Integrating Scientific Visualization with Studio Education – Developing Design Options by Applying CFD

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Abstract
To meet the urgent need of education in environmentally responsive architecture, the Architecture Department of The Chinese University of Hong Kong has organized lectures and studios to provide students with knowledge and hands-on experience in environmental design strategies. Considering the context of Hong Kong with a hot-humid sub-tropical climate and hyper-dense urban environment, the current approach in the design studio education has been mainly based on intuition with very limited supports in terms of technical know-how and scientific evidence. Many students of architecture tend to follow established paradigms that have evolved through experience with similar projects. In this paper, we report the research findings of a pilot study that applied advanced scientific simulation skills in studio education designed to help students explore environmental design strategies during early stages of project design development.

Keywords
Scientific Visualization, Studio Education, Computer-Aided Architectural Design

1 Introduction

The need for environmentally responsive architecture has been recognized in Hong Kong by government agencies, building industry and developers. For example, "Greening 2000" forum demonstrated efforts by the government and the industry towards a sustainable city. To meet this urgent need, a series of courses and a new studio have been set up by The Chinese University (CUHK) to provide architecture students with learning opportunities to acquire the required knowledge and hands-on experience. Various design strategies have been introduced to students for carrying out environmentally responsive architectural design. However, effective building performance assessment for assisting students to select and configure environmental design features in Hong Kong's hot-humid sub-tropical climate and high density context have yet to be explored. In this aspect, the current approach in design studio education has been mainly based on intuition with very limited supports in terms of technical know-how and scientific evidence. Many students tend to follow paradigms that have evolved through experience with similar projects. Because of the complex interdependencies of environmental design strategies and building control systems, the consequences of deviating from a paradigm are very difficult to predict.

Simulation provides architecture students and researchers with the opportunity to test new design concepts in laboratories and studios. It allows one to explore the interdependence of systems and the consequences of redesign. Building scientists have been applying scientific visualization technology to explore and investigate research issues. That is not new. For years, different visualization technologies and visual representations have been studied to provide better simulation. Recent improvements in scientific simulation applications have greatly increased the possibility of adopting this technology into the early design stage of a project. The idea is to put building designers in the center of the analysis process, to let them make use of visual representation as the tool to explore new design options.

In the spring semester 2001, a studio was set up at CUHK to explore the methodology and technical details for integrating advanced scientific visualization tools into studio education. Collaborating with the Architectural Services Department (ASD) of the Hong Kong Government, 12 students from the Master of Architecture program were invited to join the design of a public facility and investigate the design integration of natural ventilation (Figure 1). Computational Fluid Dynamics (CFD) is a powerful technology for students to investigate certain design problems. The goal was to achieve technologically advanced, high quality design solutions to solve the indoor air quality problem of public toilet prototypes in Hong Kong through a joint student-professional design exercise.

2 Methodology

A series of lectures and tutorial sessions were arranged to provide general knowledge of fluid dynamics and necessary techniques for applying CFD simulation to design solutions. A site visit and field measurements were conducted to understand the existing public toilet design and to investigate potential design problems associated with the natural and mechanical ventilation. Sketch design exercises with professionals were carried out. The purpose was to explore possible environmental design strategies that could be applied to the prototype design. CFD simulation was applied to explore "what-if" scenarios during the early design development.

Since the task involved extensive modeling, field measurement, data collection, and generating innovative solutions, a team approach was adopted to facilitate the process of project development. Meanwhile, project architects from the ASD

Figure 1. Final design scheme with scientific simulation as a design evaluation tool.

served as advisors to provide background information, and to give students and instruction on how to make the design options fulfill government regulations.

2.1 Lectures & Tutorial sessions

In the lecture part, basic concepts of fluid dynamics, general knowledge regarding the design of airflow in and around buildings and the simulation setup were introduced. In the tutorial sessions, based on different kinds of architectural features associated with the airflow design, three case studies were created by the research team to quickly establish the linkage between simulation and design evaluation. The principal CFD simulation tools adopted were FLUENT 4.52. It is more flexible in gird generation than other CFD simulation tools available in the market. Also, its sophisticated algorithm takes into account turbulence conditions that other simulation packages tend to oversimplify and treat as linear flow. Indeed, turbulence is an important concept in ventilation-related architectural design. For the tutorial, the research team tried to put aside the complicated theory of CFD, but highlight the basic principles of achieving airflow around or inside a building. As FLUENT 4.52 has weak linkage with conventional CAAD modeling tools, students were encouraged to start with simple models to familiarize themselves with the simulation techniques. Students first simulated a simple room in 2-D (Figure 2) and compared the results with their previous experience received from other courses in environmental technology. The steps were repeated with 3-D models (Figure 3) to consolidate the simulation techniques as well as the principles of airflow.

2.2 Field Measurement and Simulation

Supported by ASD architects, the students carried out field measurements in a newly built public toilet in the Lai Chi Kok Park (Figure 4) as a base for evaluation. Students were divided into teams to investigate the airflow pattern, including the airflow direction and speed, at all inlets and outlets in both the male and female toilet. The mechanical ventilation system was turned on and off for investigating the effectiveness of the active ventilation system of the existing toilet. Students were also asked to record their own "personal experience" concerning the ventilation in the public toilet. Students then modeled a simple indoor environment in the computer to conduct CFD simulation and to compare the results with their observation and personal experience during the site visit.

Results showed that the site is suitable for natural ventilation. Yet, the current design has little support for natural ventilation. The mechanical ventilation was too strong, to the point that it caused discomfort (Figure 5). However, its performance was far from designers' expectation.

2.3 Studio Exercise

Collaborating with professional architects from the ASD, the research team designed a series of studio exercises based on the findings of the field study to help students integrate CFD simulation skills into the design decision process. Students were divided into 3 design teams, each with 4 students, to work on the conceptual design scheme

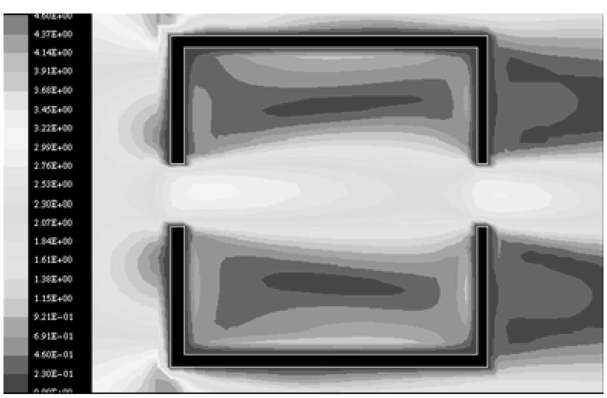


Figure 2. 2-D simulation tutorial.

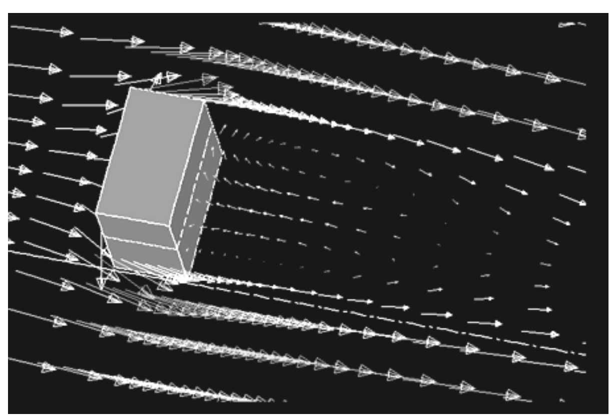


Figure 3. 3-D simulation tutorial.

of the proposed "green" toilet. They could propose new design alternatives or provide retrofit solutions in the design exercise. They had to identify the relationship between the users' behavior and functional needs and the passive or active ventilation strategies adopted in the design. The key factors, which would affect the airflow in the toilet design, were defined. The significance and interdependence of these factors in the simulation process were also explored. The CFD modeling space of the simulation served as the exploration tool and experimental platform to provide evidence to support the what-if design scenario. Although the research team did encourage students to apply the simulation during the early stage of their design exploration, they were not restricted if they wanted to apply simulation in other stages of design. Regular progress checks and discussions were conducted to monitor the whole design process.

3 Findings and Discussion

3.1 Scientific Simulation in Design Approach

The teaching group did not restrict the occasion of applying CFD simulation in the environmental design decision process. The three teams demonstrated different processes in design exploration and problem-solving regarding the simulation implementation. Teams A and C tended to provide new design alternatives based on an overall framework of green building design strategies. Team B tended to modify the existing building to a more appropriate prototype. Team A handled the natural ventilation design requirement with an *integrated approach* and limited design details for assessment. The team omitted the detailed simulation and moved directly into the design development. Team C adopted a *feature-oriented approach* as their metaphor on the use of simulation. The whole design was divided into several key areas for the implementation of natural ventilation. An in-depth study of individual architectural features based on independent topics was carried out. A comparison among different features was conducted to optimize the overall design outcomes. Team B adopted a *incremental approach*. They tended to suggest design modifications based on the current design scheme. The simulation implementation was rather a hybrid of the *integrated approach* and *feature-oriented approach*.

The different approaches adopted by the students drew attention to studio learning in an interesting way. It highlighted the relationship between design decisions and new information generated from the simulation. In this paper, we will focus on the two different approaches for developing new design options: the *integrated approach* of Team A, and the *feature-oriented approach* of Team

Figure 4. Existing public toilet.

Figure 5. Strong mechanical ventilation.

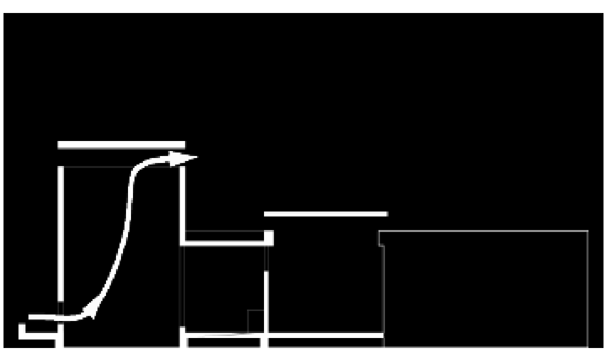
C. As Team B merely focused on modification of the existing building, we shall not discuss it in this paper.

3.1.1 Simulation in the integrated approach

Instead of looking into the principles of fluid dynamics in natural ventilation design, Team A conducted an intensive literature review to explore environmental strategies which could be applied in the Hong Kong urban context. During the beginning stage of the design exercise, limited CFD simulations based on abstract computer models were used to investigate the problem domain. In the first progress review, Team A members put their focus on presenting the conceptual thinking and the possible trade-off among various natural ventilation strategies. Since there was only limited simulation done during this design period, assumptions and common sense knowledge were used to interpret the basic theory adopted by the design team. The "conceptual" design did look very well on paper, and the students were enthusiastic on generating various alternatives. During the design development, simulation techniques were gradually applied to evaluate the environmental strategies adopted, and were also used as supporting evidence to prove that the design options were theoretically and practically sound (Figure 6 & 7). However, simulations applied in the later stage of the design development revealed many "design oversights" which the students were not aware of until the simulations identified the oversights. These design problems slowed down the progress severely since there was concrete evidence to challenge the design options. Meanwhile, the team members had to work back and forth on different levels of design features, to examine the basic theory applied, reconsider the strategies, and conduct simulation to prove the validity of the design options.

3.1.2. Simulation in the feature-oriented approach

Instead of developing the design from an overall conceptual framework, Team C focused on the contributions of various architectural features. The team applied scientific visualization to feature modifications throughout the design process. After the collection of basic context information and operation parameters from the site visit, intensive simulation efforts had been initiated to understand the problem domain and to test the basic theory involved in the planning and design of natural ventilation. Owing to the complexity of ventilation strategy and CFD simulation, the design problem was divided into several well-defined sub-problems like building form, openings, and parapet height (Figure 8 & 9), for further investigation. Basic case studies were conducted to define the design criteria and parameters to quantitatively define the contribution of individual features to the building ventilation. When the time came, they composed the overall design with studied architectural components, which were scientifically supported by simulation. Since valuable "hands-on" experience of the ventilation design had been received from the case studies, Team C demonstrated the understanding and confidence in applying basic theory to solve design problems related to natural ventilation. Only limited time was taken by Team C members to justify the parameters of individual features to form a balanced overall design option. Based on the records from the progress check, tremendous efforts were taken by the team members to generate a series of "fraction simulations", and consistent progress was made throughout the whole design process.



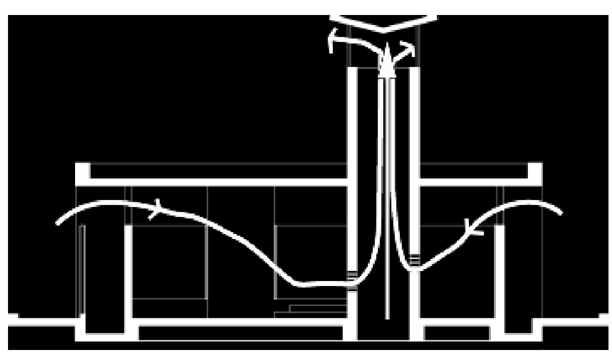


Figure 6 (Left) & Figure 7 (Right). Ventilation strategies suggested by Team A.

However, the relationship of the design options to the whole design problem could never be fully understood by the project advisors or other students until the very end of the design process.

3.2 Mode of Simulation for Design Development

For Team C, the design was composed of a series of features as well-defined sub- problems. Since these sub-problems were well tested before integrating into the overall design scheme, the oversight issue related to detail design would hardly appear in their development process. Attention was mainly drawn to understanding and adjusting key parameters of different features for the purpose of "combination".

For Team A, since the overall design concept came first, the oversight problem of detail design was clearly noticeable because of the lack of simulation support. The detail design of the exhaust chimney inlet (Figure 10) gave an example of this issue. The efficiency of the stack effect of the chimney played a crucial role in Team A's strategy. The exhaust at the toilet cabinets in the female toilet was connected to the two sides of a chimney where the stack effect was to be applied. However, the exhaust air just flew to the opposite toilet before the stack effect become effective or the wind tower effect could contribute to the natural ventilation. After several rounds of discussion based on the simulation outcome, students added a low wall at the middle of the chimney to control the airflow pattern, and adjusted the dimensions of the chimney to accommodate this new design feature. Furthermore, the flat roof proposed by the students did not facilitate the airflow using pressure difference. Also, the sloped chimney roof did not match the direction of the prevailing wind. After comparing different simulation results, the design team made major design modifications to the chimney geometry and orientation to support the ventilation strategy (Figure11).

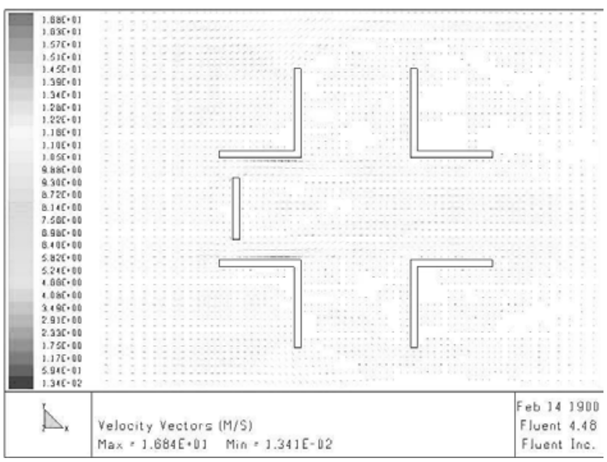


Figure 8. Study of plan strategy.

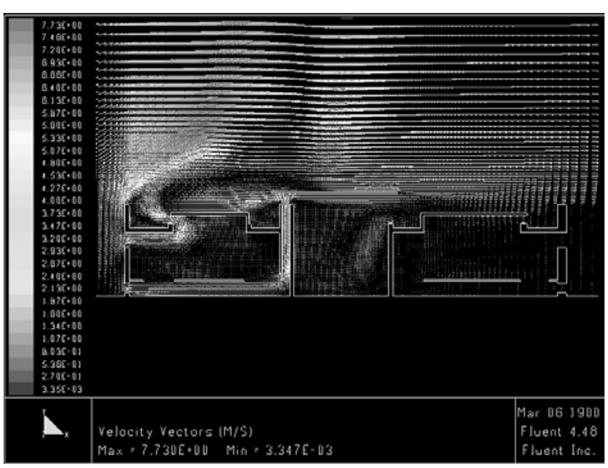


Figure 9. Study of parapet height.

3.3 Comments from the Project Advisors and Architecture Professionals

To investigate what should be the proper methodology regarding integrating scientific visualization into the studio education, special attention had been given to the quality of students' final schemes related to the design mode adopted in the process. In terms of process, the teaching group expects the students to be able to use scientific visualization as a tool to assist their design process. The project advisors and the research team paid close attention to the design scheme of each team during the full range of project imple-

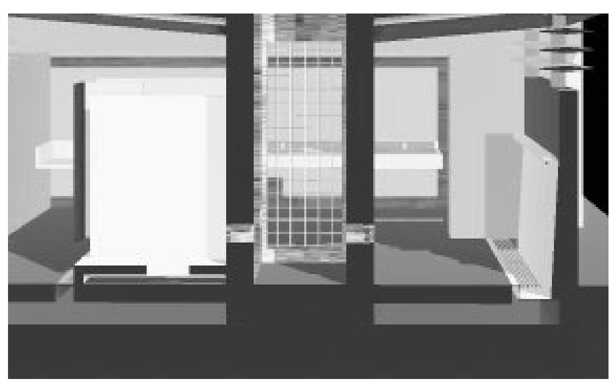


Figure 10. Design fault at the exhaust.

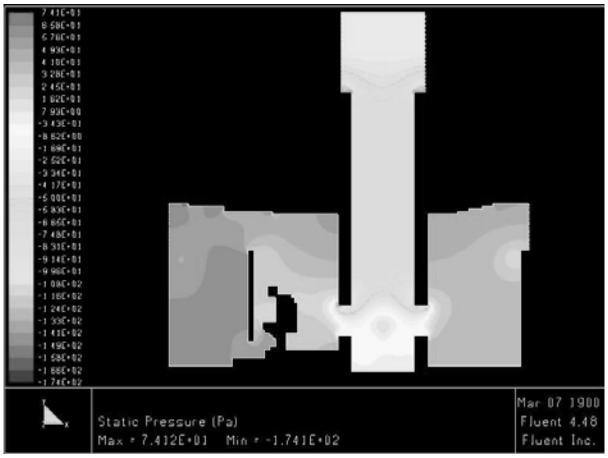


Figure 11. Slope roof for ventilation.

mentation, and we found that the methodology adopted by Team A had limited the potential of the design development. Away from conducting possible "abduction" thinking using the simulation outcomes, they focused on producing scientific proofs to support their "product" instead of other possibilities. It was also because of this that students continuously discovered design oversights. For Team C, different key factors, which might affect the airflow, were defined for detailed investigation in order to explore the problem. Considering the basic knowledge learning, microscopic investigation certainly contributed greatly to this aspect. However, considering the environment of professional practice, the microscopic investigation could easily delay the progress of the design process or "side track" the original attention of the design team. Besides, it is often not feasible to combine all valid design components to form a workable overall solution.

In spite of the design oversights, Team A. had achieved an integrated design scheme. Also, various environmental design issues had been properly weighted and arranged such as natural ventilation, natural lighting, material selection and maintenance. For Team C, the overall performance and quality of the final design scheme was not commensurate with the efforts devoted into the microscopic investigation. Although students in Team C seemed to have better understanding regarding the domain knowledge than Team A, the time required for transforming this knowledge into design strategy implementation limited the possible contribution to the overall design scheme regarding natural ventilation. The project advisors from the ASD during the project review noted this issue.

Advisors and professionals considered Team A's project as innovative, functionally sound, and achievable. The "scientific proofs" provided ensured the effectiveness of the ventilation strategies. But Team C was different. Team C's design scheme was criticized as disintegrated and something in lack of identity. Most of the effort was put on the evaluation of different options for different components. The large number of option pools limited the variety in each pool. The resulting project was not much different from any existing public toilet and contained very limited environmental strategies.

3.4 Effectiveness of Implementing CFD Simulation in the Design Process

The research team examined the effectiveness of implementing CFD simulation into the design process in terms of the mode and the impact to the design stages, and the simulation tools involved.

Team A applied CFD simulation in the late stage of design where CFD simulation was treated as an evaluation tool, and later on as a verification tool for the detail design. Since the simulation

Table 1: Comparison of CFD Simulation Implementation

	Team A	Team C
Initial progress	Fast	Slow
End progress	Slow	Fast
Stage of implementation	End of design process	Throughout the design stage
Mode of implementation	Detail model simulation	Lots of abstracted simulations

outcomes were required by the program to assess the overall design strategy, the design cycle was severely slowed down by the simulation and preparation. For Team C, the simulation had been treated as a design exploration platform in the whole process, and simulation was conducted since the beginning of the design. The comparison is illustrated in Table 1.

In terms of progress, without considering the simulation preparation, it is obvious that designers can proceed quickly and smoothly without any delay. Scientific visualization not only takes valuable time from other design activities, but also frequently interrupts the design process and demands a "paradigm shift" in the problem solving procedure. Although we encountered these difficulties in the studio, simulations conducted in this experiment have obviously provided important reference to students for initial design and modifications (e.g. understanding the problem domain).

There are pros and cons for the simulation tool. FLUENT 4.52 has weak linkage with conventional CAAD modeling tools. To analyze a design option within a reasonable time frame, students certainly could not model every detail for computation. It took much of the tutors' and students' time to abstract the model setup for simulation. Yet, through discussion with tutors and professionals, not only were the necessary components for simulation defined, but the domain knowledge of CFD was also deepened. One might argue that a different tool that offers interactivity would make a difference in the research findings. Interactivity is closely related to the algorithm and the CPU resources. Higher interactivity surely speeds up the recursive design cycle. However, high interactivity is inevitably linked with less sophisticated algorithms or built-in assumptions, and compromises the accuracy of calculation. Therefore, whether a more interactive tool can yield a different result still requires more in-depth studies.

To integrate simulation into the studio, another challenge facing both teachers and students is to figure out a process to establish an abstract model for simulation even when design is not yet fixed. Since there is a limited number of reference cases available and the user interface of the application limits the incremental approach, the time and human resource management issue represents a serious trade-off problem to the design team. In fact, the design teams would like to apply simulation to find out any unexpected design pitfalls during the early stage of design in order to save time and resources in design modification. Since simulation can only be carried out as the abstract form of a real-world entity, important judgement has to be made to modify the detailed design or construction model in order to achieve a reasonable balance among accuracy of simulation outcomes, CPU resources, and required expertise. For instance, Team A composed a detailed 3-D model for simulation, which took almost 2 days of computation. Though all details could be extracted from the simulation, the complex simulation did not promote design modifications due to the long design-evaluation-change cycle. Meanwhile, Team C decided to apply abstract models to serve the purpose of simulation. As commented by the ASD professionals, without proper engineering background, it was difficult to judge whether the abstracted form could represent the design problem. The students did not have the required expertise and experience to carry out that sort of pre-judgement. That affected the accuracy of the simulation results.

4 Conclusion

In addition to engineering knowledge and technical theories, the following issues must be considered in order to implement scientific visualization in architectural studio education:

1. Improving the module (e.g., exercises introduced to students) of CFD simulation for enhancing the simulation implementation process. Before students can implement simulation in the design process, it is important for them to have a thorough understanding of ventilation principle and the operation of simulation tools, limitations and opportunities. The design of the educational module is significant in streamlining the implementation of simulation in the design development process.
2. Emphasizing the incremental approach and also avoiding the waterfall design process. It is essential to consider simulation as a design-supporting tool throughout the whole design process. Implementing simulation and scientific visualization in the design process can help to explore the design opportunities and to discover potential design oversights.

3. Encouraging the exploration of different problem-solving possibilities. Focusing on the scientific evidence of individual components might limit the students' innovative thinking.

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