OPTIMISING HUMAN COMFORT IN MEDIUM-DENSITY HOUSING VIA DAYLIGHT AND WIND SIMULATION

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Abstract. This paper explores the pedagogical context for the inclusion of daylight and wind simulation as part of architectural design-studio teaching. The author describes both challenges as well as opportunities encountered by architecture students who applied high-end technology for optimizing environmental conditions during the conceptual design of a residential project within a thirteen-week studio. Students located their projects in an inner urban context in a ‘Temperate’ climate zone, meaning that they had to account for hot conditions in summer while considering wind-chill factors in winter. Based on the studio experience, the paper scrutinizes how students tackled Computational Fluid Dynamics (CFD) and daylight analysis on different scales of their project. The paper explores how the engagement with latest tools available to architecture students changes their ability to discuss building physics with engineers and question precedence typology. The author describes the pedagogical challenges when helping architecture students to overcome obstacles in communicating engineering aspects inherent to the design process.

Keywords. Environmental Analysis; CFD; Daylight Simulation; Design Pedagogy; Parametric Design.

1. Introduction

Advancements in daylight simulation and computational fluid dynamics (CFD) offer educators unprecedented opportunities to include environmental performance feedback in their teaching. Until recently, the application of CFD analysis was at arm’s length for most architecture students. It has been calculus-intensive and reliant on bespoke engineering software. In addition, CFD analysis tools often required a steep learning curve to master and students experienced delays in receiving feedback due to the response-time required to carry out calculations. Today, computational means to analyse environmental performance is becoming more accessible and ‘real-time’. A number of questions associated to this new-found freedom arise when considering design pedagogy: How can CFD and daylight analysis
be integrated within a semester-long design studio? What is the desired level of accuracy of analysis for design decision support? What is the desired knowledge-level of architecture students regarding building physics (and the associated analysis tools)? How can educators empower students to critically reflect on analysis outcomes and use results effectively to facilitate design changes? What level of interaction with engineering experts benefit architecture students in order to verify the validity of their analysis and design decisions? And finally, do CFD and daylight analysis make students less dependent on design based on precedent typologies by offering them alternative solutions that can be tested instantaneously? The author ran a thirteen-week Masters-level design studio at the Melbourne School of Design in order to tackle the above questions. The paper offers a brief review of approaches to daylight analysis, and it introduces the tool applied for wind analysis as part of the studio. In addition, this investigation reflects on the interaction students had with an engineering expert who offered targeted advice on environmental concerns during the second half of the semester, thereby scrutinizing the extent to which architecture students can/should engage with environmental analysis as part of their design process. The paper offers insights about the extent to which architecture students can most purposefully take their building sustainability exploration, complement their design-thinking, and prepare them for informed conversations with their engineering counterparts.

2. Methodology and Approach

The findings presented in this paper draw from two approaches of inquiry:

1. A literature review of selected papers that report on past efforts in applying computational analysis for testing the effects of daylight distribution and wind/natural ventilation on human comfort in an academic setting.
2. A critical account of the pedagogical approach towards teaching current daylight and wind simulation software as part of a reference project developed by a group of Masters-level architecture students at the Melbourne School of Design.

The key interest of the author was to understand the characteristics of applying latest technology for wind and daylight testing as part of conceptual design in a semester-long studio setting. Compared to previous efforts in the field, what are the opportunities that present themselves to designers who apply daylight and CFD analysis as a matter of course in their early stage design process? The Design studio was subdivided in three phases. From week one until four students dedicated their time on site analysis, including an in-depth study of the prevailing climatic conditions on site throughout the year. In this first phase students developed their preliminary building morphology based on both environmental factors, as well as social aspects of cohabitation and social interaction in a medium-density housing setting. In order to achieve the above students spent the first four weeks of the semester in groups learning about the principles behind CFD and solar/daylight analysis. It was pivotal for students to be able to tie their investigation about environmental performance back to urban planning constraints as well as human experience, behavior and comfort levels. The second phase from week five until nine was dedicated to fine-tuning and advancing design proposals individually. That
phase included iterative processes where students frequently went back and forth from analysis to update their design and verify validity of their assumptions both on a qualitative (aesthetic/social) as well as quantitative (plot ratio/daylight exposure and wind-scenario) level. The third phase form week nine until thirteen resulted in detailed optimization of facade articulation in conjunction with apartment layout and the integration of (semi-)public spaces and circulation. The diagram in figure 1 highlights a process chosen by a student in the use of environmental analysis that spans from an urban scale to a precinct environment and ultimately to the apartment layout.

3. Background

The application of computational means for assessing environmental conditions in architectural and urban design has advanced steadily over the past three to four decades. Initially relegated to a peripheral aspect of architectural design-education, and often carried out via custom scripts and experimental software applications (Maver 1987; Maver and Petric 1995), environmental analysis has moved ever more central-stage. In addition, environmental performance guidelines and associated building codes have led to an ever-increasing use of applications for assessing urban micro-climates as well as building sustainability by architects and engineers. Upon review of existing literature, three key developments become apparent. Firstly, environmental analysis get increasingly applied in early stages where designers still juggle with rapid changes and incomplete information (Den Hartog and Koutamanis 2000). Secondly, advancements in analysis tools allow users to simulate environmental performance of their design ever more accurately without depending on heuristic methods (Fraser and Donn 2011). And thirdly, the increasing proliferation of environmental analysis applications hand in hand with the integration of these tools with existing parametric modelling and topology optimization applications, allowing - in some cases - for multi-criteria optimization across different environmental analysis domains (Sheikh and Gerber 2011;
Kaushik and Janssen 2012). Despite the advances mentioned before, the proliferation of various types of environmental analysis into the design studio has not occurred uniformly. Drawing on ten years of studio teaching where environmental analysis formed a pivotal part of the design process the author could observe that tools associated to sun-path analysis, solar gain, daylight performance, or even carbon-footprint have seen the highest uptake by students. High levels of uptake are due to the relative low level of complexity and computing power required to carry out calculations. For these types of analysis, energy performance results can be mapped onto building topology in a graphically explicit manner by a large number of design tools (Ecotect (TM), IES (TM), Ladybug (TM) & Honeybee(TM)). In contrast, the calculus-heavy approach for measuring the impact of wind via CFD poses much higher performance requirements on computer hardware, in addition to requiring more expert knowledge on how to set up the boundary conditions and how to interpret simulation outcomes.

3.1. DAYLIGHT SIMULATION WITHIN THE ARCHITECTURE CURRICULUM

The availability and quality of natural daylight is an important factor associated to human comfort in residential design. Being able to predict and regulate daylight access in residential design and to test compliance against local regulations has become a crucial component of architectural design. The simulation of daylight is an advanced application of solar analysis. It is based on ray-tracing algorithms that determine daylight (luminescence) factors drawing on exposure to solar gain taken from artificial sky conditions. RADIANCE (Ward 1994) is one of the most commonly applied applications for validated lighting simulation; and it integrates with a great number of design modelling/analysis applications. Hanna (1996) reports on early attempts to integrate daylight analysis software with commonly used CAD tools, highlighting the benefits of using photo-realistic renders for teaching architecture students and practitioners about the use of daylight enclosed spaces. The effects of student learning experience through daylight simulation has been addressed in greater detail by Almaiyah and Elkadi (2014) who report on the relevance of careful integration of technical aspects within design studio teaching. They highlight the need for group work, expert feedback and verification to avoid for the analysis part to become self-referential. An example of daylight distribution on an apartment floorplan carried out in McNeel’s Rhino/Honeybee interface can be seen in figure 2.

Figure 2. Daylight distribution on apartment floorplan based on season and facade variations, image A.Clemens.
3.2. CFD FOR WIND ANALYSIS IN THE ACADEMIC DESIGN STUDIO

A number of researcher have studied the application of CFD for supporting early-stage architectural design. Den Hartog, Koutamanis and Luscuere (2000) focused on indoor climate analysis in their quest for software applications that help the bridge the gap between design analysis and synthesis using CFD tools. They see the ‘formalization of design experience in base cases’ as a pivotal means to facilitate the definition of solution types, thereby simplifying access to analysis results. The accuracy of CFD tools in comparison with physical wind-tunnel testing gets interrogated by Moya et al. (2013) who assess their usefulness for small-scale architectural interventions (wind-shelters) in an urban context. The findings presented in their paper highlight the usefulness of such studies in support of architectural design-decision making. Looking at wind-flow on an urban scale, Kaushik and Janssen (2015) report on means to diminish the time required to carry out CFD analysis via two predominant means: Solution Approximation and Solver Approximation. Whereas the former relies on the transformation of 3D geometry into 2D representations (and therefore lacks the accuracy required for simulation in an urban/architectural context), Solver Approximation shows more promise for scenarios typically encountered in architectural design. Drawing on feedback within existing literature, the author has applied a recently developed tool that promises to overcome some of the challenges typically encountered when using CFD analysis in a quickly changing early-design context. With the tool Flow Design (TM), the software company Autodesk (2014) has released an application that is suitable to approximate CFD for wind analysis on both an urban as well as an architectural scale. The characteristics of Flow Design(TM) include a user interface that requires minimal input from designers who quickly want to explore preliminary - early stage - options for their projects.

4. Reference Project - Master’s level Design Studio

When setting up the program for the reference project presented here, the author was able to draw on prior experience in implementing environmental analysis as part of an architectural design studio (Holzer 2008; 2015; 2016). Feedback from these efforts highlight some key challenges when integrating a strong analysis component with the design process:

- The need for students to first engage with basics of environmental analysis
- A steep learning curve by students associated to learning environmental analysis tools
- Understanding what to measure and determining the level of accuracy of analysis
- The clarity of results allowing architecture students to interpret building physics behaviour
- The students’ ability to verify and discuss analysis outcomes with engineers
- The ability to question building typology that’s based on precedence due to alternative solutions emerging from analysis.

In a 13-week design studio setting it is pivotal to allow students to focus on design rather than being sidelined by steep learning curves for tool-uptake and technical
analysis. The focus of the studio therefore was on place-making with a strong emphasis on human interaction and comfort. Students were tasked to develop a proposal for a medium-density residential project in an inner-urban setting. Environmental analysis was a supportive component of this effort. It was introduced on two levels:

1. as part of the optimisation of the urban microcosm of a medium-density residential project; there the focus lay on optimizing climatic conditions of public spaces
2. as part of the design and layout of residential apartments, in terms of their orientation, solar/daylight access as well as cross-ventilation opportunities within each apartment

The exemplar project was located in the town of the author’s home institution where a moderate climate with cold winters and hot summers is prevailing. One particular climatic condition at the location is the change in wind direction between winter and summer. In order to study this wind condition, students set up their project’s geometry parametrically so to be able to quickly adjust orientation and building height in the early conceptual stages of their project. This flexible setup lent itself to preliminary testing of sun-hours exposure of individual apartments. For CFD analysis, output from their parametric models was then combined with the surrounding urban context model and exported into Flow Design(TM) to check for wind-performance. Figure 3 shows an example of early-stage wind-analysis based on differences in summer/winter wind directions in Melbourne.

![Winter North Wind](image1.png) ![Summer Southeast Wind](image2.png)

Figure 3. Seasonal differences in prevailing wind direction, image by Jinhui Zhu.

5. Discussion

Reflecting on the studio outcome as well as the process leading up to its completion, a number of observations can be made about the students’ use of wind and daylight analysis as part of their exploratory design process.

5.1. ENGAGING WITH THE BASICS OF CFD ANALYSIS IN THE STUDIO SETTING

Feedback gathered during the case-study design studio highlighted that the limited knowledge about building-physics by architecture students and the lack of knowledge about the correct setup of virtual wind-tunnel boundary conditions can lead to incoherent results when using CFD in support of the design process. When it
came to articulating solutions for the urban context, students needed to test and understand the impact of wind-direction on the building typology, orientation, and morphology of their design. Whereas animated wind-breezes in the warm season were welcome, students needed to find ways to adjust their project’s morphology in a way that would allow them to block out unwanted wind-gusts in winter. The wind-chill factor is a major impediment to human comfort in open/public spaces and it needed to be considered as part of the urban design element during the semester. As for daylight analysis, students were quick to realize the basics of daylight distribution, but they struggled to work towards specific targets.

5.2. CFD SOFTWARE LEARNING CURVE EXPERIENCED BY STUDENTS
In contrast to the author’s prior experience related to CFD software uptake by students, Flow Design’s pre-set environment for wind testing allowed users to master its key functions within days, if not hours. One major reason for the quick engagement with Flow Design is due to the great number of pre-set physics and calculus parameters. They allow users to focus on analysis itself without requiring in-depth knowledge about specific physics benchmark. As an example: A parametric setting within Flow Design constrains the relation between the boundary size of the area to be solved and its voxel grid-size, thereby limiting the time required for any given analysis run.

5.3. LEARNING WHAT TO MEASURE (AND HOW ...)
All 16 students participating in the studio struggled initially to grasp what exactly they should measure when it comes to assessing environmental performance. As much as they were quick to set up boundary conditions for simulation and get going with analysis runs, when probed about the exact purpose of their investigation, they could only refer to vague assumptions of what it is they were testing. Students first needed to learn how to associate qualitative aspects of human comfort to quantitative parameters inherent to and stemming from analysis. It took most at least two to three weeks to get a grasp on key benchmarks to work towards, either relating to desired wind-speeds and behavior, or related to luminescence factors at a certain depth of the floor-plates of their apartments (figure 2).

5.4. INTERPRETING RESULTS
Depending on the level of detail desired for CFD output, calculations took between 2-4 minutes before ‘live’ flowline diagrams and flow-vectors were used to display the analysis results. Whereas architects are trained to question design decisions and to detect flaws in their conceptual approach, they are not equally trained to scrutinize results from building performance tests. It could be noted that at the start of the semester students often followed the principle of: ‘what looks right may as well be right’, leading to confirmation bias and skewed results. The students’ inability to critically reflect on simulation output was one of the key obstacles in the effective use of CFD in the design studio.
5.5. INVOLVEMENT OF ENGINEERING EXPERTS TO HELP VALIDATE RESULTS

In order to counter the effects of confirmation bias, the studio was set up to include industry-experts with engineering background who would engage with students face to face to go through their projects at regular intervals throughout the semester. That way, confirmation bias could be eroded over time as the engineers explained in more detail who results from wind analysis needs to be interpreted and what benchmarks to work towards. Three such feedback sessions throughout the semester led to an increase in understanding for students to advance the CFD-related aspects of their design. Once students were confident about the validity of results, they were able to step back and analyse the articulation of their facade solution in a holistic fashion, addressing desired views, regulating daylight access, and providing options for natural ventilation. At the final crit each student presented provided a well-argued-for outcome highlighting how they incorporated feedback from CFD and daylight analysis in their final design (both an on urban as well as architectural level). The crit-panel included an environmental engineer who was probing students on this aspect.

5.6. SCRUTINISING PRECEDENCE VIA THE APPLICATION OF CFD AND DAYLIGHT ANALYSIS

Morphology of medium-density housing projects traditionally often result from typologies that draw on precedence. One major goal of the case-study design studio was to test to what extent CFD and daylight analysis can reduce a designer’s dependence on precedence typology and allow them work on alternative typologies with confidence. All students were encouraged to start of their environmental analysis based on basic geometric blocks (with various scale and orientation) to then conduct wind and solar analysis on well-known residential typologies (tower/block/etc.). The next step was to move away from these known typologies and introduce variations that maintained functional relations, while exploring unprecedented building morphologies. In that sense precedence served as a stepping stone for a more flexible, experimental setup, supported by immediate performance feedback facilitated via CFD and daylight analysis. During the course of the semester, students progressed from a focus on typology and morphology towards a focus on the building-skin definition. Students used analysis results from both CFD and daylight simulations to inform their parametric setup of window sizing, louver-system geometry and the positioning of balconies. Figure 4 illustrates how CFD was applied on this detailed level in order to maximize air-intake for cross-ventilation based on predominant summer-winds.
6. Conclusions

Reflecting on the author’s 10+ year experience in applying environmental analysis in an academic design studio settings, the current suite of computational tools assisting daylight and wind analysis represent a major step forward. Optimizing human comfort in consideration of daylight and wind is increasingly becoming accessible to architecture students with no or little prior knowledge about building physics or associated tools for testing aspects of it. Existing literature highlights the advancements in software application over the past two decades. As shown on the exemplar project, the use of tools such as Grasshopper/Honeybee(TM) and Flow Design(TM) has become ‘second nature’ to students in due course of a 13-week design exercise. The major step forward for daylight analysis is the opportunity to link parametrically defined geometry directly to solar/daylight simulation, thereby avoiding time-consuming re-modelling when creating multiple options for testing. As for CFD analysis, it is mainly the availability of sufficiently precise near-time solvers that approximate the otherwise calculus-heavy and lengthy CFD process. Observations during the exemplar project highlight the need for educators to monitor tightly how students apply boundary conditions for simulation and how they interpret results from analysis runs. In addition, it is essential for students to be able to tie physical building performance to social behavior and human comfort. Understanding the often complex interplay between people’s behaviour and their...
built environment under varying climatic conditions (both indoor and outdoor) is pivotal to the successful design of medium-density housing. One major obstacle for efficient CFD testing of various design options remained the lack of fast CFD (approximation) solvers that integrate with parametrically set up geometry. At the time of writing this paper, such as solution (Butterfly) is seemingly being developed for McNeel’s Rhino/Grasshopper software environment, but thus far, students still had to rely on ‘one way’ software exports of their Rhino/Grasshopper models into Flow Design for further analysis. With this obstacle hopefully removed in the not too distant future, students should be able to speed up their virtual analysis of wind behavior in a parametrically defined setting.

References