Computational Fluid Dynamics in Building Design Practice

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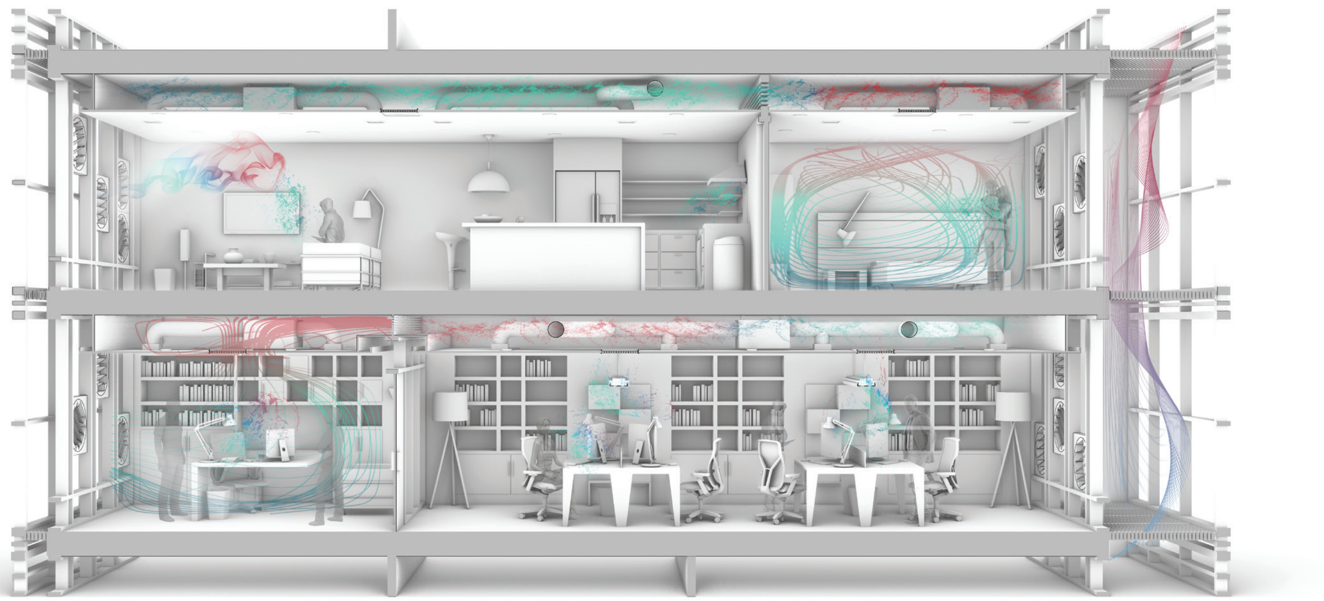


1 A sectional rendering showing fluid flow through different spaces.

ABSTRACT

This paper provides a state-of-the-art of computational fluid dynamics (CFD) in the building industry. Two methods were used to find this new knowledge: a series of interviews with leading architecture, engineering, and software professionals; and a series of tests in which CFD software was evaluated using comparable criteria. The paper reports findings in technology, workflows, projects, current unmet needs, and future directions.

In buildings, airflow is fundamental for heating and cooling, as well as occupant comfort and productivity. Despite its importance, the design of airflow systems is outside the realm of much of architectural design practice; but with advances in digital tools, it is now possible for architects to integrate air flow into their building design workflows (Peters and Peters 2018). As Chen (2009) states, "In order to regulate the indoor air parameters, it is essential to have suitable tools to predict ventilation performance in buildings." By enabling scientific data to be conveyed in a visual process that provides useful analytical information to designers (Hartog and Koutamanis 2000), computer performance simulations have opened up new territories for design "by introducing environments in which we can manipulate and observe" (Kaijima et al. 2013). Beyond comfort and productivity, in recent months it has emerged that air flow may also be a matter of life and death. With the current global pandemic of SARS-CoV-2, it is indoor environments where infections most often happen (Qian et al. 2020). To design architecture in a post-COVID-19 environment will require an in-depth understanding of how air flows through space.

METHODS

This experiment came about as part of a search to find computational fluid dynamics (CFD) software that could be used in a generative design process. There were two parts to this study: (1) a series of interviews with architecture, engineering, and software professionals, and (2) an evaluation of several CFD software packages used in the building industry. It should be noted that parts 1 and 2 were not carried out in isolation, and the results from the software investigations helped to inform the interviews questions, and vice versa.

Industry Professionals

In part 1, interviewees (Table 1) were asked about their integration of airflow analysis into their design processes, revealing existing design technology, workflows, and projects. Interviews were conducted in person, using a series of standard questions:

- Does this firm study/analyze airflow?
- If yes, what is the use of air flow analysis at the firm?
- Which CFD softwares are being utilized?
- At which phase of the design process is airflow considered?
- What are common issues involving CFD that arise in practice?
- What are the challenges when working in a collaborative team involving architects and CFD specialist consultants?
- Is there any postoccupancy data being collected?
- What are your future hopes and outlook for CFD applications?

The direction of the conversation was allowed to deviate and new questions were introduced based on the interests and knowledge of the interviewee. In this way, the interview process was both structured and unstructured (Kvale 1996).

CFD Software Packages

In part 2, software was evaluated in terms of accessibility, hardware requirements, costs, learning resources, and the level of difficulty learning the program. The selected software packages (Table 2) were tested through form-finding exercises. These exercises looked at air flow in interior conditions, such as impacts of mechanical ventilation, the effects of elements such as walls, and the influence of furniture layout and floor plan adjustments.

RESULTS

Industry Interviews

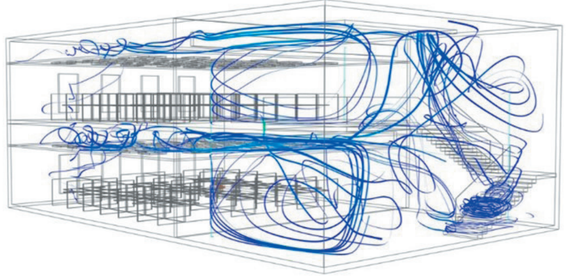
One of the key findings of the interviews was that not only

Table 1 Industry professionals.

FIRMS	INDUSTRY	SOFTWARE
BIG IDEAS	ARCHITECTURE	OpenFOAM SWIFT/Butterfly
KPMB ARCHITECTS	ARCHITECTURE	SimScale Autodesk CFD
ERA ARCHITECTS	ARCHITECTURE	N/A
UNITED NATIONS	ARCHITECTURE	Autodesk CFD
ARUP	ENGINEERING	Inhouse Software
RWDI	ENGINEERING	Inhouse Software
AUTODESK	DEVELOPER	Autodesk CFD Flow Design

Table 2 CFD software packages.

SOFTWARE	DIFFICULTY	TUTORIAL	STRENGTH
RHINO CFD	INTERMEDIATE	LIMITED	BUILT FOR RHINO
SIMSCALE	INTERMEDIATE	DETAILED	CLOUD COMPUTING
BUTTERFLY OPENFOAM	INTERMEDIATE	LIMITED	GRASSHOPPER INTEGRATION
OPENFOAM PARAVIEW GMSH	ADVANCED	AVERAGE	OPENSOURCE



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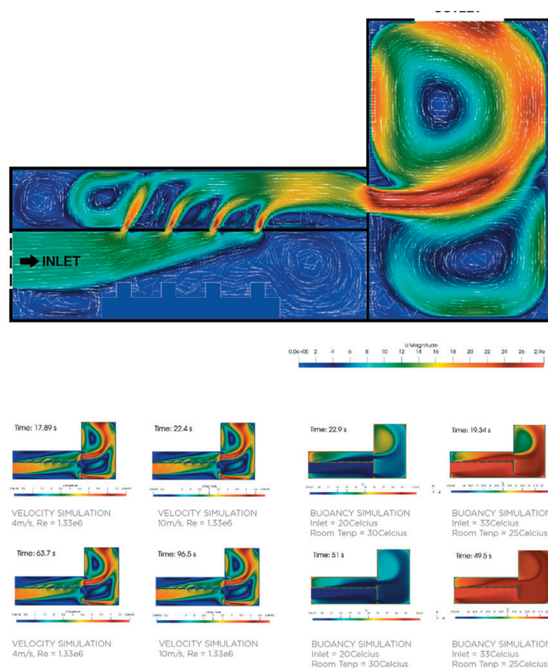

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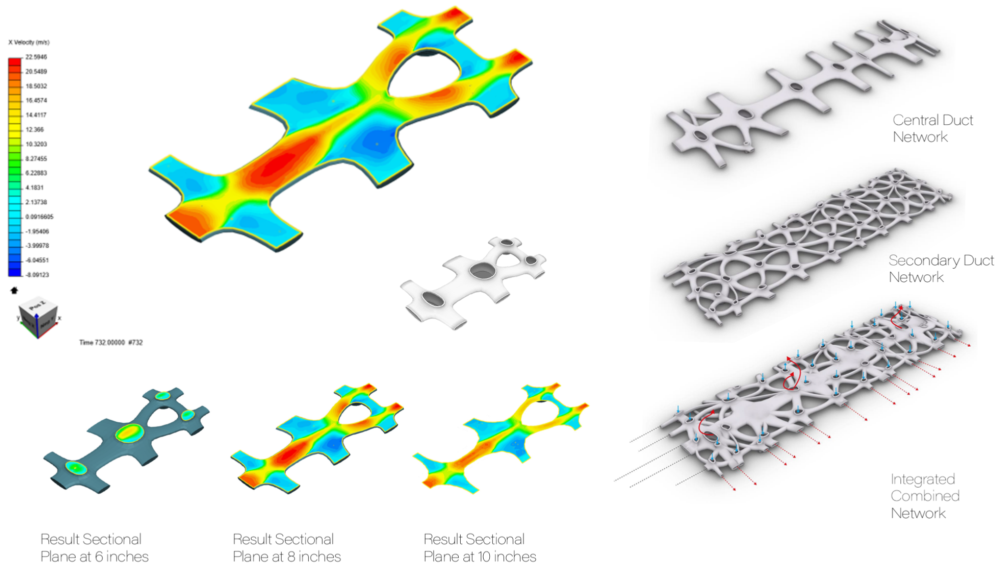
are architects aware of CFD and its potentials, but they have clear objectives for its use, and are already using it in multiple ways (Table 1). The interviews reveal a recent interest from architects in CFD, which is attracting the attention of software developers. As a result, software developers are already beginning to target the architecture market with CFD analysis for interior and exterior building elements (Table 2). The answers to the question regarding the role of air flow revealed the wide differences in terms of the analyses being done, which can range in scale, location, program, design stage, and desired results. Although professionals may have different needs for CFD, the underlying consensus is that CFD is a valuable and important tool but needs to become more user-friendly. What was surprising to discover during these interviews is that even though architecture firms are using CFD, no postoccupancy data has been collected to validate its performance.

ERA Architects Inc. is a practice started in 1990 with offices in Toronto, Montreal, and Ottawa. The firm specializes in heritage conservation, architecture, landscape, and planning as they relate to historic places. Their core values are about addressing heritage-related issues to a broader consideration of urban design and city building. ERA often partners with other firms in projects involving city building, conserving heritage architecture, and improving the built environment. Noah McGillivray, a staff member at ERA Architects, states that a lot of their projects involve working on heritage buildings where it is not possible to implement mechanical systems for cooling, leaving only passive ventilation as a viable method. Hence, the factor of airflow analysis is an important element early on in the design process. A common issue is the retrofitting of interior conditions where transom windows have been covered up or the hallway system has changed, impacting the airflow performance of the original design. The firm does not employ anyone with knowledge in the field of CFD. As a result, most of the work gets outsourced to consultants such as RWDI and Arup, incurring extra costs and time. On average, a consultant takes three weeks to return the results of an airflow analysis, by which time the submitted design may have already progressed drastically or been canceled for another option. The postoccupancy data specific to airflow analysis is dependent on the type of project and done by consultants. A basic tool to allow ERA architects to get some in-house feedback regarding airflow analysis in between concept iterations would be of great interest to ERA.[1]

Natalie Sham is an architectural designer specializing in automation at Arup's Toronto location. She was formerly an architect part II working for the United Nations Office in Geneva, where her work involved passive airflow improvement studies through the use of CFD software with genetic algorithms. The research was primarily focused on the conceptual design phase and never published due to its sensitive nature. The scope of the project entailed furniture orientation and wall placements as the driving factors for the generative design constraints. A combination of Revit and Rhino were used to develop 3D models, and Autodesk CFD was the program used to run airflow analysis. As this project was only a study, no postoccupancy data exists.



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2 A passive ventilation study for an open office floorplan layout simulated in RhinoCFD.

3 SimScale's browser based interphace displaying its new collaboration feature.

4 Buoyancy and velocity studies for an open office floorplan using OpenFOAM, GMSH and Paraview.

5 A study of various ventilation shaft designs done in SimScale.

Sham states that this study highlighted the importance of CFD from the concept phase instead of integrating it towards the end of the design development.[2]

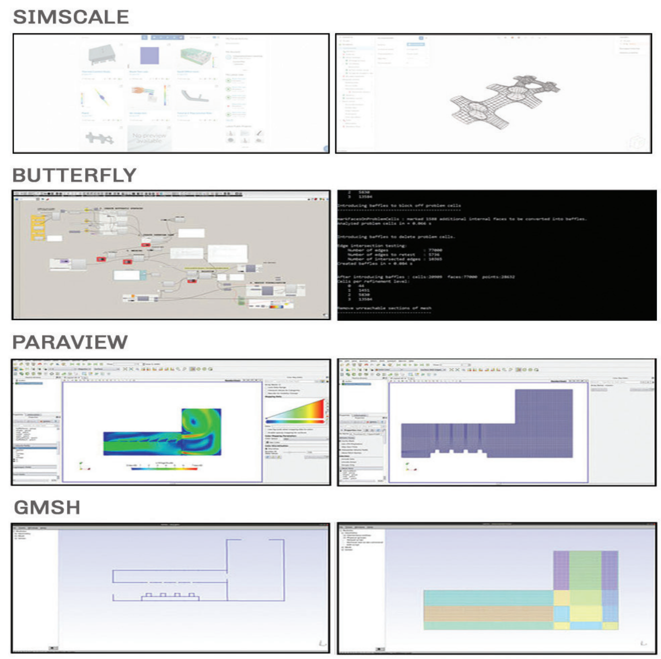
Geoffrey Turnbull is the director of innovation at KPMB Architects in Toronto, one of Canada's leading architecture firms. KPMB's projects encompass all elements of building practice, where, according to Turnbull, the analysis of fluid flow in itself is not of great interest to the firm's workflow in contrast to flow as a factor for microclimates. KPMB's research laboratory is collaborating with Ryerson University to develop tools that allow the firm to understand and analyze the impact of microclimates within buildings so that climate factors can be taken into consideration from the earliest design concepts through to the detailing stage. The objective is to achieve optimized designs that have higher performance levels, lower environmental impact, and increased user comfort. Although KPMB does not have a dedicated CFD specialist, its technical team does utilize Simscale and various CFD applications to the extent of testing initial designs.[3]

BIG IDEAS was founded as a product design firm and branch of the architecture firm Bjarke Ingels Group (BIG) in 2014. Over time, it has transitioned to become an in-house specialist group for the main architecture firm BIG (Maescher 2016). "Its three primary objectives are: simulations, product design and conceptual ideas. The simulations are carried out by a team of experts in computationally derived methods of design. With this close collaboration, they solve the designs from BIG's architectural department while addressing sustainable and environmental needs of a project" (Sayer 2016). Tore Banke is the head of computation, and Alexander Matthias Jacobson is a computational design specialist with a specialty in climate modeling and energy analysis. In our conversation, it was revealed that BIG IDEAS has been working with CFD applications in a substantial manner, where concept sketches are informed by team members' intuition about airflow, which are processed through CFD simulations, and any feedback is iterated back into the design process for further prototyping and repeated until the team is satisfied. This information is then shared with the design team at other BIG offices. BIG IDEAS is currently working on an in-house project called Adele, where three-year-old computers are bridged to create a physical cloud computing network for CFD simulations. The team is developing software that will allow all of BIG's offices to access CFD data, simulation, and updates in real time. Currently, the BIG IDEAS team primarily utilizes ODS Studio and SWIFT for CFD analysis, where SWIFT is used to study multidirectional wind analysis. The results are represented in a multitude of graphical standards in line with the firm guidelines using Paraview and in-house scripts, where data files from OpenFoam are processed and the points are extracted into Rhino/Grasshopper for color adjustments or graphical adjustments. Banke mentions that it is important for the simulation results to be presented legibly so that the resulting data output does not become overwhelming. The preferred way of going about this is to utilize two-dimensional planes that limit the visual information of the results to a specific sectional slice of fluid flow. CFD is now something that more clients are insisting be included as part of the design process, as there is inherent value in maximizing fluid flow performance. Although a lot of the initial stages of CFD analysis are conducted in-house, an external consultant is hired to validate the data at various stages prior to finalizing the documentation. As it stands, all projects inside BIG IDEAS are influenced by CFD analysis in some aspect. Jacobson states that 30 projects with which he has been involved leveraged CFD studies within just the last three months. Banke predicts that in the next five years, all the projects inside the BIG offices will involve CFD as part of design processes, as clients will demand it. According to Alexander, the use of CFD analysis has also allowed the architects to work more closely with landscape architects, as the types of trees and landscape topology can have a major impact on a building's fluid flow performance. Although CFD simulations are prevalent within the BIG IDEAS workflow, no postoccupancy data has been collected on any of the projects to validate these performance metrics produced by the simulation results.[4]

Rowan Williams Davies & Irwin Inc. (RWDI) is an engineering consulting firm founded in 1972, specializing in wind and environmental engineering. The company has offices around the world due to their industry-leading expertise in wind engineering. The firm utilizes in-house wind tunnel testing (WTT) in combination with CFD software to assess various wind conditions (RWDI n.d.). Eric Li is a senior project engineer at RWDI specializing in CFD. He states that when working with architectural firms, each project is often very different due to the constraints that must be specifically tailored to conditions such as offices, hospital, or schools. These spaces have different conditions that impact the level of granularity that needs to be analyzed and the data produced have to be adjusted accordingly. As a firm specializing in wind engineering, RWDI uses different CFD software packages according to the scenario, some of which are developed in-house and use OpenFOAM. Li mentions that there is some interest in looking at Grasshopper workflows for future applications. A combination of data between WTT or water bath modeling (WBM) testing is also utilized to validate or enforce simulation results from CFD simulations. A combination of these varied methods is done based on cost savings benefits and time sensitive cases for data output.[5]

Arup's wind engineers are specialists within the larger multinational consulting service. They specialize in using advanced analysis and design techniques to ensure feasibility, safety, durability, and occupant comfort for structures that go beyond the standard. Arup visualizes wind behavior through WTT and CFD studies along with other alternative methods of analysis. The fluid dynamics group is another specialist subset within Arup that deals with how gases and fluids move and interact in buildings regarding fire engineering and clean water supply. Erthan Hataysal is a senior mechanical tunnel ventilation engineer at Arup London, specializing in CFD for internal and external investigations. He frequently works with architects on projects and states that differences in terminology regarding fluid flow can sometimes result in miscommunication and frustration between architects and engineers. Hataysal thinks that the current state of CFD requires architects to increase their understanding of basic fluid dynamics in order to reduce miscommunications and expectations regarding fluid flow studies. This would also help speed up the setup and processing of simulation studies, as architects can produce 3D models with an understanding of how meshes and boundary conditions are set, so that the CFD team does not need to reconstruct their 3D models, saving time and associated expenses. Arup develops in-house software that runs on OpenFOAM or leverages industry-available CFD packages depending on the situation. Oftentimes, in a city like London, a single new high-rise building requires a majority of the city to be modeled in order to produce the correct granularity level for accurate results. In these types of situations, CFD is extremely useful, as building an entire wind tunnel or water bath model of a city is not only time-consuming but cost-prohibitive. It is up to the team of CFD specialists to decide which approach to take and proceed with the best option.[6]

The Complex Systems Research Group is a specialist team within Autodesk Research that helps designers and researchers develop greater knowledge and understanding of complex systems such as ones found in the biological world. Azam Khan is the head of complex systems research at Autodesk. In our conversation about why CFD has such slow adoption rates within architecture, he recalls that there was a lot of interesting CFD-related work done in the early 2000s but that interest was primarily by the entertainment and gaming industry, while the architectural industry showed little interest. This caused most software developers to focus fluid dynamics simulations towards the gaming and entertainment industry, while any architecture, engineering, and construction (AEC) software focus for CFD was geared towards engineers. However, that is changing, as there is an increasing need to understand data for microclimates as part of the building information modeling (BIM) package. Khan states that Autodesk Research is currently looking at integrating deep learning into its Autodesk CFD solver to speed up the process and reduce the resource intensiveness associated with complex



6 CFD software application interfaces.

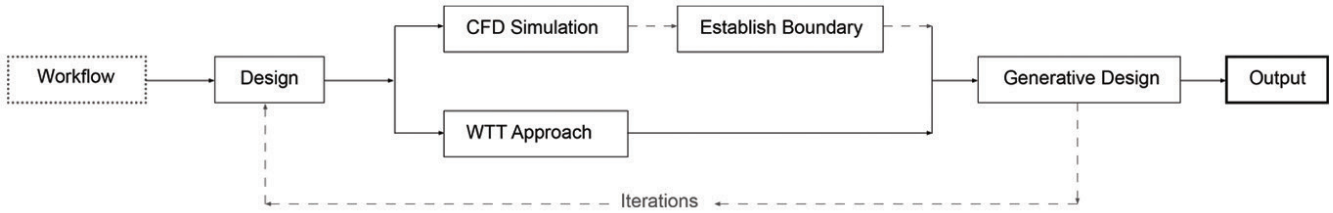
CFD analysis. This in combination with its SyDevs framework for simulation-based analysis of complex systems involving people, devices, physical elements, and dynamic environments will help make CFD much more accessible to everyone in the future. Khan believes that as the time and resource intensity of CFD simulations are reduced, architects will be more willing to invest resources into learning and using CFD applications. His vision of future workflow for architects is to provide a framework where the designer specifies where and how they want the fluid to flow, and the software will make the necessary modeling changes seamlessly without the need for an engineer. All this can only become feasible if the data sourced and produced for these CFD simulations can be optimized for cloud computing, as the current situation does not allow for this to occur effectively on local desktop systems.[7]

Software Evaluation

How air transverses through a space has direct impact on building performance and occupant health (Wilson 1963). Given the situation of COVID-19, CFD analysis techniques are appropriate for studying infectious pathogen particulate transport. CFD can provide a highly resolved estimate of air and species transport within the region of interest in lieu of obtaining field samples (Richmond-Bryant 2008). The CFD software evaluation used a case study project of a complex ventilation shaft design (Fig. 5) and ceiling opening placements (Figs. 2, 4), and asked how these can impact air movement. Throughout this study of software, a challenge of how to convey and visualize CFD results effectively for different use cases is an evolving pursuit, as different firms have their own stylistic preferences and these may differ from the representation options provided in CFD packages (Fig. 6). Furthermore, the interoperability between these softwares can be challenging, as not all the programs allow for ease of visual data extraction and visualization, such as making animations, or extracting streamlines.

SimScale is a cloud-based CFD platform (Guenther 2020). It is comprehensive in nature, allowing for not just fluid flow analysis but also thermal studies to be conducted. Of particular interest to architects are the options for compressible and incompressible flow analysis, and convective and conjugate heat transfers (e.g., auditorium/large open office plans). The inclusion of free cloud core hours with options for more to be acquired through fees for larger scenarios make it appealing for architects to invest time into the platform as it does not require new hardware or take away computing resources from other projects. That said, any work performed with a free account is publicly accessible on the online depository that functions similarly to Google SketchUp's Warehouse. The benefit is that it can help users learn by looking at how others have set up their files and access the 3D files without the need to remodel the scenario. A downside is that the settings may be incorrect as data input can be wrong. Furthermore, any testing of unpublished work is exposed to the public, which can prevent firms from testing ongoing projects. A lack of streamlined animation export options is apparent for such a comprehensive platform. However, the files can be downloaded and exported into Paraview as a workaround. SimScale has a great depository of online tutorials on its official blog and a YouTube channel, which is beneficial to new users.

RhinoCFD is a plugin by CHAM's Phoenics that is built for Rhinoceros 3D (Concentration, Heat and Momentum Ltd. 2018). In its framework, an option titled FLAIR allows for the analysis of fluid flow and thermal simulations. It is intuitive for Rhinoceros users to navigate, as modeled objects can be easily converted to meshes for analysis without usual interoperability issues between different software packages where closed boundary errors often arise. An issue that RhinoCFD shares with most other CFD software packages is in its physics settings. A lack of foundation in fluid dynamics makes it difficult for new users to know what physics values to implement. The user interface does not structure the entering of these settings in chronological steps, in contrast to SimScale, which does this exceptionally well. Online resources and tutorials are available, but are limited and sometimes outdated. Official tutorials consist of a handful of short PDF files where external flow around buildings and HVAC tutorials may be of direct interest to



7 Workflow diagram.

architects. Both these tutorial's PDF files were produced in 2017. The official YouTube channel CHAM lacks any in-depth instructional videos that would be of interest to architects. Visualization options are similar to other CFD applications but benefit from the Rhino3D platform by allowing geometry to be directly called into Grasshopper.

OpenFOAM is a free open-source software provided by the OpenFOAM Foundation (2020). It is a powerful platform that is able to run advanced simulations. It has a large user base spanning across industry and academia. However, it requires a foundation in fluid dynamics and C++ abilities due to the lack of a graphical user interface (GUI) that architects are accustomed to. Everything is entered through command lines. As a software development kit, OpenFOAM at its core contains only the basic essentials, where anything more complicated than a simple geometry cannot be processed using blockmesh but instead needs to be combined with external programs such as GMSH for meshing and Paraview for data visualization and animation output. In comparison to other CFD packages on the market, OpenFOAM is the least user-friendly. That said, it is built as a development kit intended for experienced users to develop their own programs or scripts. Online learning resources and tutorials tend to be very topic specific or advanced and not welcoming for architects.

Butterfly is a plugin for Ladybug Tools Suite for Grasshopper in Rhinoceros 3D and Dynamo for Autodesk Revit. It leverages OpenFOAM to run advanced CFD simulations. According to the Ladybug Tools website, "Butterfly is built to quickly export geometry to OpenFOAM and run several common types of airflow simulations that are useful to building design. This includes outdoor simulations to model urban wind patterns, indoor buoyancy-driven simulations to model thermal comfort and ventilation effectiveness" (Ladybug Tools LLC n.d.). From a user's perspective, Butterfly is easy to grasp for anyone with moderate Grasshopper experience. However, an understanding of meshes and fluid dynamics is required. The example Grasshopper scripts provided are helpful in running basic buoyancy and velocity studies for forced air and heat stack scenarios. As Butterfly is a work in progress, some of the online video tutorials are outdated. A new initiative to develop a paid video tutorial platform is mentioned to be in progress. The installation of OpenFOAM in a virtual box environment to run Butterfly was a major problem for many users, as it produced a variety of issues making Butterfly unusable. However, the recent transition to using blueCFD-Core in early 2019 seems to have circumvented this issue. In regards to data output, vector coordinates can be exported, graph charts are built into the example scripts, and the utilization of colored grid cells with directional vector arrows is the primary method of visualization. Unfortunately, results do not allow for streamline extraction at the time of testing, which would be of interest to architects.

WORKFLOW

As a result of the interviews and software experiments conducted, we derived a workflow that utilizes a combination of (1) generative design, (2) CFD simulations, and (3) WTT method (Fig. 7). This approach was based on the information shared by Natalie Sham regarding her research at the United Nations where she used generative design with Autodesk CFD for passive ventilation studies, Erthan Hataysal's expertise at Arup, and Eric Li's specialty at RWDI, where both used either CFD or WTT methods paired together or separately, depending on the project requirements. Although each interviewee mentioned their work involving two of the three methods, none linked all three approaches into one workflow. The benefit of combining all three approaches is that the shortcomings in one method can be addressed by another. WTT studies can be cost-prohibitive and time-consuming to set up, as was made aware in the interview with Erthan Hataysal, where the city of London needed to be physically modeled to conduct a wind flow analysis for one new high-rise building. CFD simulations can address this shortcoming by leveraging 3D modeling and computational power. However, depending on the situation and granularity required, results produced by CFD may need to be validated and can take longer to simulate in contrast to conventional WTT studies. These shortcomings in CFD and WTT can be

8 WTT study in progress.

disruptive to an architect's design process, where ideas are rapidly evolving through numerous iterations. As Noah McGillivray from ERA Architects mentioned, designs sent to consultants for airflow analysis can take three weeks to complete, by which time the original design may already be obsolete. Generative design can assist in this scenario by providing architects with a tool to create design permutations informed by fluid flow parameters that are established through constraints from existing CFD data. However, initial value ranges for the constraints need to be established and validated through CFD simulations or WTT measurements if scenario-related numerical data does not already exist. In this study, the combination of all three approaches into a workflow begins by running an initial design through several CFD simulations to create a matrix of conditions where elements such as distances between ceiling returns placements can provide the boundary values to be utilized as generative design constraints to create different permutations. Specific results from these permutations can then be individually selected and studied in further detail through the WTT method where a scaled prototype of the model is built and tested in parallel with CFD applications. As seen in Figure 4, a CFD's buoyancy study is used to reveal issues regarding areas within the design where the use of a passive cooling approach does not fully circulate cool air through the entire space, allowing for other studies from the design matrix created to be selected and studied.

WTT METHOD TESTING

This study looked at using the WTT method to validate data derived from CFD simulations by leveraging architects' expertise in building physical scaled models as part of the process. These models were scaled based on matching Reynolds numbers (NASA n.d.). A mixture of distilled water and glycerin filled in modified vape pens was utilized to generate the smoke using remote-controlled activation. The smoke was visualized using wide-angled lasers that can produce vertical and horizontal planes of vision. These lasers were attached to a remote-controlled automated dolly, which allowed the sectional planes of vision to be moved in real time during simulation studies. Different types of mechanical fans were used to produce the necessary cubic feet per minute (CFM) in relation to the matching Reynolds number conversion requirements. Although the initial objective for leveraging this WTT method as a data validation tool for CFD output was inconclusive due to the erratic nature of the eddies produced, it did provide basic information such as the type of flow produced and how this flow is moving through the interconnected spaces within the model. This real-time visualization can help architects understand fluid flow in their designs at a basic level throughout the initial conceptual design phases. This experiment also revealed a need for further investigation into the types of sensors that are required to measure fluid flow within the model for numerical data to be collected, as the images and videos recorded of the experiment were limited to qualitative visualization.

CONCLUSION

The interviews and software evaluation reveal a great interest in, and emergent potential for, CFD in architecture. As a result, software developers are already beginning to target the architecture market with increased CFD analysis resources for interior and exterior building elements. However, throughout this study, it became apparent that before CFD can be used properly, an understanding of the underlying physics is required. Upon being able to produce CFD simulations based on this knowledge, opportunities for leveraging other computational aspects as part of a generative design workflow in combination with WTT methods are discovered. Additional research and laboratory testing needs to be conducted with regards to the WTT approach to establish its purpose as a validation tool. The answers to the question regarding the role of airflow revealed wide differences in terms of the analyses being done, which can range in scale, location, program, design stage, and desired results. Although professionals may have different needs for CFD, the underlying consensus is that CFD is a valuable and important tool but needs to become more user-friendly. What was surprising to discover during these interviews is that even though architecture firms are using CFD, no postoccupancy data has been collected to validate the performance.

NOTES

1. Noah McGillivray. Interview by authors. Personal interview. Toronto, October 9, 2019.
2. Natalie Sham. Interview by authors. Personal interview. Toronto. October 10, 2019.
3. Geoffrey Turnbull. Interview by authors. Personal interview. Toronto. October 24, 2019.
4. Tore Banke and Alexander Jacobson. Interview by authors.

Personal interview. Toronto. October 27, 2019.

5. Eric Li. Interview by authors. Personal interview. Toronto. October 30, 2019.
6. Ertan Hataysal. Interview by authors. Personal interview. Toronto. November 11, 2019.
7. Azam Khan. Interview by authors. Personal interview. Toronto. November 13, 2019.

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IMAGE CREDITS

Figure 3: © Simscale, 10/08/2020,

All other drawings and images by the authors.

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