced for the full year. For every data point on the façade of the Centre Point tower and all its direct surroundings, a full implicit energy balance was calculated, taking into account all the energy exchanges due to direct and indirect solar radiation, long-wave radiation from the sky, heating or cooling by convection, long-wave radiation reflected by the surrounding geometry, and finally the conduction through the surfaces. This resulted in a surface temperature for every data point on the façades for every hour of the year. The surface temperatures from the current

P (U_{THR} > 5 m/s in % hours per year)	Grade	Activity		
		Traversing	Strolling	Sitting
<2.5	A	Good	Good	Good
2.5–5.0	B	Good	Good	Moderate
5.0–10	C	Good	Moderate	Poor
10–20	D	Moderate	Poor	Poor
>20	E	Poor	Poor	Poor

Figure 5. The Dutch wind nuisance criteria according to NEN 8100:2006 connects the probability of wind speeds occurring with the intended use of a space.

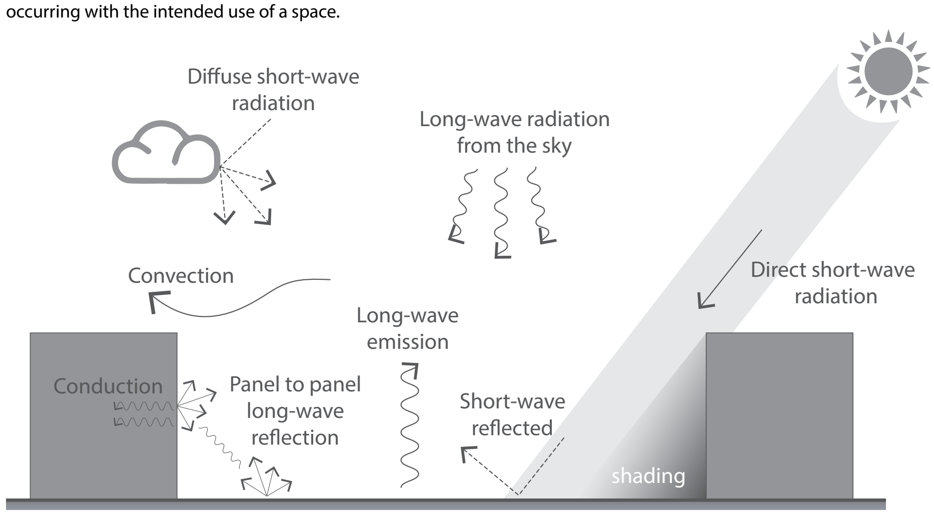

Figure 6. Overview of the full energy balance that needs to be calculated, for every hour of the year, for every data point within the urban domain.

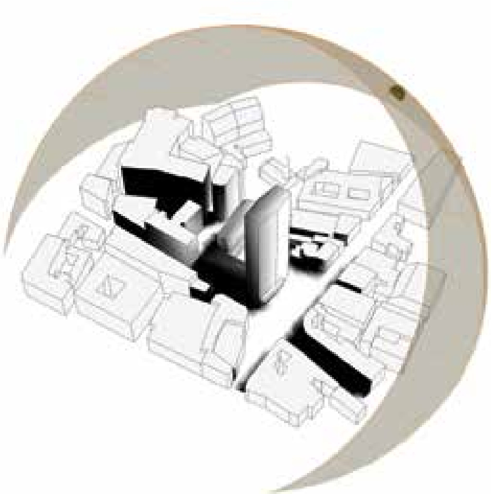

Figure 7. Shadow map for the area around Centre Point Tower on April 29,1:00 p.m.

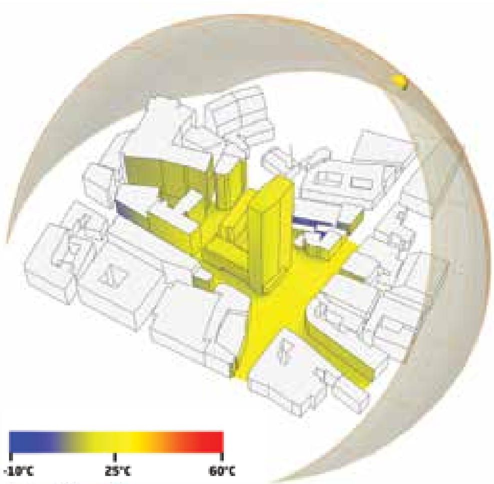

Figure 8. Simulated surface temperatures as a result of the full thermal energy balance simulation on the Centre Point Tower façades and surroundings on April 29,1:00 p.m.

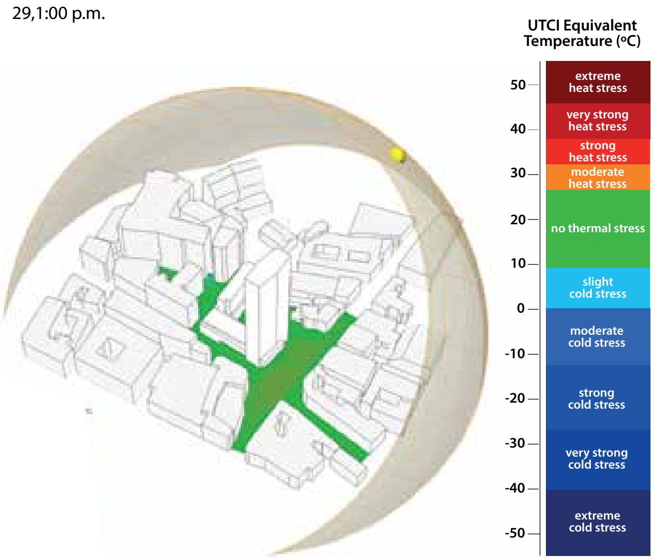

Figure 9. Simulated UTCI Equivalent Temperature on a horizontal plane at 1.5 m above grade for the area around Centre Point Tower on April 29, 1:00 p.m.

time-step were then used as an initial condition for the next hourly time-step for the next energy-balance calculation (see Figure 8).

In order to then visualize the thermal comfort of a space, a horizontal analysis plane at 1.5 meters above grade was generated, cutting through the urban domain. For every sample point on that plane, the UTCI Equivalent Temperature was computed, dependent on the distance and influence of the latent heat in the geometry and the climatic inputs of the environment. This index was then plotted via a color gradient, visualizing how successfully the space performs (see Figure 9). The UTCI Equivalent Temperature shows a relative temperature, normalized for a typical body, a reference activity, and a reference climate. With these results in hand, different urban interventions and configurations can be meaningfully compared, and the shape of the building can be optimized.

Pedestrian Wind Comfort Assessment For the Millbank Tower

Besides the full thermal radiation modeling as shown above, the toolkit can also investigate levels of pedestrian wind comfort in isolation around new and existing developments. For the redevelopment of the Millbank Tower, the team compared the pedestrian wind comfort for the existing situation of the tower and its adjacent buildings against that of the proposed architectural design. In order to assess the year-round comfort levels, the wind flow can be assessed by means of a CFD simulation for all 12 directions at 30º intervals, covering the full range of wind directions. Results of the individual directional simulations can be visualized on horizontal planes, showing not only the behavior of the wind around the buildings at a specific height, but also as streamlines showing a detailed path of wind velocity and direction around the corners of the buildings (see Figure 10). Typically, when assessing pedestrian comfort, these simulations would be run with a logarithmic atmospheric boundary layer input of wind equivalent to a constant velocity of 10 m/s at 10 meters' altitude, corrected for the local terrain roughness and elevation (Norris & Richards 2010).

This informs the design team about the specific behavior of the wind around the urban development for every direction, which can then be statistically related back to the wind rose, and the probability of wind blowing from a certain direction, with a certain speed, at this specific location. These statistical probability factors can be read from measured datasets from a nearby airport over a period of 30 to 50 years and accurately transposed to the terrain roughness and elevation of the site under investigation. These probabilities can then be related to the intended use of a space and put into a range of categories according to the appropriate year-round comfort criteria, such as the Lawson Comfort Criteria or the Dutch Wind Nuisance Criteria (see Figure 11).

The results can be used to inform the massing of the development, allowing comfort levels to be assessed, compared, and improved. In the case of the Millbank Tower, closing the roof on the courtyard area improved the comfort levels at the street level in front of the development dramatically. Multiple further iterations can be easily assessed due to the digital character of the simulations.

Applying the Toolkit to Optimize The Structure of South Bank Tower

A third case study shows the potential of the toolkit for its application in structural optimization of high-rise buildings, and how this has been applied during the design for the redevelopment of the South Bank Tower.

The existing South Bank Tower, built in the early 1970s, consisted of 31 floors. The initial architectural design for the redevelopment allowed for six new floors to be added to the existing tower. Building regulations for the effects of wind loading on structures often look at generic cubic or cylindrical building forms. Therefore, these codes often prove to be too conservative. The expressive shape of the architectural proposal for the South Bank Tower led the design team to determine the structural wind loading early on in the design phase with the aid of a CFD simulation with the Bioclimatic Design Toolkit workflow (see Figure 12).

From the results of the simulations, pressure values on the façades were extracted, examined and filtered, and directly linked into the structural analysis models, via a seamless workflow of in-house-developed interoperable digital tools. While reviewing the results of the structural analysis, the required allowance for wind loading was going down to almost half of the requirements imposed by the codified method. This then, in turn, unlocked a further five new floors to be added, bringing the total number of new floors on top of the existing building to 11. Planning permission was granted and construction finished at the end of 2016.

Validation

In order to use the toolkit with confidence, it was essential during the development process to validate all the aspects of the toolkit. The toolkit is a collection of small pieces of validated third-party research and tools, such as the UTCI Equivalent Temperature or the OpenFOAM CFD framework, which is then combined with a custom in-house-built workflow that prepares all the inputs, runs the simulations in the background, and visualizes the results within the 3D CAD environment. Extensive research and corroboration with measured data was performed while developing the custom algorithms that would act on the hour-by-hour thermal energy exchange model (Lindberg, Holmer & Thorsson 2008).

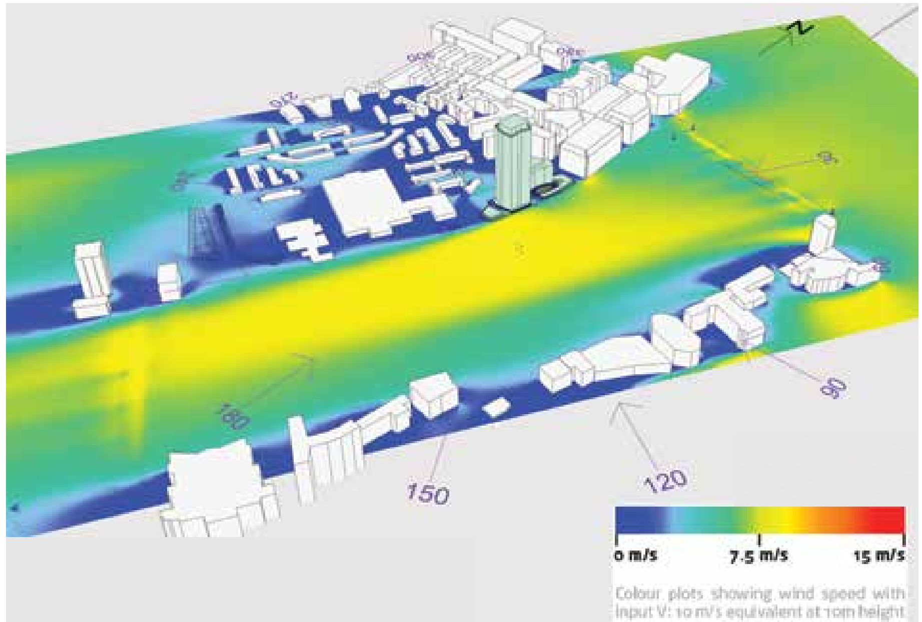

Figure 10. Results of the CFD simulation visualizing wind velocities on a horizontal plane at 1.5 m above grade for the 30° heading (NNE) for the Millbank Tower in London.

Figure 11. Year-round pedestrian wind comfort visualization on a horizontal plane at 1.5 m above grade, according to Dutch Wind Nuisance Criteria, for the Millbank Tower.

“Typically, when assessing pedestrian comfort, these simulations would be run with a logarithmic atmospheric boundary layer input of wind, equivalent to a constant velocity of 10 m/s at 10 meters’ altitude, corrected for the local terrain roughness and elevation.”

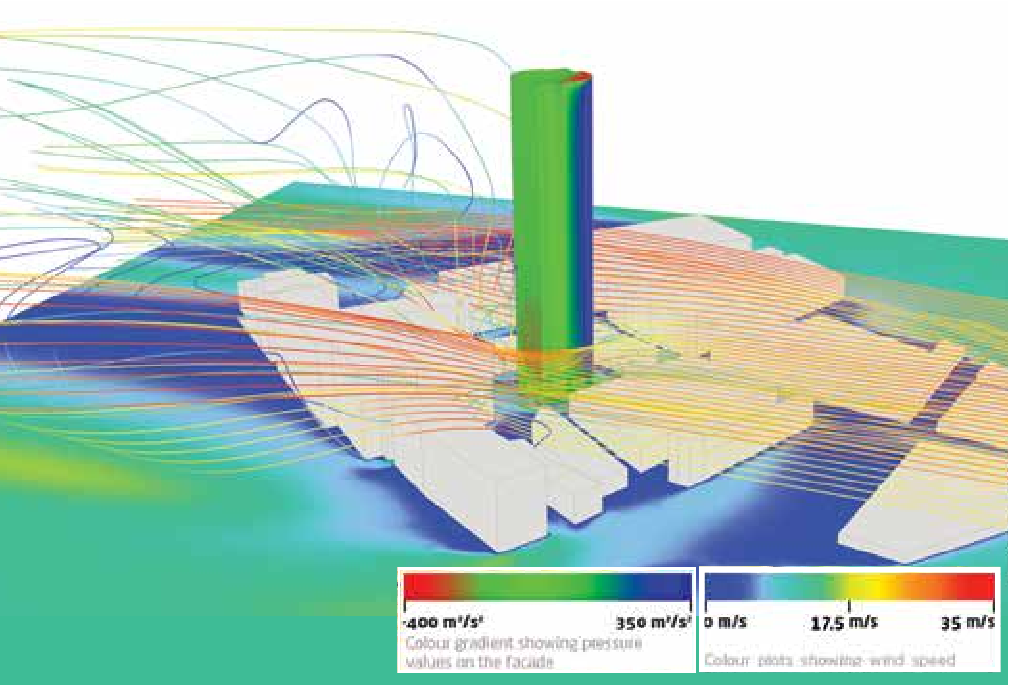

Figure 12. Results of the CFD simulation visualizing façade pressure values on the South Bank Tower.

The inputs for the CFD simulations are set up to conform to the best-practice guidelines set out by Franke, the Architectural Institute of Japan, and others (Blocken, Janssen & van Hoof 2012; Blocken 2015; Franke et al. 2010; Tominaga et al. 2008). Additionally, the team had access to several reports of physical wind tunnel tests performed during the design of high-rise buildings in London. A number of these models were simulated within the workflow of the toolkit and showed an excellent agreement with the physical results.

Next Steps

The toolkit is part of ongoing research and is constantly being expanded and improved in usability. Looking at the near future, specular reflections will be the first new factor included, allowing the modeled material properties to include highly reflective surfaces, as well as enabling glare studies.

Another field of research would be to expand the toolkit in conduction through 3D geometry, including lateral relations. This would enable detailed models of thermal bridges in window frames and façades.

A further big potential lies in the continuous development towards structural applications for the aero-elastic behavior of high-rise buildings. What happens when the dynamic behavior between structure and wind start to influence each other and therefore determine the structural properties of a supertall building? It is reasonable to conclude that the toolkit will have many applications beyond its initial design purpose. ■

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