SIMULATING INTUITION

EXPLORATIONS OF AN APPLIED FLUID VERNACULAR

Stephen Caddy

SIMULATING INTUITION

EXPLORATIONS OF AN APPLIED FLUID VERNACULAR

Stephen Caddy

Bachelor of Applied Science
Queen's University | 2018

Submitted in partial fulfillment of the requirements for the degree of Master of Architecture in The Faculty of Applied Science, School of Architecture and Landscape Architecture.

Committee Chair:
Adam Rysanek

Committee Members:
Dorit Aviv
Jason Heinrich

Abstract

As society furthers its understandings of the impact architectural design decisions can impose on natural processes, the desire for architectural projects to show increased awareness of technical thinking is becoming invaluable. However, traditional architectural pedagogy offers limited technical training. This lack of holistic understanding on the designer's behalf supports a perpetual reliance on external specialists to carry out performance analysis. This thesis is an exploration on effective design process augmentation in the attempt to create performative design tools that are accessible to a wider range of design experts.

Computational Fluid Dynamics (CFD) is the realm of simulation and computer aided design that engages the multiphysics coupling of flow kinetics and heat transfer. Through the knowability of CFD, this thesis hypothesizes that mixed mode ventilation can become more accessible if it approaches the reliability of mechanical systems. But to what extent is simulating digital environments a necessity. Through processes of experimentation, the thesis provides insight on the simulated versus the intuitive. Could a more fluidly aware architecture be achievable through cognitive processes alone? Can adjustments to architectural teaching provide just as much effective fluid design as the most cutting-edge building simulation techniques? The development of this fluid vernacular is carried out in the creation of an office space that utilizes waste heat flows generated from an adjoining data center facility. In what new ways can designing for fluid efficiencies not only provide improved comfort but create new avenues of tangible architectural experience.

Table of Contents

List of Tables

List of Figures

Preface

“The most beautiful experience we can have is the mysterious. It is the fundamental emotion that stands at the cradle of true art and true science.”

~ Albert Einstein

Architecture has long existed in a state of flux as a practice curated by builders, by artist, and increasingly that of the scientist. I see architecture continuing this path towards an extensive integration of scientific phenomenon and technological advancements. I write this thesis from the perspective of an engineering graduate. Someone who has had the philosophy of logic and rational process instilled in them. While I understand the preconceptions my perspective imparts on my undertaking of an architectural thesis, my aim is to highlight the strengths that technical processes can impose on design choices and convey the societal need for such a shift.

As a technically driven thesis, the basis of my work stands on top of centuries of scientific discoveries. While an introduction to relevant scientific principles and phenomenon will be outlined in the body of this work, the scope of the thesis design project is incapable of covering all relevant contextual information. I can only hope to scratch the surface in a meaningful way to provide clarity to the design work. As such, I encourage the reader to further explore the realms of knowledge pertinent to the outcomes of this thesis.

Lastly, the thesis has been laid out in a similar manner to that of a scientific research report. The purpose of this is to establish a literal parallel between design and experimentation. To dive into design experimentation and reveal the tangible applications our choices in process can yield. Architecture has long been a field dominated by verification based on what has been, and what is known. I offer this approach to further knowledge, in a way to explore that which is mysterious and make it known.

Problem Definition

Now more than ever, buildings are required to operate under a wide array of design constraints both intrinsic to the project itself and towards the external natural, societal, and economic context. At the same time, we are asking more of our buildings than ever before. As technology advances, we are becoming increasingly aware of the impact that our design decisions have on human existence and natural sustainability. We know the desire to develop a more rigorous architecture that responds to issues like climate change is becoming more and more crucial. However, the environment in which architecture is created today is still largely based around the development of structures from times unfamiliar with the challenges of today. The idea of the contemporary architectural profession lacks progress and distinction from methods of the past. There are problems today, climate change chief among them, that are not being benefited by scientific developments as greatly as they could be.

Climate change lies at the heart of many modern design constraints. The desire to produce buildings with increasingly reduced impacts on the environment is quickly progressing to the level of a societal need. The building industry alone accounts for the largest fraction of greenhouse gas emissions on the planet at 40%.[1] A large portion of this metric is tied to resource extraction and production of the materials designers select in their projects. Creating change in this level of architectural design requires a fundamental shift in manufacturers and product availability to see any tangible change. Therefore, building operations are often the focus of a designer looking to reduce environmental impact for more efficient building performance. This has led to the development of passive house technology, and the concept of net zero buildings. One of the greatest influences in the operating carbon of a building is the active systems responsible for supplying heat and fresh air. 60% of the operational energy of a building is due to air ventilation and heating alone. A thoughtful response to this facet of architectural design is poised to deliver the largest efficiency improvements in building performance. Therefore, systems like passive house are becoming more and more sought after as a means of producing buildings with negligible operating energy.

Mechanical systems have commanded such a hold on the functional capacities of ventilation within architectural design thanks to their reliability and operable consistencies. Despite the shift towards designing for greener futures where buildings make use of passive design principles, there will always be some degree of dependance on mechanical systems. For example, in high sensitivity realms like laboratories and surgical rooms. While passive ventilation strategies are not new, their widespread adoption into architectural discourse is met with several accessibility issues. Buildings designed with natural ventilation strategies typically have limited formative options given the constraints of passive systems and our lack of understanding of their broader application. However, a system of design where passive ventilation strategies offer a comparable degree of design certainty, controllability, and predictability would not only serve to improve the performance of naturally ventilated systems but would vastly increase the accessibility of these practices into a wider range of architectural projects.[2]

A tool that has seen increased use in the technical understanding of the built environment, and one that offers the ability to predict passive ventilation functionality prior to construction, is computational fluid dynamics. While pressure coefficient studies and simplified orifice equations common in passive design have been shown to have measurable performance discrepancies of up to 32%, computational processes can reduce measured performance to a minimum deviation of just 3%.[3] My background in engineering posed the opportunity to question, what value would the integrated application of computational fluid dynamics processes have on increasing the accessibility of natural ventilation systems. For those unfamiliar with the concept, Computational Fluid Dynamics (CFD), refers to the realm of science and math associated with predicting fluid movements and heat transfer. It is used to great benefit in the motor racing and aerospace industries and has even seen use in the development of artificial heart ducts. While CFD has greatly increased the level of design optimization in these fields, the simulated results involve substantial computational power and time. A CFD result can predict flow velocity, pressure, turbulence, heat, and much more, allowing us to quantify predicted fluid behavior before something is built. CFD process require several steps including digital modelling, mesh creation, parameter selection, post processing, and more. It is not uncommon for CFD simulation processes to take weeks to months to solve. This means that the most effective CFD applications make use of simplified design loops for solving multiple geometries.[4] Another issue regarding the practical application of this tool is the utility of the simulation result. Does the large investment of CFD testing yield proportional benefits? If CFD modelling is the answer to elevating the predictability and performance of passive ventilation to a similar degree of mechanical systems, substantial changes to traditional creative design processes will need to take place. The successful application of this tool will only be possible through a carefully considered integration of the rigid technical processes of CFD design.

In conclusion, as architecture responds to global issues of climate change, we need some form of design certainty in new technology to justify new techniques and processes. Increasing the accessibility of passive ventilation strategies by creating systems with operable certainty like that of mechanical ventilation, would provide the designer with far greater options for energy efficient operations. The tool which offers the most promise in enhancing the function and providing predictability in passive systems is that of CFD. But the CFD process must be applied to design in a conscious and careful manner. Simulations are costly and must therefore be implemented effectively into the design process to yields tangible benefits.

1 Jomehzadeh et al., “A Review on Windcatcher for Passive Cooling and Natural Ventilation in Buildings, Part1.”

2 Stavridou, “Breathing Architecture.”

3 van Hooff, Blocken, and Tominaga, “On the Accuracy of CFD Simulations of Cross-Ventilation Flows for a Generic Isolated Building.”

4 Kormaníková et al., “Parametric Wind Design.”

Hypothesis

For passive ventilation strategies to become more accessible to contemporary designers, this thesis proposes the concept of the fluid vernacular. Developing the fluid vernacular is as much about designing in ways that provide controllability, predictability, and reliability to passive systems as it is about informing design process overhauls required to provide a form of design validation. This thesis explores the extent by which simulation and intuitive design practices can enhance holistic design for natural ventilation strategies. By establishing the vernacular of fluid dynamics, this work will propose an architectural model that not only develops effective functional designs but new avenues of flow-based experiences.

It is not hard to comprehend the reasons behind the monopoly mechanical ventilation has on the built environment. A form of architecture created from a conscious understanding of flow principles and the ability to justify performance results prior to a project's completion, would greatly increase the ability for passive ventilation to compete with their mechanical counterparts. This thesis hypothesizes that through carefully constructed massing, and flexible control systems, passive buildings can be designed in such a way to optimize passive ventilation and bring its operable capabilities closer to that of mechanical ventilation. At the same time, this work recognizes the fantasy of designing a global architectural model which relies solely on well crafted passive ventilation principles. While some climates simply provide environmental circumstances that go beyond the range of passive conditioning, other occupied spaces require a level of air control that is too complex to be achieved through passive means alone. That is why this thesis takes the stand of designing the fluid vernacular with the mindset of utilizing mixed mode ventilation systems. With renewable and low carbon energy sources on the rise, it is not unlikely that an efficiently designed mixed mode system with minimal mechanical ventilation, could be powered solely through sustainable means. The addition of mechanical ventilation should therefore be viewed as augmented passive ventilation. Designs with this approach in mind will hope to achieve a high level of passive operation with the understanding that to reduce issues with reliability, isolated applications of mechanical intervention will promote the continued use of passive ventilation concepts.

Second to this is the concept of informing design process changes. It is largely due to the uncertainty of passive ventilation systems that designers and clients are reluctant to utilize their energy saving benefits. The function of mechanically ventilated systems comes with desirable controllability. This controllability nearly guarantees that well designed systems will be able to reach performative targets. Alternatively, passive ventilation fails to provide the same degree of control and knowability. This is where the adoption of computational fluid modelling into the design practice would equip passive systems with the tools of optimization and predictability that would make them more accessible to the client. The process of conducting CFD studies, while time consuming, provides accurate results for what the built environment will achieve before a building is built. For new systems to fully grasp the energy savings and performative benefits they advertise; a simulation process must be used to provide design credibility.[1] While the thesis anticipates the need of this level of simulation to be a necessity, an effective use of this tool must be met with conscious design integration strategies.

Due to the large time investment associated with CFD simulation it is reasonable to predict that a selective use of this tool will balance design utility with the investments associated with conducting the simulation. I believe an approach that would increase the accessibility of CFD analysis would be to apply the tools at different levels of design resolution. Early design moves, while important and fundamental to design progression, offer a level of design complexity that is much easier to solve by a computer. Narrowing the focus of a design early on by using rapid CFD testing may be one way to successfully integrate simulation tools into the design of the fluid vernacular. It is also apparent that some form of design validation beyond initial iterations must be conducted for adequate validation. The design project carried out in this thesis hopes to determine the effectiveness of when designers should effectively implement CFD practices.

Lastly, embedded into the addition of CFD, this thesis hypothesizes that to develop more efficient design processes for more accessible passive ventilation strategies, the designer should operate as much as possible as an intuitive extension of a the CFD process. While a complete matching of intuitive fluid understandings and CFD results is highly unlikely, the designer who makes informed choices based on a developed knowledge of fluid mechanics could offer a substantial reduction in the effort required for final design convergence. By iterating plans, sections, and massing moves with an understanding of how architecture can impact its fluid environment, rapid development of initial concepts can be created intuitively. A design project conceived under this informed intuitive process would most likely see a reduction in the number of crucial design changes that a CFD analysis would recommend.

1 Schulze and Eicker, "Controlled Natural Ventilation for Energy Efficient Buildings."

Introduction/ Background

Overview

We will first identify the relevant contextual framework that the fluid vernacular exists within. In the development of a technically inspired thesis project, identifying relevant precedents and contextual information will aid in positioning argumentation and design concepts. Fluid dynamics is a scientific field encapsulating a wide array of physical phenomena and math theory. The application of fluids to buildings themselves, requires us to identify this thesis' connection to the context of building ventilation and heating technologies.

Furthermore, in establishing a framework on which to promote a new architectural vernacular, we will specify the nuances of thought that highlight the capacities of a greater involvement of technical processes into design thinking. What would a space with heightened understandings of fluid multiphysics provide functionally, as well as experientially? With a more precise understanding of the fluid environment our buildings create, we will be able to better understand parameters of fluidic space sensed by the human body and develop new design necessities and experiential dimensions of architecture. To begin, I will identify a brief history and contextual placement of ventilation strategies pertaining to architectural concepts. This will help to identify the differences in existing techniques to the concepts that are proposed in this thesis and developed further in the design project.

Precedent Analysis

To better understand where within architectural discourse this thesis resides, we will look at a series of precedent studies to position the cultural, technological, and scientific context of the project. Since designing the built environment around airflow and using computer modeling to explore architectural functionality is not new, the projects discussed here will highlight current shortcomings in the approach to fluid design in architecture. Historically, architecture has been a practice carried out by builders relying on known methods of construction. The many architectural works that engage fluid design have as a result, done so in limited capacities. The following projects will not only provide insight into the nuances of the proposed fluid vernacular but highlight the need for further integration of simulation-based practices.

If an architectural work is unfit for human occupation, it has ultimately failed as a space of habitation. As architects furthered their technical understandings of the impacts of their design choices, they began to find ways in which to relay not only their aesthetic work, but the intended functional goals as well. However, due to the architectural paradox that the designer can never work physically with their built project, performative desires exist largely in the realm of hypothesis. The Barcelona pavilion designed by Mies van der Rohe was constructed to represent Germany at the 1929 Universal Exposition. Void of a functional program, the building itself constitutes the exhibition content. The design is notable for its rekindling of modernist design philosophy. To better grasp the intended spatial impacts of the design, a collaborator of Mies', Paul Rudolph, created a series of study sketches to visually represent the perceived qualities of the space. These drawings we're created to convey the architectural impact on spatial qualities such as air flow, circulation, view paths, and sound transmission.[1] What is important to draw from this project and the era of architecture in which it was created, is that functional depictions such as those drawn by Rudolph are entirely based on intuitive estimates and hypothetical predictions. As communicated in the problem definition, new forms of architectural design that the fluid vernacular aims to propose, require substantially high levels of performance accuracy to exist as an accessible design tool.

The Autodesk office at the Medical and Related Sciences (MaRS) building in Toronto, Canada represents the next step in functional planning in architecture. This project occupies three floors in the Toronto Mars facility. As an interior project, the uniqueness of the design stems from the method of floor plan conception which was achieved through

1 Blake, "Conversation At 23 Beekman Place."

a generative artificial intelligence. Users of the space were surveyed to define office constraints and required metrics to establish future features. From this data, algorithms were created which would feed user preferences into an evolving matrix to develop a host of optimal solutions based on six key metrics. This form of intellectual pipeline highlights the incorporation potential of computation and data driven processes in architectural design. Within just a few days, over 10,000 possible floor plan options were created; an infeasible task by human effort alone.[2] The Autodesk office at MaRS is significant in its use of a generative design process for floor plan development. The project uses real data to predict performative outcomes on the scale of a single floor. The level of iterations used in this type of design work has been made possible through the benefits of computer aided design. While this project makes a substantial leap away from works like the Barcelona pavilion studies, the process used here engages scientific studies from a brute-force perspective. The development of architecture with a computational system as heavy as CFD would simply not work in the same iterative environment. The development of a thoughtfully integrated CFD process must be established.

In addition to the discussion of performative representation, it is important to identify qualities of fluid architecture. Alan Short's Contact Theatre in the UK is one such project designed with the intent of being largely guided by passive ventilation in both its function and design. In addition to the number of passive house projects that have a functional focus on airflow, there is another realm of architecture associated with the aesthetics of fluid flow. The Hotel Tierra designed by Cazu Zegers in Chile is one such structure that is designed as a windswept dune as if it were shaped by the air currents. In addition to physical forms, architecture can also represent fluids through a more experiential lens. Projects like the Blue Building by Diller Scofidio + Renfro and Cloudscapes by Tetsuo Kondo and Transsolar are both projects that seek to work with the concept of the visible invisible. Whereas the Contact Theatre and Hotel Tierra, evoke a sense of fluid driven massing, these projects represent architectural experience through the manipulation of air itself. What separates these projects from the proposed fluid vernacular, is their separation from functional motives. Whereas these projects bring visibility to the invisible through the development of artificial fog or cloud formations, architecture can also bring visibility to airflow through several design moves. Architectural projects can make use of kinetic façade elements to provide a degree of connection between the invisible fluid flow and the users experience. Seasonally, the drifting of snow or leaves can also provide insight in the invisible flow patterns that represent a built project. Lastly, particles in the air provide an easily graspable visual to understand flow patterns. Everything from pollen and dust floating in air currents, to birds and gliders riding thermal columns from heat island effects provide insight into the invisible qualities of fluid flow. The architecture of fluid dynamics sits at the forefront of these concepts. The representation of that which cannot be seen.

2 "The Promise of Generative Design -."

"Equipped with his five senses, man explores the universe around him and calls the adventure Science."

~ Edwin Powell Hubble

Ventilation

With an understanding of the position the fluid vernacular occupies within contemporary architectural discourse, we must also understand the medium in which we will be developing the project. Concerned with the accessibility of natural ventilation systems and the tools architects can utilize to create fluidly driven projects, it is important to identify the fluid itself we are designing for. In architecture, whenever we delineate boundary conditions between one room and the next, or between the interior and exterior, we are cutting an air volume off from its replenishing source. Whenever we contain space, we need to develop an additional capacity of the indoor environment beyond the protection and separation provided by walls. Spatial comfort is crucial to not only human senses but to functional energy demands as well. Comfortable spaces create desirable architecture. Adequate lighting plays a critical component in whether spaces are deemed comfortable, even functional in most circumstances. Acoustical performance can also be tied to comfort. Treating the idea of spatial comfort within architecture literally, we can draw from Hubble's quote and categorize our ability to perceive space based on the 5 senses. Already mentioned, acoustics is detectable through hearing and lighting is perceived through sight. Our sense of smell indeed plays an important role in the perception of a comfortable space. We are then left to consider touch and the mediums we physically contact in space.

While there are many architectural features that are tactile by nature, railings, furniture, warning pavers at the foot of crosswalks, and air, the medium in which we exist, is the only ever-present physical conduit that literally connects us to space we are within. Going back to other senses, by which medium does smell reach the nose? By particles carried in air currents. Even waves of light that reach our eyes travel through air and are affected by density gradients that refracted light on its journey from emitter to receiver. I would argue that the fluidic medium in which we exist has the broadest ability to affect our perception of space, whether that is a sense of feeling air rush across the skin, experiencing the optical illusion of bending light, or even simply carrying particles that we inhale and perceive as smells. Even sound waves would cease to exist without the fluid medium.

The Multiphysics understanding of fluid motion can therefore be understood as one of the key drivers in our perception of the environment and by extension, architectural space. Ventilation is the term we are most familiar with when engaging fluid flow in buildings. When speaking about ventilation the most common metric by which we quantify fluid flow is the air changes per hour (ACH). This value identifies the number of air volumes that are exchanged through a define space in an hour interval. This value is the metric by which comfortable environment standards are ranked because it accounts for so many qualities that define what comfortable air environments feel like. On one hand though, it is limiting in its quantification of fluid flow. An architecture in tune with the multiphysics problem of fluid dynamics would be poised to engage airflow beyond values associated with just fresh air exchange rates. If the other senses can be informed by this fluid environment, does our understanding and parameterization of fluid environments present opportunities to better grasp our connection to space through fluid flow? The bladeless Dyson Fan explores this concept of multi-conditional airflow experiences. Their approach to airflow experience is that moving air from traditional fans create turbulent air that can be uncomfortable to humans. Dyson's solution is to maintain the functionality of a fan but respond to the delivery of air not just to cool down, but in a way that is more comfortable, and in their case, more energy efficient as well. This concept has the potential to translate to architectural design, but we first need to define the context of the air we exist within and how we are affected by it. How can the human body perceive fluid and in what way then does this impact an architectural experience?

Composition

Table 1 : Global Average Concentration of Well-Mixed Atmospheric Constituentes, Trenberth and Guillemo, 1994

MAJOR CONSTITUENTS	FORMULA	CONCENTRATION (%)	TOTAL MASS (G)
NITROGEN	N_2	78.084	3.87×10^{21}
OXYGEN	O_2	20.946	1.19×10^{21}
ARGON	Ar	0.934	6.59×10^{19}
PARTS-PER-MILLION CONSTITUENTS (PPM = 10^{-6})			
CARBON DIOXIDE	CO_2	400	3.11×10^{18}
NEON	Ne	18.2	6.49×10^{16}
HELIUM	He	5.24	3.70×10^{15}
METHANE	CH_4	1.83	5.19×10^{15}
KRYPTON	Kr	1.14	1.69×10^{16}
PARTS-PER-BILLION CONSTITUENTS (PPM = 10^{-9}) NOT LISTED HERE			

What values do we use to quantify air? Air itself has a global average composition by mass of 78.08% Nitrogen, 20.95% Oxygen, 0.93% Argon, and several hundred trace gases that exist as either parts-per-million (ppm) or parts-per-billion (ppb) constituents (see Table 1).[1] As previously mentioned, ACH is the most used metric to describe air quality and for good reason. The composition of air is largely controlled by how long it remains stagnant in an indoor environment. Inhaling between 10,000 and 20,000 L of air per day means that even small concentrations of particulates in the air have a high probability of making it into our lungs.[2] When we think of air that is "unhealthy", air that contributes to sick building syndrome, we are talking about air that lingers longer and has more time to collect bacteria and dust. Constituents that have the greatest impact on our perception of fresh air are carbon dioxide, relative humidity, and volatile organic compounds.[3] The growth of microorganisms is promoted in confined spaces which is why our perception of indoor comfort is so closely tied to that of air composition.

1 Schlesinger and Bernhardt, "The Atmosphere."

2 Bere Semeredi et al., "Indoor Air Quality Monitoring and Human Perception Survey on Air Quality in Public Buildings in Timisoara."

Temperature and Humidity

Air also contains water vapor, the concentration of which is referred to as humidity. Humidity levels are a function of both temperature and pressure. Humidity can be measured as either absolute, relative, or specific. No matter how it is quantified, the human body can perceive humidity with 40% to 70% being identified as a generally accepted range of comfortable humidity levels.[4] Because humidity is a function of both air temperature and pressure, a multiphysics understanding of the airflow within buildings can aid in understanding spatial comfort. Humidity plays a substantial part in spatial comfort as it has a very direct impact with how air feels. Directly related to the humidity level is air temperature. Because humans rely on both evaporation and perspiration through the skin to regulate body heat, changing the air composition in such a way that hinders or promotes this natural process has a large part to play in our understanding of comfortable spaces. For example, if both the humidity and temperature are too high, this limits the ability for perspiration to evaporate, therefore making us feel hotter than the air temperature. Similarly, if humidity is low, perspiration evaporates more readily, and we feel cooler than we should. The coupling of air temperature and humidity is important to consider when conditioning interior air.

Airflow Velocity

Lastly, like any fluid, air can take the shape of spaces it occupies. This kinetic nature of fluids means that air is suspect to frequent, often chaotic, changes in velocity. It is important to note that velocity is in reference to both a magnitude and direction, and as we will see later, this means that air can have either turbulent or laminar qualities. In buildings we can refer to airflow by its flow rate, how much a specific volume of air passes through a space per unit time. We often represent exterior airflow by its average velocity. These two methods of quantification are directly proportional to each other and effect our perception of space as well as the aspects of air listed above. Our sense of touch is the predominant method in which we perceive airflow, but like humidity, airflow also plays into our perception of temperature. Windchill is a tangible way that we feel the cooling impacts of air. In fact, the entire process of passive cooling through air movement relies on this effect. Higher air velocities across our skin increase the evaporative rate by which heat is dissipated from our bodies, hence the term, evaporative cooling. Velocity also plays a substantial part in auditory experience, buffeting turbulent air creates rapidly oscillating air pressure fronts that our ears perceive as uncomfortable static, or noise. Velocity can also be felt of as pressure distributions on the body.

3 "How to Measure the Indoor Air Quality of Your Buildings - DEXMA."

4 Monceaux, "What Is Comfortable Air?"

Passive Ventilation

Now that we have identified the means in which airflow can be perceived, we must address how airflow can be delivered. We will explore the general concepts behind both passive and active ventilation to understand where a fluid vernacular would and should position itself. Prior to the automation of the mechanical era, airflow inside of buildings was established through passive means exclusively. One of the best-known examples of early passive ventilation strategies are the many wind towers that still exist today in cities that reside in hotter climates, like Yazd, Iran. These structures are approximately 1500 years old and were a means of harvesting the natural force of the wind and drawing it down and into the building below.[1] The premise behind modern passive ventilation has remain largely unchanged. By allowing for the air to flow within a building (from positive to negative pressure regions), we increase the rate by which air is exchanged in a space. Because passive systems are inherently void of any active processes, they must utilize the natural principles of fluid motion to achieve ventilation effects. Air can either diffuse, convect, or advect through a space. Diffusion in fluids is typically a much slower process than the other two transport mediums which is why successful uses of passive ventilation do not rely heavily on diffusion processes. Advection refers to the physical movement of air particles that causes a stirring action of active mixing. Advection is a result of exterior influences that physically push air particles to move them. Wind is often a driving force behind advection in passive strategies. Lastly, convection refers to the body effect of air particles as they experience temperature changes. As particles heat up, the gas they create becomes less dense, and the resulting buoyant force drives an upward movement. In architecture, we refer to this phenomenon as the stack effect.

In addition to the extremely low to negligible energy required to create passive ventilation, architecture that applies passive ventilation to its spaces sees several formative benefits as well. The inclusion of passive ventilation promotes the use of narrower floor plates. This in turn increases views to the outside as well as providing more natural lighting. Passive ventilation also forgoes the requirement for large ductwork networks like those required for active systems. This allows for floor-to-floor heights to be drastically reduced which has several positive benefits on both embodied and operation carbon, as well as material use, and spatial density.

It is because of the formative benefits but primarily the energy efficiency of a passive approach that the vernacular proposed in this thesis will make as great of a use of passive ventilation strategies as possible. To do this effectively it will be critical to engage with the natural landscape, and design systems that respond to the natural environment as opposed to treating the indoor and outdoor spaces as separate entities. Despite the energy benefits of the passive system, this thesis recognizes and hopes to address several issues of passive ventilation. Firstly, passive ventilation often has issues with flow rates consistency. Relying on wind or other natural process to carry out environmental conditioning means that there will be fluctuations in the ability for passive ventilation to function as expected. Similarly, in colder climates or climates that experience a highly variable range of yearly temperatures, passive ventilation lacks the ability to operate while maintaining adequate heat comfort within a space. Allergens and pests also pose an issue. Passive ventilation relies on removing barriers to the outside world, the same barriers that we have traditionally built to keep pests away. The adoption of a fluids approach to architectural design would provide a framework to address many of these concerns.

1 Dehghani Mohamadabadi et al., "Numerical and Experimental Performance Analysis of a Four-Sided Wind Tower Adjoining Parlor and Courtyard at Different Wind Incident Angles."

Because society has valued the reliability presented by mechanical systems that can easily solve several of the problems associated with natural ventilation, passive strategies have had difficulty in their application and uptake as a common practice. The fundamental aim of this thesis is to increase the accessibility in which passive ventilation simulation can be used by the designer so that they can design with similar operable capabilities to mechanical systems.

Active Ventilation

While passive ventilation strategies are making a resurgence in modern architectural design as a means by which to reduce operating energy, most buildings today rely heavily on mechanical ventilation. Mechanical ventilation refers to the process in which indoor and outdoor spaces are separated and treated as distinct volumes. It is the responsibility of mechanical systems to push and pull air through a space to provide ventilation. Mechanical systems can be classified as either coupled or decoupled systems regarding their ability to use airflow to distribute heating and cooling in addition to fresh air. Mechanical ventilation was first used in the modern era where buildings were thought of as climate machines. Spaces inside could be completely removed from the outdoors, and through mechanical processes, we could simulate the effects provided by nature in a more controlled manner to fit our liking.[1] This flexibility and ease of use is the reason why active ventilation is the favored system today. But with this tremendous functionality comes a cost.

In recent years, the COVID-19 pandemic has brought an increased awareness to the ineffectiveness of these types of systems. The contained nature of mechanical systems has led to a term known as "Sick Building Syndrome". Contained spaces that recirculate air through mechanical means, are prone to the issue of recirculating pathogens and failing to deliver the adequate levels of ACH as a result. The other key negative to mechanical systems is their energy use. A system that relies on airflow as both a temperature and fresh air regulator is among the least efficient forms of ventilation. Advancing to a decoupled system in which heat is transferred through alternative means does provide substantial increases in operating efficiencies. However, heating and ventilation systems still account for one of the largest fractions of a buildings operational energy. Despite the drawbacks, the design work conducted in this thesis will not eliminate the integration of active systems. It is difficult to envision a future that is fully reliant on passive systems. But instead of generalized integrations of mechanical systems, a fluid vernacular is poised to make use of fluid phenomenon in providing more efficient means of hybrid ventilation strategies. Thinking again to the Dyson fan technology, the bladeless performance relies on a form of air velocity multiplication through formative interventions that aid in an active delivery of airflow. A similar approach to design and modelling will be undertaken in this thesis.

1 Short, "The Recovery of Natural Environments in Architecture."

Computational Fluid Dynamics

Having developed the contextual realm and the position on ventilation strategies that this thesis addresses, we need to outline a solution to the difficulties of passive ventilation strategies. This thesis hypothesizes that the inclusion of some form of simulation verification process will provide passive ventilation designs the predictability required to compete with mechanical systems. As previously mentioned, it has long been the case that the functionality of architectural design is difficult to achieve due to the paradox of working purely from representation. How then do we bring a level of predictability to something that does not exist? Within the last few decades, advancements in computation have led to the development of Computational Fluid Dynamics (CFD) simulation. By digitally modelling environments and predicting their airflow through CFD solvers, I argue that the fluid vernacular can be achieved. A design process which utilizes computational simulation tools will be capable of developing architecture whose performance is predicted and controllable thanks to an in-depth understanding of systems prior to construction.

CFD is the area of study responsible for practical applications of the Navier Stokes equations. CFD software is a valuable tool that allows us to predict a wide range of characteristics regarding fluid flow. CFD is used today in a wide variety of applications. Airfoil design, F1 car optimization, even fluid transport mechanics in your blood, all benefit from the predictions made by a CFD process. Examples of typical CFD results are represented in Figures 1 to 3. The intricacies of this type of simulation work requires a thorough understanding of the principles and practices behind the CFD tool. In developing an architecture based on the fluid vernacular, it is crucial to develop a methodology which incorporates modeled and simulated systems as a means of predicting end state functionality. Having a tool that allows us to represent specific functional and experiential realms regarding air flow will allow us to design based on theory and not hypothesis. Due to the design framework of the construction industry, the architect's ability to predict design impacts inherently must rely on intuitive understanding of spaces and natural phenomena. This manner of thinking is limited in its ability to achieve increased rates of innovation and higher realms of efficiency. That is why a computational tool such as CFD will be utilized in the design process of this thesis. While there are a vast range of applications for understanding the aerodynamics of architecture, common ones include modelling wind-induced pressures on facades, influencing airflow at the pedestrian level, optimizing passive ventilation, and managing thermal comfort.[1]

1 "Building Aerodynamics 101 – Complete Guide."

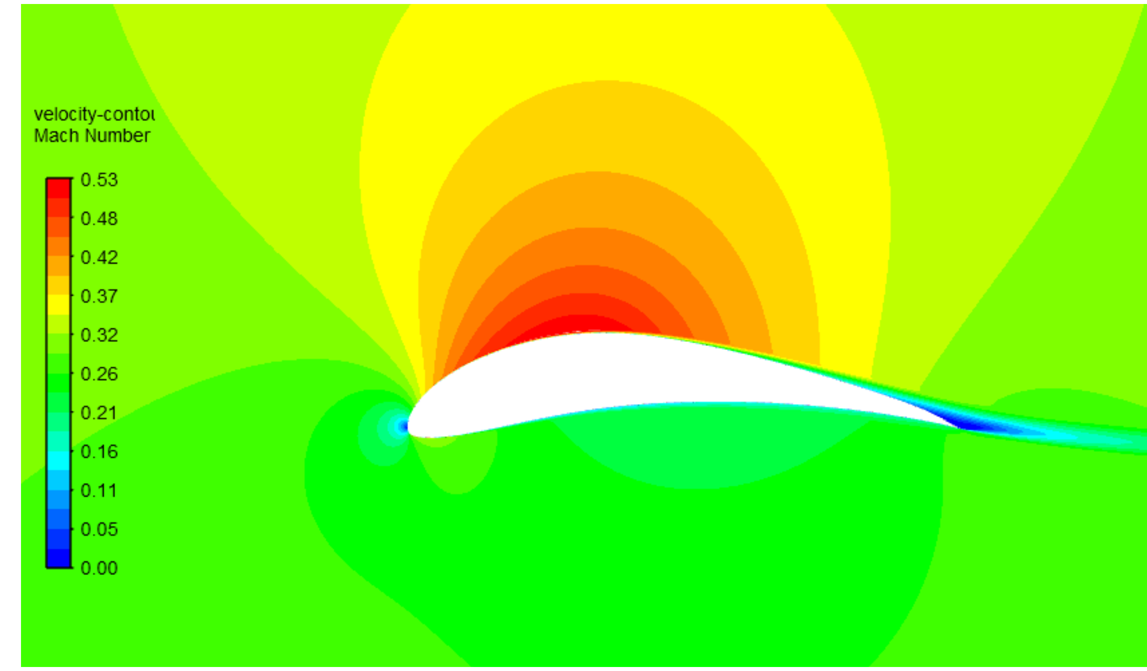


Fig. 1 | Airfoil Velocity Contour Study

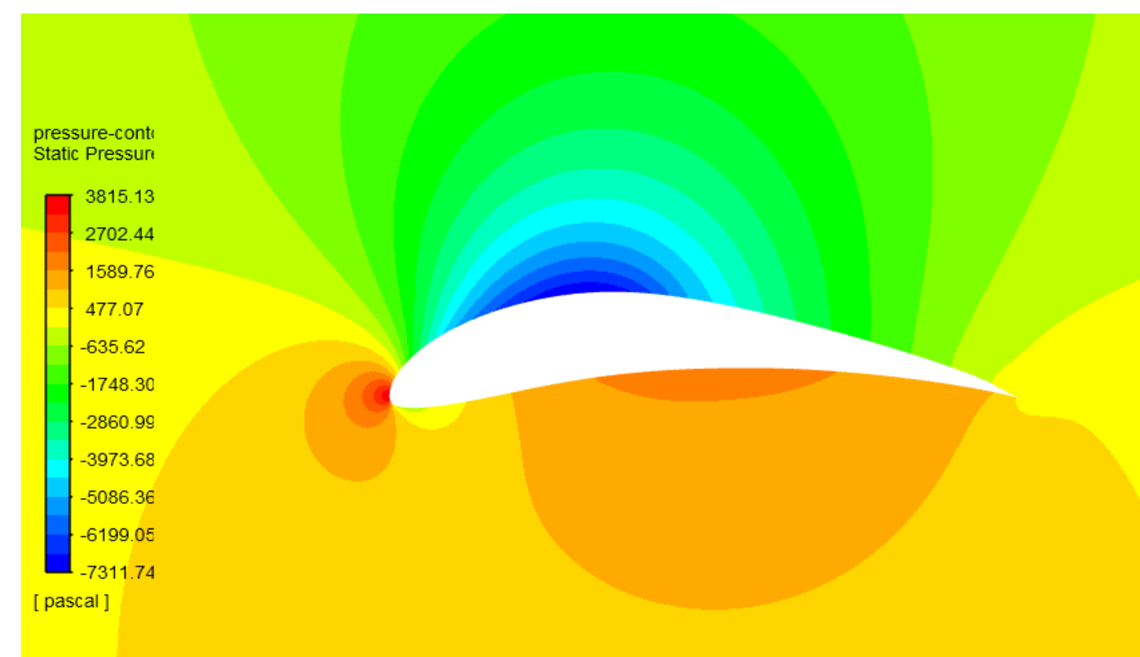


Fig. 2 | Airfoil Pressure Contour Study

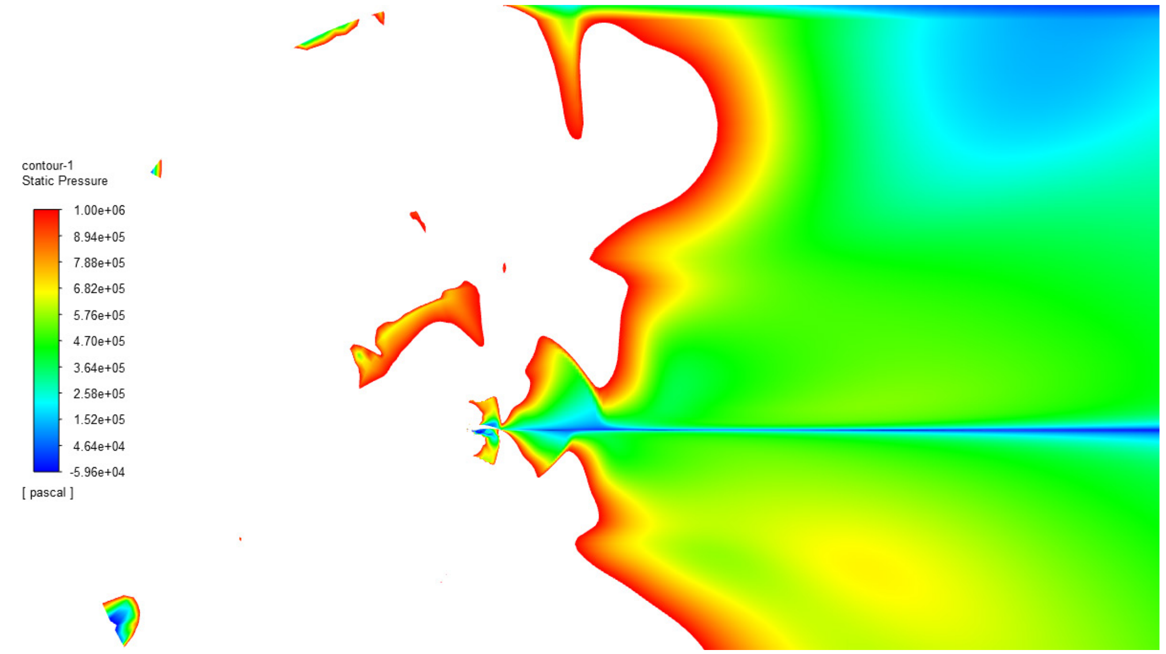


Fig.3 | Divergent CFD Example

Issues and Limitations

When CFD has been used in design environments, it is typically in the place with an end state verification tool. As a result, designs lack the level of sophistication that a much more integrated process could develop. Furthermore, the accuracy of CFD results for building applications, creates an additional challenge that an integrated process must account for. This scale and validity of the spaces we live in, produces an inherent gap between that which is simulated and that which is perceived. By this I mean that even though CFD results can be achieved to a high level of accuracy, we can only ever model a defined environment and any deviation from this environment has the potential to offset simulation results entirely. As such, a process that relies on a CFD verification at the end of a project design may use months of simulation time only to model something that would never be achieved in real operation scenarios. This challenge however could be mitigated through the appropriate applications of CFD and the experience of the CFD user. The other challenge that must be addressed is the time investment associated with CFD design.

CFD process require several steps from digital modelling to mesh creation, parameter selection, post processing, and more. It is not uncommon for CFD simulation processes to take weeks to months to solve for just one result. This poses a significant challenge when compared to the flexibility and iterative capacity of an intuitive or creative design process. Even computationally aided creative pursuits such as those of parametric applications, show a substantial difficulty in applying a simulation process with such a large time requirement. Using the Autodesk Mars project as an example, if each one of the 10,000 design iterations required even just one day of calculations, the solver would require over 27 years of processing time.

It is due to these challenges that an effective application of CFD tools must be done so in a considerate manner. It is the goal of this thesis to produce an architectural vernacular which provides predictability and reliability to passive ventilation strategies, but to do so with CFD tools, we need to reform design process. the fundamental experiment undertaken in the design project is to assess the appropriate applications of CFD tools to inform not only the fluid vernacular but architectural pedagogies as well. This thesis hypothesizes that a blending of simulation and intuitive understandings of fluid flow could lead to a more integrated design process. If the applications of CFD have issues regarding the utility to time ratio to generate performance results, to what extent can the informed designer create systems that anticipate fluid simulation outcomes. A hybrid system that utilizes advanced knowledge of fluid mechanics could benefit from the iterative flexibility of an intuitive creative process, reducing the dependency on simulation. the following chapter will identify the intuitive process and how it could be used to strengthen a hybrid approach to fluid design.

Scientific Context

Before addressing the intuitive process, a contextual understanding of the science behind fluid modeling processes will aid in the comprehension of the development of fluid design processes. An architecture of a fluid vernacular that makes use of fluid modelling, must develop an awareness for the scientific principles it hopes to employ. The work done in this thesis aims to highlight the benefit that exists in an approach to architecture that sees creative design and functional design carried out as one. This can only happen if we understand the scientific context we operate within.

Architecture concerned with fluid multiphysics, that being the coupled properties of heat transfer and fluid flow, must be aware of the governing natural laws outlined by science, math, and engineering. In general, there are two ways in which we can model and approximate fluid flow. Physical testing was the first fluid simulation model to exist and has the benefit of producing real world data. Wind tunnels and climate chambers allow for both a quantitative and qualitative analysis. The difficulty here is that we are limited by physical scales. The permanence of architecture means that a full building cannot be tested in this manner. Designers may hypothesize with scale models, but no amount of testing in this way can prepare a project for its final development. This is where computational fluid dynamics is often utilized. Based on standard laws of physics and mathematics, we can digitally simulate full or partial environments before they are built. But development in this field has only occurred recently, as the math behind the equations that govern fluid mechanics are complex and require the calculation abilities of computers. The following topics, outline the relevant context of scientific knowledge that the fluid vernacular must engage.

Navier Stokes

To place this thesis within the scientific context of fluid mechanics, it is imperative to understand the scientific advancements that made simulation systems such as CFD possible. As we will see, the equations that dictate fluid flow are so computationally dense, that it is only with the power of computer calculation that we are able to model to any level of accuracy. Fluid flow is an incredibly involved field of mathematics due to the coupled nature of fluid motion and heat transfer. The set of equations that define fluid are represented by the Navier Stokes equation seen below. Derived from the law of conservation of mass and conservation of energy, these differential equations account for fluid pressure gradients, body forces (buoyancy and gravity), and diffusion to predict the change of velocity with respect to a given time. These equations govern all fluid motion, from blood flow within veins and arteries, to ocean currents.

Continuity Equation :

$$\nabla \cdot \vec{u} = 0$$

Momentum Equation :

$$\rho\left(\underbrace{\frac{\partial \vec{u}}{\partial t}}_{\text{Local Acceleration}} + \underbrace{(u \cdot \nabla)u}_{\text{Convective Term}}\right) = \underbrace{-\vec{\nabla} p}_{\text{Pressure Gradient}} + \underbrace{\rho \vec{F}}_{\text{Body Forces}} + \underbrace{\mu \nabla^2 \vec{u}}_{\text{Diffusion Term}}$$

Despite the development of these equations, their application must be carefully considered. From an applications perspective, these equations are true as we have based them off universally accepted laws of conservation of mass, momentum, and energy. However, with these equations, mathematicians have yet to know if a solution in any given context exists all the time. For this reason, whenever we undergo fluid analysis, we must be aware of the manipulation of parameters and assumptions we make to allow for these equations to work. This challenge within the Navier Stokes equations is so difficult that it constitutes one of the million-dollar millennium prizes (a series of math questions that have historically resisted unified solutions).[1] Let's look at an example of where these equations behave strangely. If we try to model the velocity of fluid flow around a 90° bend, according to the Navier Stokes equations, at the point of the corner we will have infinite velocity. While the broad applications and practical uses of these equations work, we need to understand that there are limitations and considerations that must be kept in mind when we conduct CFD processes.

The reason we have outlined the above, is that to develop adequate simulation results, users of CFD tools must be familiar with the math and science principles behind the operation of their simulation. It is not enough to treat CFD tools as black boxes that deliver outputs. In fact, the application of the Navier Stokes equations must be carefully balanced to operate within the inherent limitations of the equations themselves. Fortunately for this thesis, modern CFD programs reduce the calculation of these equations to a set of input variables and output data. That said, there must be a strong base of knowledge of the underlying principles that make the simulation possible.

1 "Millennium Problems | Clay Mathematics Institute."

Reynolds Number

An important parameter in understanding definitions within the Navier Stokes equations is the Reynolds Value. The Reynolds Value is a dimensionless number that represents the ratios of internal inertial forces to viscous forces within a fluid. What the Reynolds number of a fluid allows us to assess is the behavior of the fluid to act as either turbulent or laminar. Laminar flow is characterized by fluid particles moving with each other in parallel, or near parallel lines with no lateral mixing. This unique fluid state produces a uniform air pattern and is often found in smaller scale, slow moving, or very viscous fluids. The turbulent flow regime on the other hand is where most fluid in the universe resides. Fluid in this state is chaotic, with a heavy degree of mixing in every direction. Flow patterns are irregular with frequent oscillations in direction and magnitude. To determine the Reynolds number of a fluid, we use the following formula.[2]

$$Reynolds\ Number = Re = \frac{\rho v L}{\mu}$$

ρ Fluid Density [kg/m^3]
v Flow Speed [m/s]
L Characteristic Linear Dimensions [m]
μ Dynamic Viscosity of the fluid [kg/m*s]

As a function of flow speed, fluid density, dynamic viscosity, and characteristic length, we can determine what flow regime we are likely to encounter in the built environment. Depending on the magnitude of the Reynolds number, we can determine if a flow is laminar or turbulent. While external flows do not follow a strict guideline, the larger the Reynolds number the more turbulent the flow. Reynolds values in a pipe for example, reach turbulent flow at around Re = 4000. For our purposes we will simplify the equation to determine the approximate flow regime context. The density, and dynamic viscosity for air, 1.225km/m^3 and 1.8x10^{-5}kg/m*s respectively, will remain relatively unchanged which means we can simplify the equation to the following.

$$Re = 67679.56[m^{-2}s] * vL$$

What this shows us is that only at extremely low speeds, or extremely short distances, will our flow ever be laminar. The extremely low viscosity of a gas means that laminar flow is very difficult to achieve. Therefore, in our analysis we must be aware that all environments will fall into the context of a turbulent flow regime.

2 “Reynolds’ Number - an Overview | ScienceDirect Topics.”

Design Process

So far, we have discussed the application of a fluid vernacular by identifying the challenges it hopes to tackle and the way computation must be adapted to establish effective design processes. The final trait of this work rests on the utilization of intuitive design process alongside computational tools. While it is known that there is no one design process that architects must adhere to, the philosophy behind an iterative approach to architecture has long been entrenched in academics. Working towards an undefined end goal, the bottom-up approach, has proven to yield more creative design solutions. On the other hand, working towards a defined objective, the top-down approach, often leads to a realization of measurable goals but fails to develop the same breadth of design solutions. To establish the position of a hybrid design process that makes use of both CFD simulation and creative intuition, we will begin by classifying design theories into 6 main categories:[1]

Rational and Empirical Theory
Exercising an “if, then” approach to design, often to achieve specific goals.

Procedural and Substantive Theory
Following a design framework which diverges through multiple steps and converges upon a final solution.

Normative Theory
Adhering to specific value-based results as a means of design driver.

Design participation Theory
Allowing for the inclusion of multiple stakeholders to contribute to a fluid approach to design.

Form Oriented Theory
Classical iterative design approaches, often rooted in artistic practices or informal exploration.

Place and Non-place Theory
Focusing on the physical environment, townscape, land use, etc. as generative driver.

1 Rezaei, Reviewing Design Process Theories.

While this list is indicative of major distinctions between different design theories, the scale in which design operates is by no means this definitive. On this spectrum of design thinking, we must blend approaches that benefit from creative liberties while finding means to include rational concepts of order and outcome if we strive for designs that see measurable functional outcomes. This thesis will position itself on the design theory spectrum in a hybrid realm between rationalist outcomes, and procedural development in a way that makes use of digital technology.

The integration of simulation into a bottom-up method of iterative design is the desire of this project. Providing an effective design process that goes beyond hypothesis will be much more effective at engaging the challenge of increasing the accessibility of unfamiliar fluid systems. The term theory is important to distinguish from that of hypothesis. The principle of a scientific theory is that it is a product of a process that is supported by measurable evidence. Hypothesis on the other hand is constructed prior to the development of theory and is the realm we are condemned to exist if a rigorous process is not followed to prove the theory. The first buildings were constructed based on hypothesis alone. Without past works to look towards, or a scientific background to provide justification, testing of building structures came through practical experimentation. The pantheons of Greek and Roman construct exist today as the justified theory that a post and lintel type construction can hold up buildings.[2] But this process of converting hypothesis into theory has its bounds. With the development of geometry and math we saw the opportunity to develop a system, structural engineering, that would allow us to break free of this trial-and-error method of technological advancements. Buildings are unique in the sense that their development has no opportunities for full scale prototyping. Yet if a building fails, the fallout can be disastrous. There simply was no room in structural development to rely on a system of experimental hypothesis and real-world testing. We needed to develop theories on which we could rely to further structural advancements.

In the development of a process capable of effectively utilizing CFD, the creative process of generating flow hypothesis will be verified using CFD simulation results. Effective developments of the fluid vernacular strive to not only benefit from the design certainty provided by CFD but by the intuitive iterative capacities of informed design practices. If provided the proper education, can intuitive designing reach acceptable levels of design performance without being hindered by the investments and lack of accessibility of CFD analysis. The conclusions of this thesis hope to provide insight not only on the process of design but how, in any way, should architectural pedagogies be reflective of increasingly technical design requirements.

2 Yi and Yi, “Utilization of Scientific Method as a Tool of Architectural Design.”

Natural Phenomenon

While the Navier Stokes equations allow us to simulate fluid mechanics in a digital space, and our understanding of the Reynolds regime begins to inform the types of spaces we will encounter in a fluid vernacular, the largest change to architectural form will come from the manipulation of fluid flow from physical objects. If we want to develop a system that is more in tune with the nuances of fluid mechanics and aims to hybridize active and passive systems in an efficient manner, it is valuable to understand fluid mechanics and flow phenomenon. The fluidly informed design process asks the designer to be knowledgeable in a wide range of flow mechanic principles. Much the same as an architect must design within the constraints of building code, a similar framework exists in the fluid vernacular and the laws of physics it must work with. The following outlines several natural phenomena related to fluid mechanics that show potential in the adoption of architectural systems. It is the intent of the intuitive process that the designer has a working understanding of these principles to inform the intuitive design process. This list serves as a starting point, a place from which we can suggest formative implications that make use of scientific discovery. In reality, the list of fluid mechanics to be aware of could constitute its own thesis document.

Coanda Effect

In short, the Coanda effect outlines the tendency for fluids to remain close to the physical body in which they flow across. This phenomenon is graphically represented in the diagram below. The results of this phenomenon are largely due to the viscous nature of fluids as well as what is defined as a no slip boundary condition between the fluid and physical object that it passes by. A common example of this in everyday life is a tendency for water poured from a measuring cup to hug the surface of the pouring vessel. This results in water dripping from the bottom of the cup as opposed to flowing perpendicular to the vessel’s mouth. By creating surfaces that are aware of this effect, we will have a higher understanding of air movement through spaces and how air could be passively redirected in open spaces. This is important to understand from an early phase of design as it allows us to incorporate these phenomenon as inherent functional and formative design interventions.

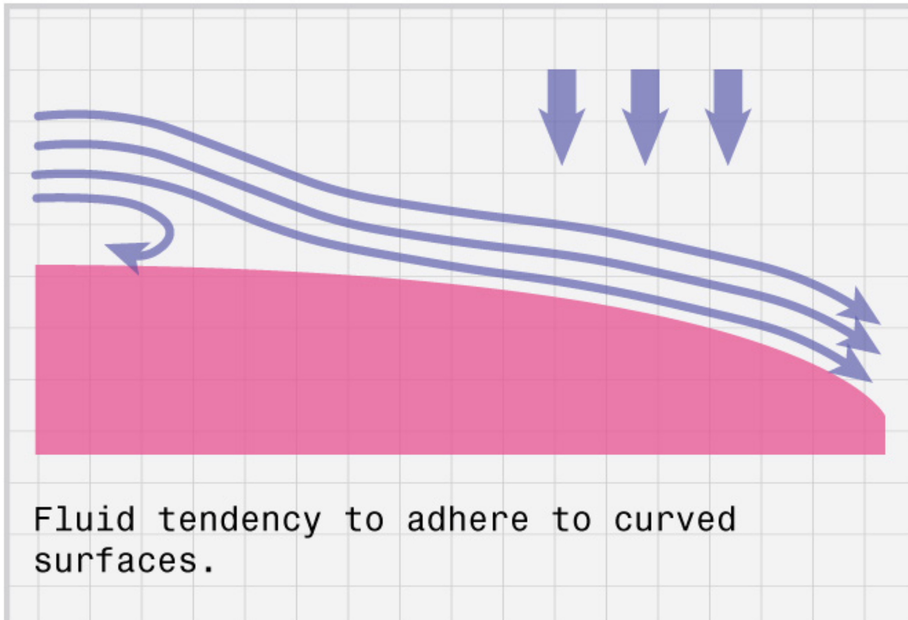


Fig. 4 I The Coanda Effect

To further elaborate on the potential of the Coanda effect in the built environment, we will classify realms in which the Coanda effect could be implemented. Firstly, the Coanda effect can control fluid flow through contact. Surface shape, roughness, porosity, and even the temperature of the boundary a fluid exists within can control flow direction and magnitude. At small scales this can even control fluid flow between laminar and turbulent states. Secondly, we can look at how outer flow fields are affected by the Coanda effect. This being the tendency for fluid further away from the surface to develop characteristics of the boundary layer.

Coanda effect applications can also be classified by their active or passive status. Streamlining airfoils for example can manipulate airflow based on the geometric properties of the solid mass. This is an example of passive fluid control. In an active system greater care is required to maintain energy efficiency. The last distinction we will make regarding passive applications is the fact that air operates within the compressible fluid realm.[1] This has very different functional applications compared to incompressible flows.

Venturi Effect

One of the more common fluid phenomena already known to the architectural design discipline is the Venturi effect. This principle is present in most buildings when you approach the entrance in a façade through a long-confined space. As you approach the structure you find air speeds and turbulence increases. This is due to the compression of fluid flow which results in a velocity change. The coupled effect between fluid pressure in compressible fluids and velocity is known as the Venturi effect. Simply put, as a fluid is compressed its velocity increases, the inverse is also true. This is a common

1 Ahmed, "Coanda Effect"

phenomenon in building design as narrow spaces or buildings placed within proximity to each other not only affect internal fluid flow but surrounding wind environments as well. The following diagrams display a visual representation of the Venturi effect. While recent studies suggest that outdoor environments maybe more influenced by a wind blocking effect due to their openness to the atmosphere, contained spaces within a building show the most promise for a thoughtful use of Venturi principles.

The largest architectural factor that controls Venturi characteristics, is the change in cross sectional area as fluids travel perpendicular to them. This phenomenon has been widely modelled to understand its application in buildings. An important distinction however is the differences between what is simulated and what is perceived in a built reality, something this thesis hopes to understand further. Using this concept, we will be able to inform design decisions to achieve higher performative output. An example of this would be the recommendation to use an angle of 15º between converging faces to optimize pedestrian comfort in cold climates for smoother flow changes.[2]

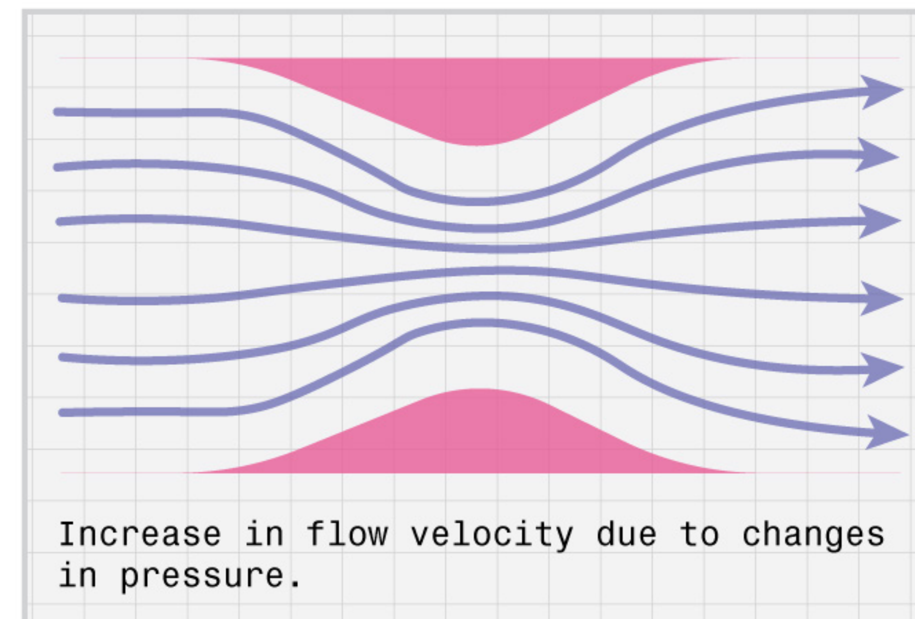


Fig. 5 I The Venturi Effect

2 Li et al., "Revisiting the 'Venturi Effect' in Passage Ventilation between Two Non-Parallel Buildings."

Methods and Materials

The Design Project

As this is a thesis focused on the analysis of design process as opposed to the architectural merit of the design outcome, the design project will feature a site and program to serve as an experimental vessel to explore the proposed concepts. Because the architectural outcome is intended to be digitally modelled and simulated using CFD solvers, a large portion of the work has been dedicated to understanding the scope limitations associated with time-intensive computation. A suitable canvas to experiment with fluidic design would therefore be enhanced by an architectural typology with an inherent need for carefully designed fluidic systems.

The architectural program that will be used in this experimentation process, is that of a hybrid data center and office space. This typology was selected based on the potential for fluid relationships between the occupied office space and the unoccupied data center. The focal point of the design will be centered around the discussion of how hot air exhaust from the data center can be used in the rest of the building to provide either passive heating or stack effect cooling. Key design attributes will be focused on the adequate delivery of air flow into the unoccupied data center to provide passive cooling for the electrical components. Secondly, the design will utilize this heated air exhaust to inform the occupant comfort of the office spaces above. In addition to flow design within the building, architectural massing moves will also consider the flow relationship to the surrounding site, specifically the adjacent paragliding facility.

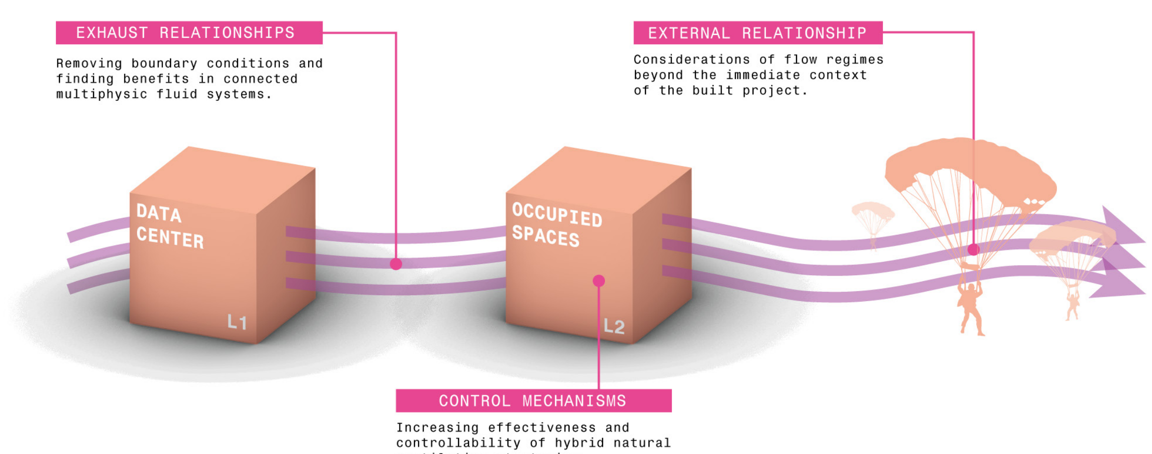


Fig. 6 | Design Project Attributes

Process

As an analysis of design process, it was imperative to outline the types of processes used in the development of the design project. Firstly, we have the simulation-based approach that makes use of the computational power of CFD. This process is valued due to its high degree of performance predictability. However, an effective use of CFD must balance this benefit with the time and resource investment required to conduct such work. The simulation time itself accounts for only a small portion of the total time investment. Due to the linear nature of the simulation process, CFD analysis traditionally resists the opportunity for design flexibility.

To compliment this process, we also define the intuitive approach that currently governs most design thinking. While intuitive design outcomes do not have the performance predictability that comes through simulation, the ability to work iteratively promotes rapid design convergence. Working between plans, sections, and elevations interchangeably, allows the designer to think holistically when it comes to building systems and design aesthetics. It should be noted that the intuitive process undertaken in this thesis differentiates itself from that used by most designers. The fluid vernacular is designed with a heightened understanding of fluid mechanics and thermodynamics. This allows the designer to create informed solutions with a greater likelihood of achieving performance goals without the use of CFD testing.

To broaden our understanding of how the designer should properly implement CFD into the design process, a hybrid approach was used. Largely based on the iterative benefits of the intuitive process, the approach proposes the use of low-investment, broad-scope CFD early in the design process to establish confident massing moves and reduce large scale design changes later in development. This should save time by initializing designs to appropriate standards. Through a series of intuitive, yet informed iterations, a design solution will be created, that to the best of the designer's ability, will function as desired. Finally, iterations of CFD testing and responsive design from simulation results will allow the designer to adjust and ensure the design hypothesis translates into the built environment.

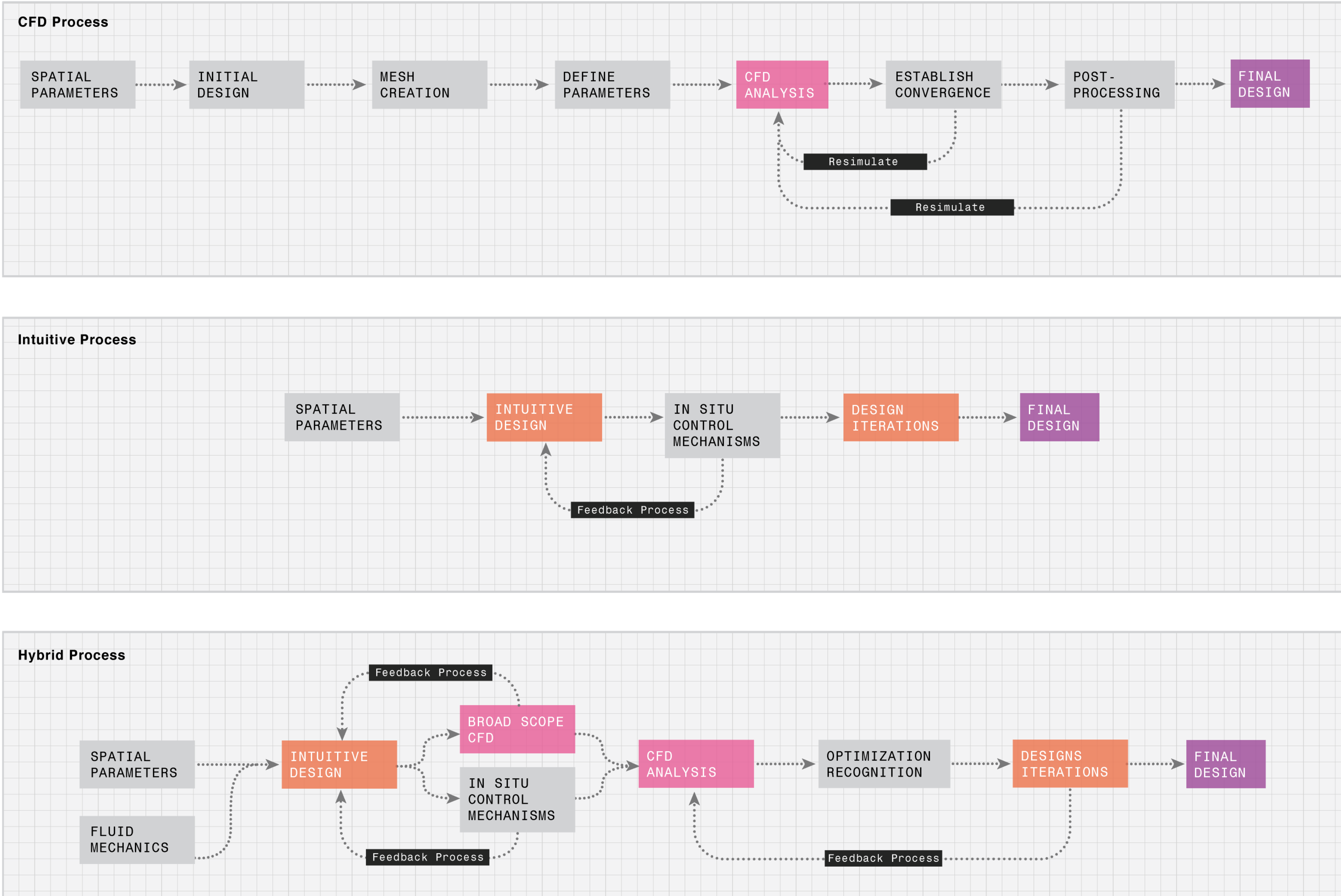


Fig. 7 | Design Processes

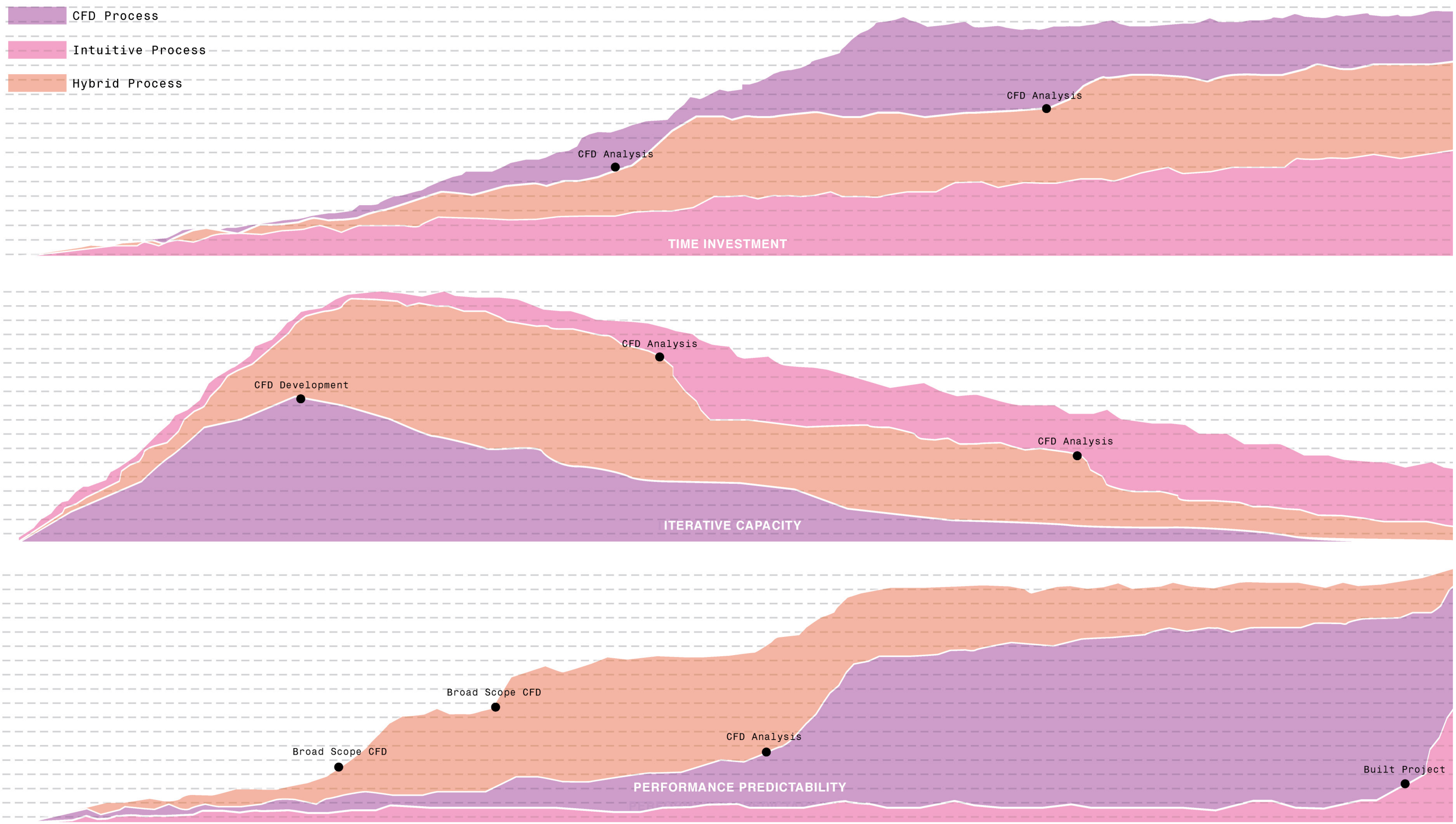


Fig. 8 | Speculative Process Attributes Compared to Lifespan

Site

Architecture created with heightened understandings of fluid dynamics and intimate connections to passive performance principles should possess a working dialogue with the natural area in which the building resides. A prominent location which experiences consistently high winds will not only provide benefits to the high cooling demands of the data center but will magnify the formative impositions of a fluid vernacular.

Design work for the thesis will take place on an area known as “The Bench” in Cochrane, AB, Canada. A total distance of 36km from the site to the nearby Calgary city center means that the typology will benefit from the rural qualities of the landscape while remaining reasonably attached to a larger urban audience. As the 4th fastest growing municipality in Alberta, Cochrane has a population of 32,010 people spread over approximately 30km^2. The town sits at an average elevation of 1186m, with an unobstructed view to the Rocky Mountains to the West. As a site that experiences average temperatures in the range of -11.8^{o}C to 16.4^{o}C, the coupling of fluid flow with heat transfer to maintain adequate thermal comfort will be critical to the development of functional architectural systems.[1]

This specific location was selected as the hill, known locally as “The Big Hill”, will serve to exacerbate the naturally high winds of the area. The hill acts to compress and accelerate airflow from the Rocky Mountains. The consistently high wind patterns of the site make it a popular destination for paragliding enthusiast of the area. Enough so that the top of the hill adjacent to “The Bench” is dedicated land owned and operated by Muller Windsports. In addition to the flow requirements of the program itself, the flow relationship between the project and the adjacent community will be taken into consideration.

1 “Demographics | Cochrane, AB.”

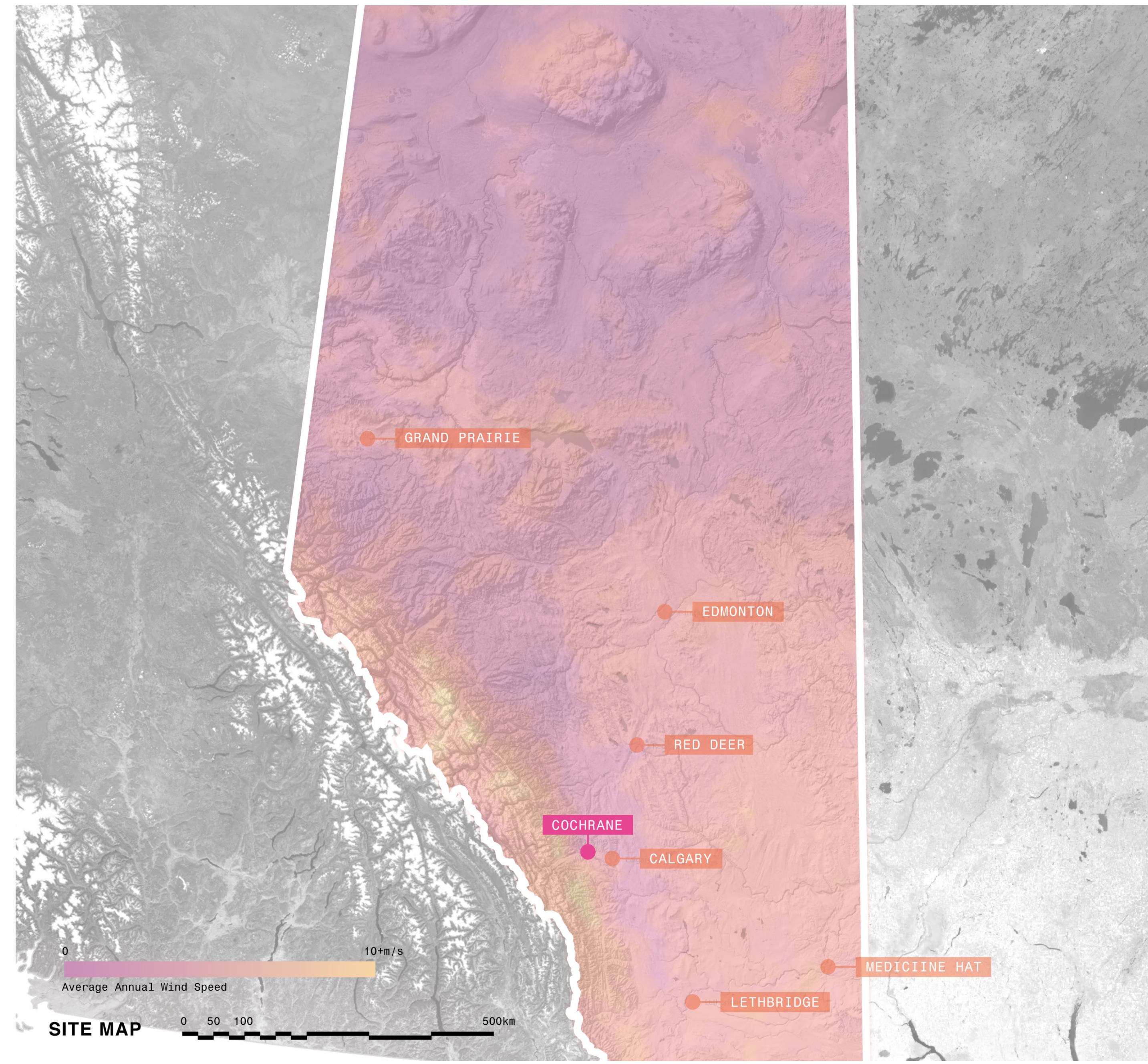


Fig. 9 | Provincial Site Map with Wind Speed Overlay

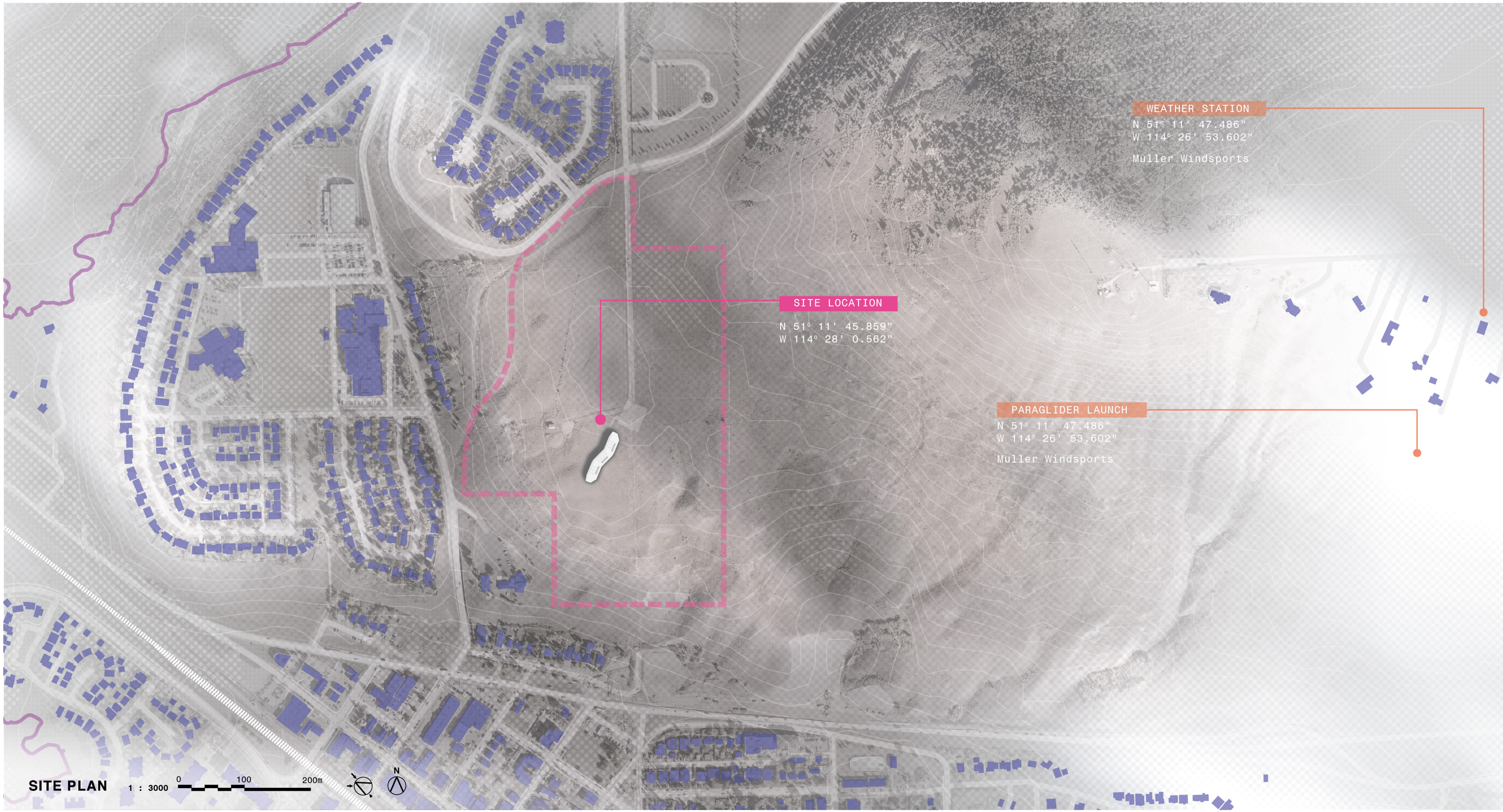


Fig. 10 | Site Plan

Site Data

Because the vernacular of fluid mechanics is so closely tied to the environmental flow conditions of any given site, it is imperative that accurate and local site data be used to inform design iterations. As indicated in the site plan, average weather data was collected from the adjacent paragliding facility and will serve as an accurate representation of low characteristics on the site. From the average wind rose data, for this specific site the principle of bilateral symmetry will work best to account for flow in two primary directions. The design will have to account for major winds which represent the highest frequency of kinetic air flow, minor winds which come from the opposite direction in less frequent intervals, and Chinook winds that appear in relatively high frequency with high speeds and warm weather.

From this data the building aims to increase operable ranges by designing around the ability to function in a bilateral capacity. This strategy of designing with fluid flow primarily from two main directions will result in the creation of a weak axis. Winds coming from the Southwest and Northeast will present a challenge to the operable range of passive ventilation. To combat this, flexibility in massing structures or the augmentation of passive ventilation with mechanical ventilation may be used in these circumstances. In addition to the design concept of establishing bilateral symmetry, we can establish the concept of “Wind North”. The Wind North direction positions the active facade of the building perpendicular to the major wind direction we are designing for. While True North represents the true geographic qualities of the site, Wind North is reflective of the flow directions we are designing for.

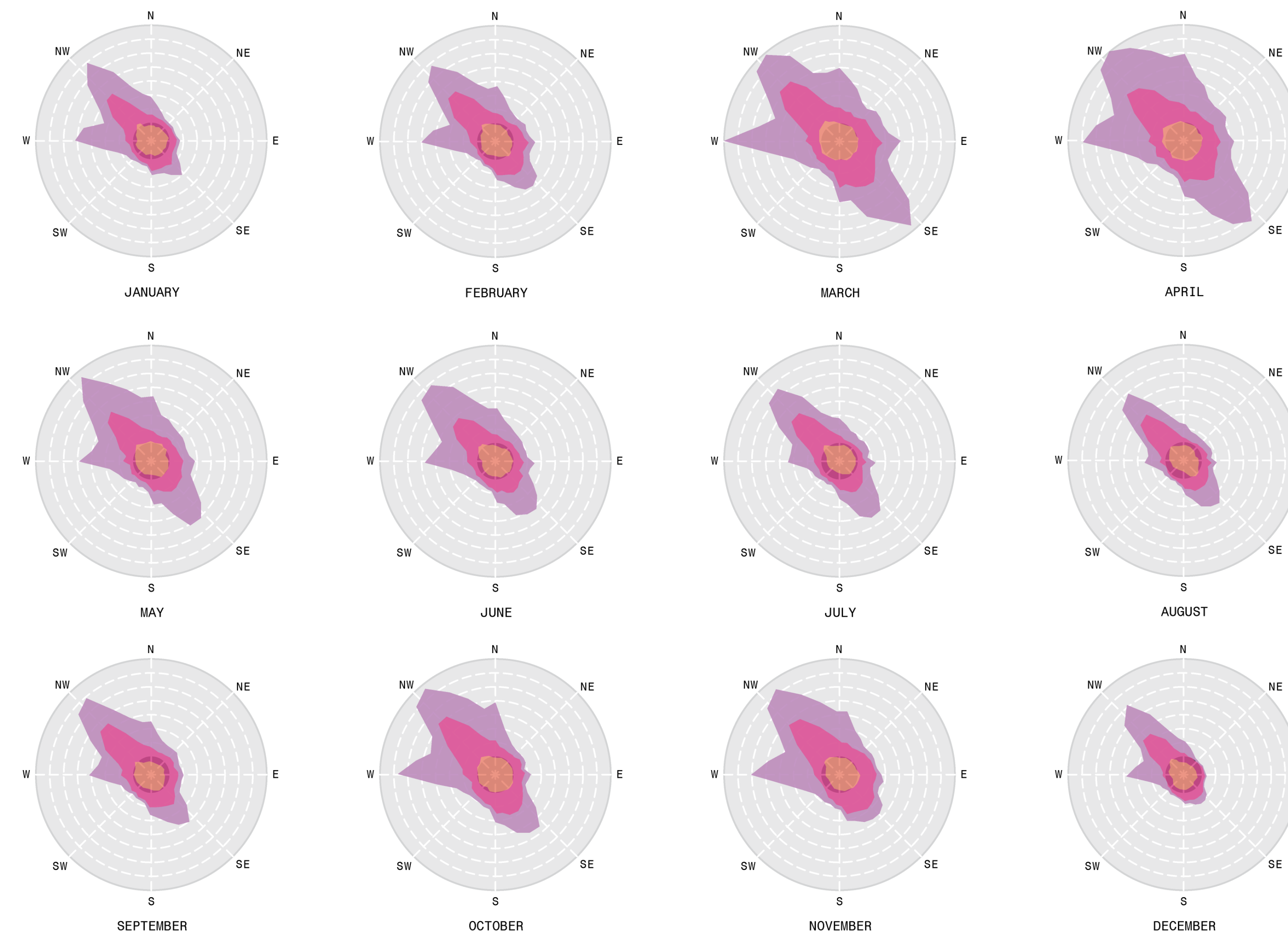


Fig. 11 | Monthly Wind Rose Data

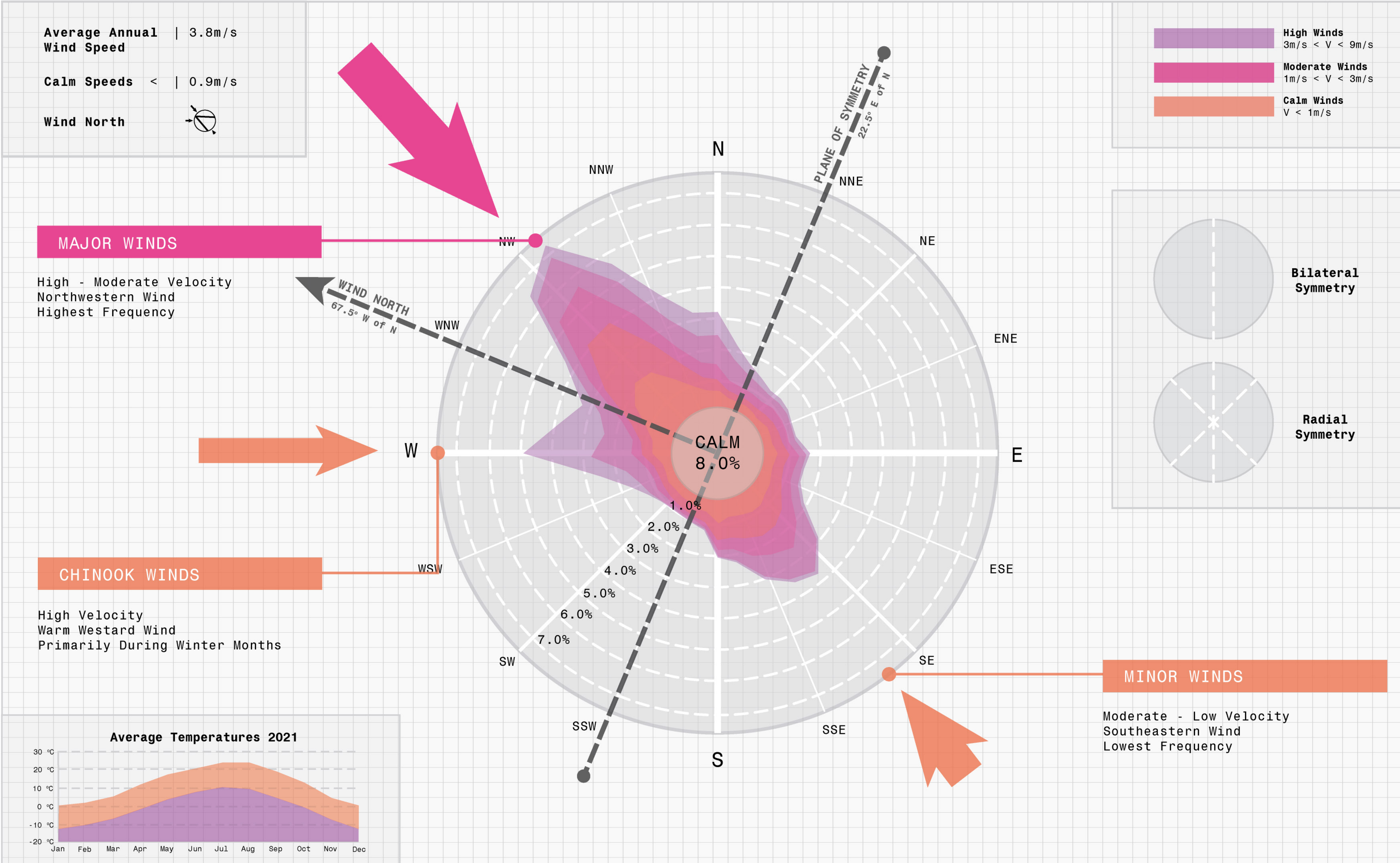


Fig. 12 | Average Site Data

Procedure

Introduction

Framed as an experiment to inform integrated technical design practices, the work of this thesis engages the analysis of design process to provide insight into the appropriate applications of CFD. Through the development of the data center, the efficiencies, deficiencies, and performative outcomes of the process will lead to the establishment of the thesis conclusion. While the building must be largely functional and architecturally compelling as a tool to inform the fluid vernacular, the focus of this procedure remains on the design process itself. This chapter highlights the work conducted during the design phase of the thesis project. The following representations constitute the entirety of the visual work presented during the thesis review. Drawings have been reformatted to fit within the context of this report.

Intuitive Design

The hybrid design process used in this thesis project, places heavy emphasis on the intuitive applications of fluid mechanics and thermodynamics. Traditionally, it has been outside the architect's role to have a holistic understanding of how massing moves and fenestration patterns have the potential to effect fluid kinetics. The intuitive design process of the fluid vernacular asks the designer to have a level of proficiency and knowledge in working with fluid mechanic principles. The intended effect of this background understanding is that this will provide a level of analog performance design that will compliment simulation practices later in the process. With a more considerate approach to fluid design, discrepancies in CFD simulation work done later in the project, should require less severe design interventions. Depending on the effectiveness of this form of iterative approaches, the thesis hopes to inform architectural pedagogy and the level of understanding the designer should have when designing with passive strategies in mind.

The flow mechanics summary on the following page highlights a small portion of fluid mechanic principles that the designer of a fluid vernacular building might use to benefit the architecture. The following figures represent a distilled collection of intuitive documentation of the design iterations used in the development of the data center. Not unlike the iterative solvers of CFD software, iterating between plans sections and elevations hopes to converge towards a design that balances architectural experience with fluid functionality.

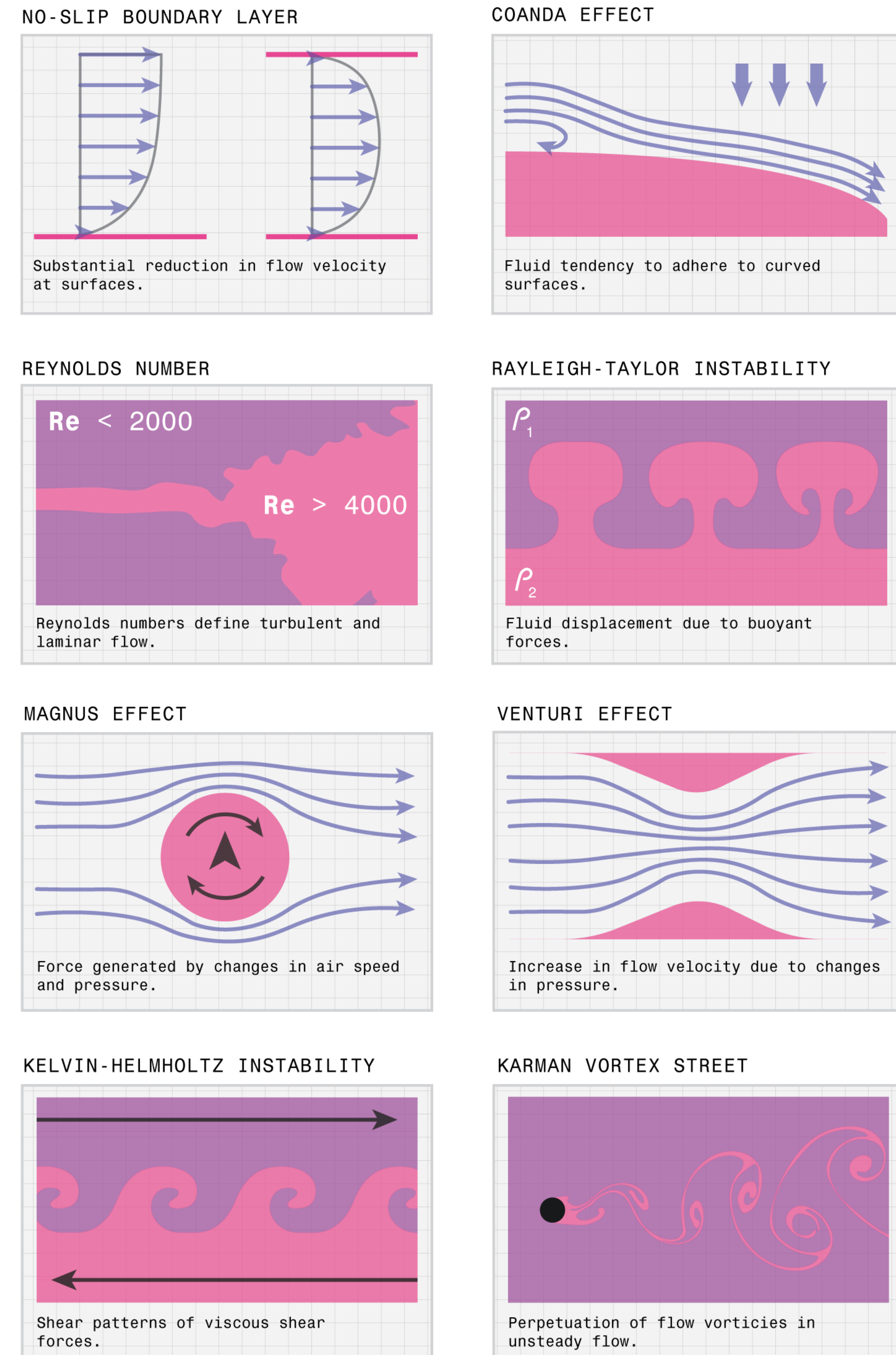
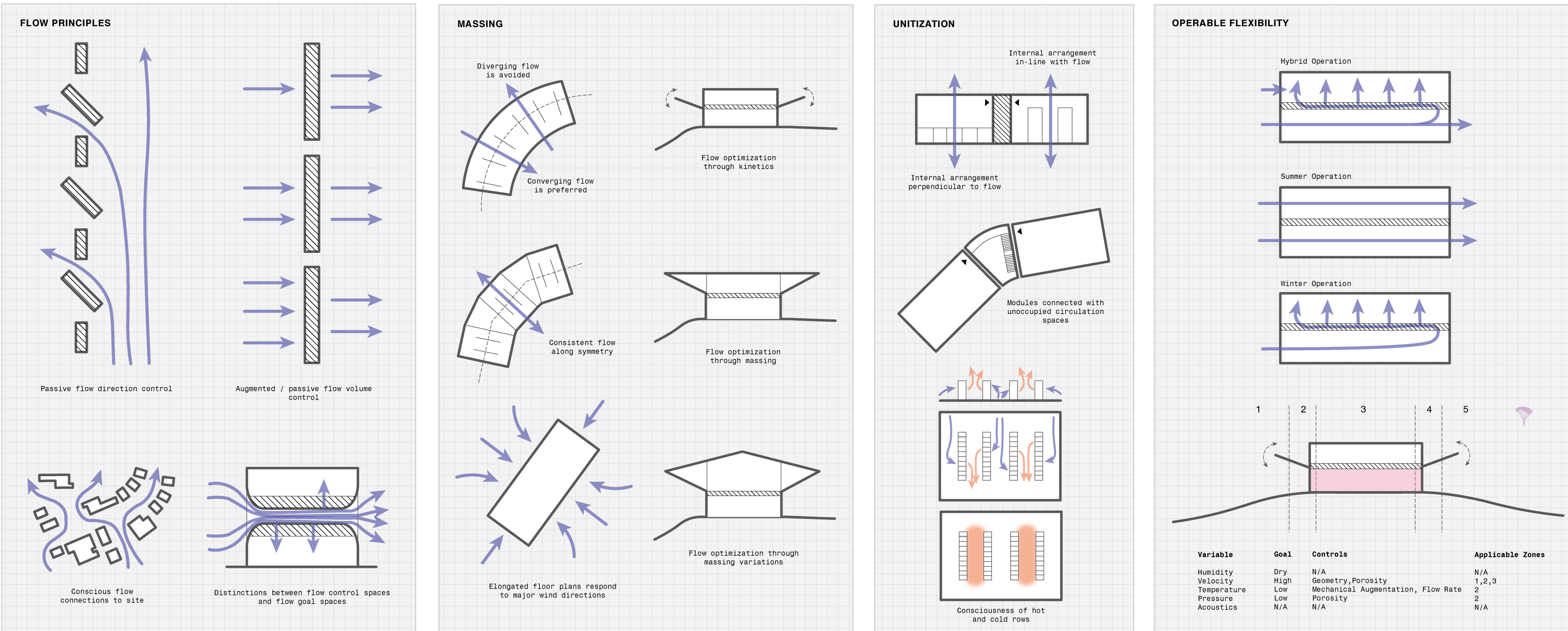


Fig. 13 | Flow Mechanics Summary



Variable	Goal	Controls	Applicable Zones
Humidity	Dry	N/A	N/A
Velocity	High	Geometry,Porosity	1,2,3
Temperature	Low	Mechanical Augmentation, Flow Rate	2
Pressure	Low	Porosity	2
Acoustics	N/A	N/A	N/A

Fig. 14 | Primary Intuitive Iterations

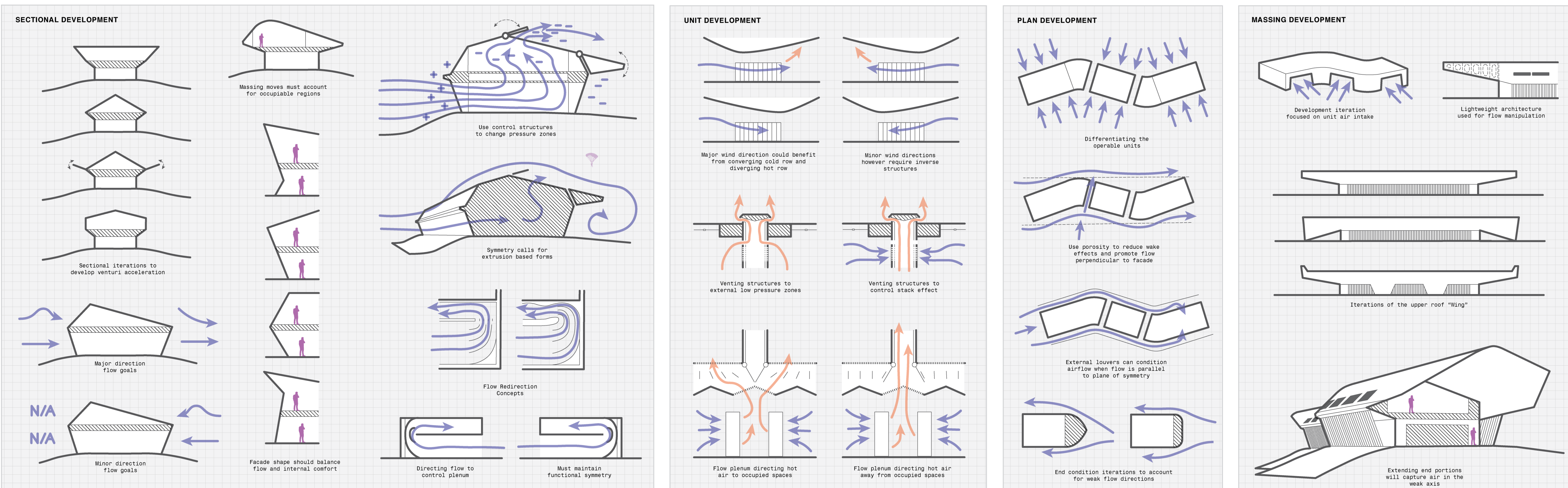


Fig. 15 | Secondary Intuitive Iterations

Control Systems

While the design iterations above have been established using the concept of bilateral symmetry to optimize performance for the site conditions, some form of flexible systems would provide substantial benefits in responding to ever-changing wind conditions. Permanent architectural moves have an inability to account for changes or abnormalities in wind flow patterns beyond those accounted for in the bilateral design. How then can we design the fluid vernacular to increase the performance of passive ventilation systems by increasing operable ranges and controllability. To respond to this functional goal, the fluid vernacular considers several passive control systems to manipulate fluid flow and standardize the fluid experience of the internal environments. While mechanical systems rely on active control and delivery of airflow, the control systems used in the fluid vernacular are designed as passive elements with the ability to move mechanically. By altering fundamental geometry of the built space much in the same way that an airplane can manipulate its control surfaces, the building can alter its fluid performance to respond to a wider range of flow inputs.

The development of control systems began with an analysis of the different flow regimes the building should account for. While an infinite number of control system scenarios could be developed for any given wind speed, direction, and temperature, the following sectional permutations outline nine key scenarios the design must consider. Permutations for control system manipulation should account for environments where the wind flow is sufficient for providing fresh air, insufficient for providing the required fresh air, and in environments where there is no airflow at all. In addition to air flow rates, the building must operate in summer conditions where the ambient temperature is hotter than the desired indoor temperature, winter conditions where the outdoor temperature is cooler than the indoor temperature, and environments where the indoor temperature is approximately equal to the outdoor temperature. These studies will inform the placement, magnitude, and functional capacities of the required control systems.

While these control systems are fundamentally created to account for different flow scenarios, they are also situated with the knowledge that CFD testing might require changes to the building's form. By strategically placing these control systems in areas where the informed designer might expect optimization recommendations from simulations done in later stages of design, the designer can reduce the impact and time requirement of drastic design changes.

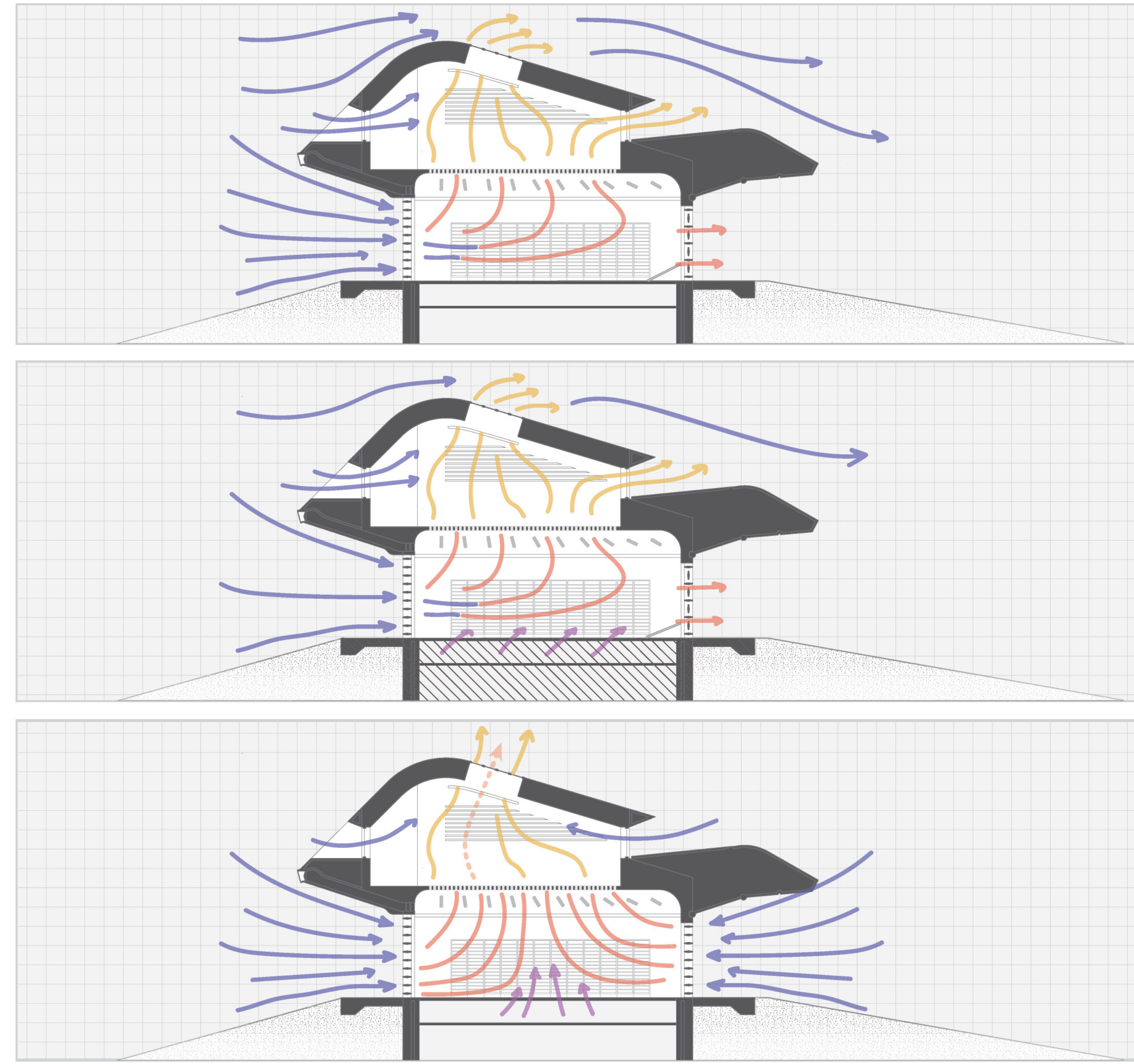


Fig. 16 | Sectional Permutations for Spring/Fall Operation

The figure above represents the changes in control systems for spring and fall operation. From top to bottom, the building has been designed to account for airflow supply rates equal to or greater than the required airflow, airflow supply rates less than the required airflow, as well as negligible airflow scenarios. In the figure above, we can see the intuitive understand of airflow movement and heat transfer through the placement of flow lines. In this scenario, the goal is to mix heated air with cooler air to promote temperature control and fresh air supply simultaneously.

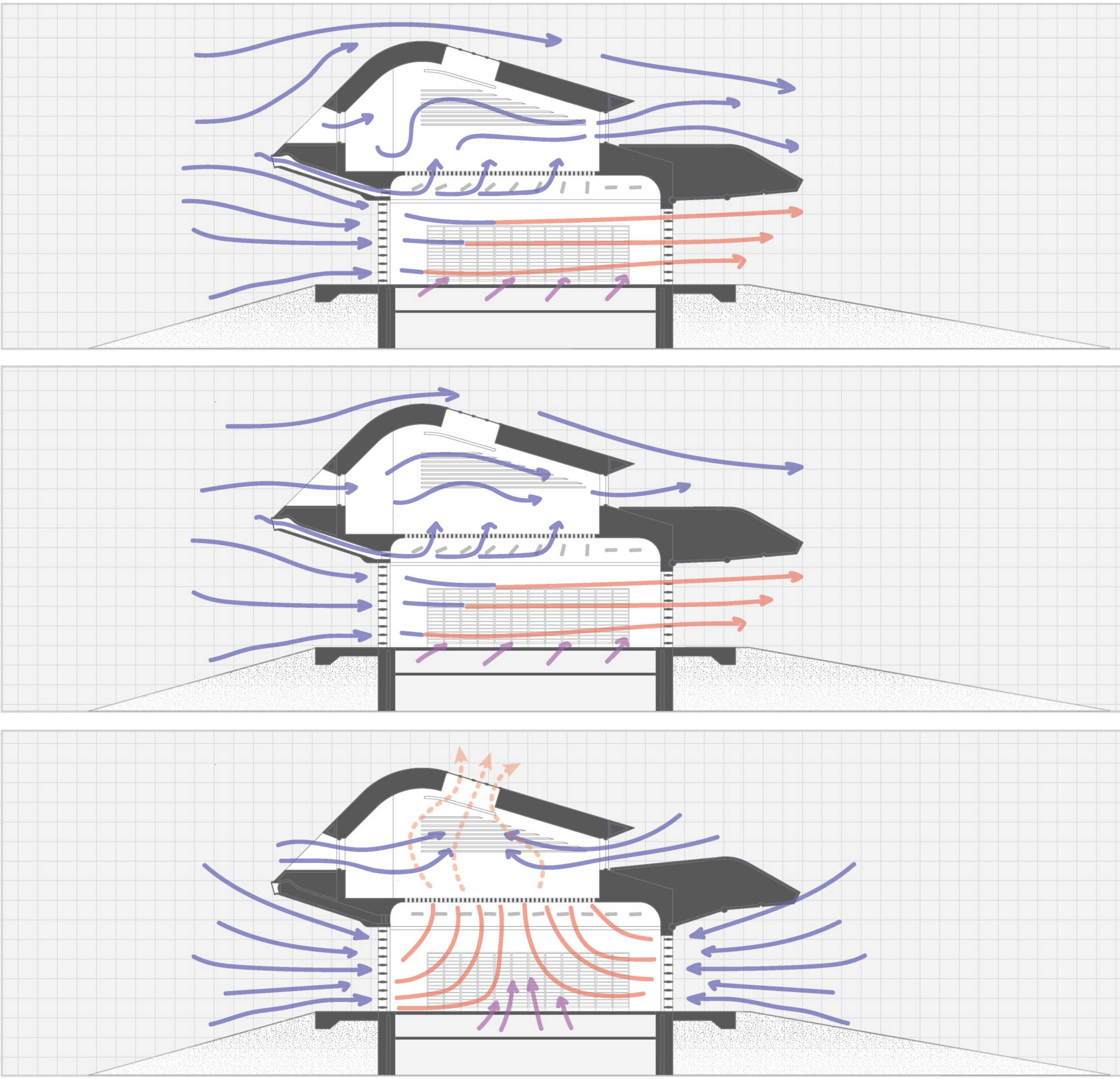


Fig. 17 | Sectional Permutations for Summer Operation

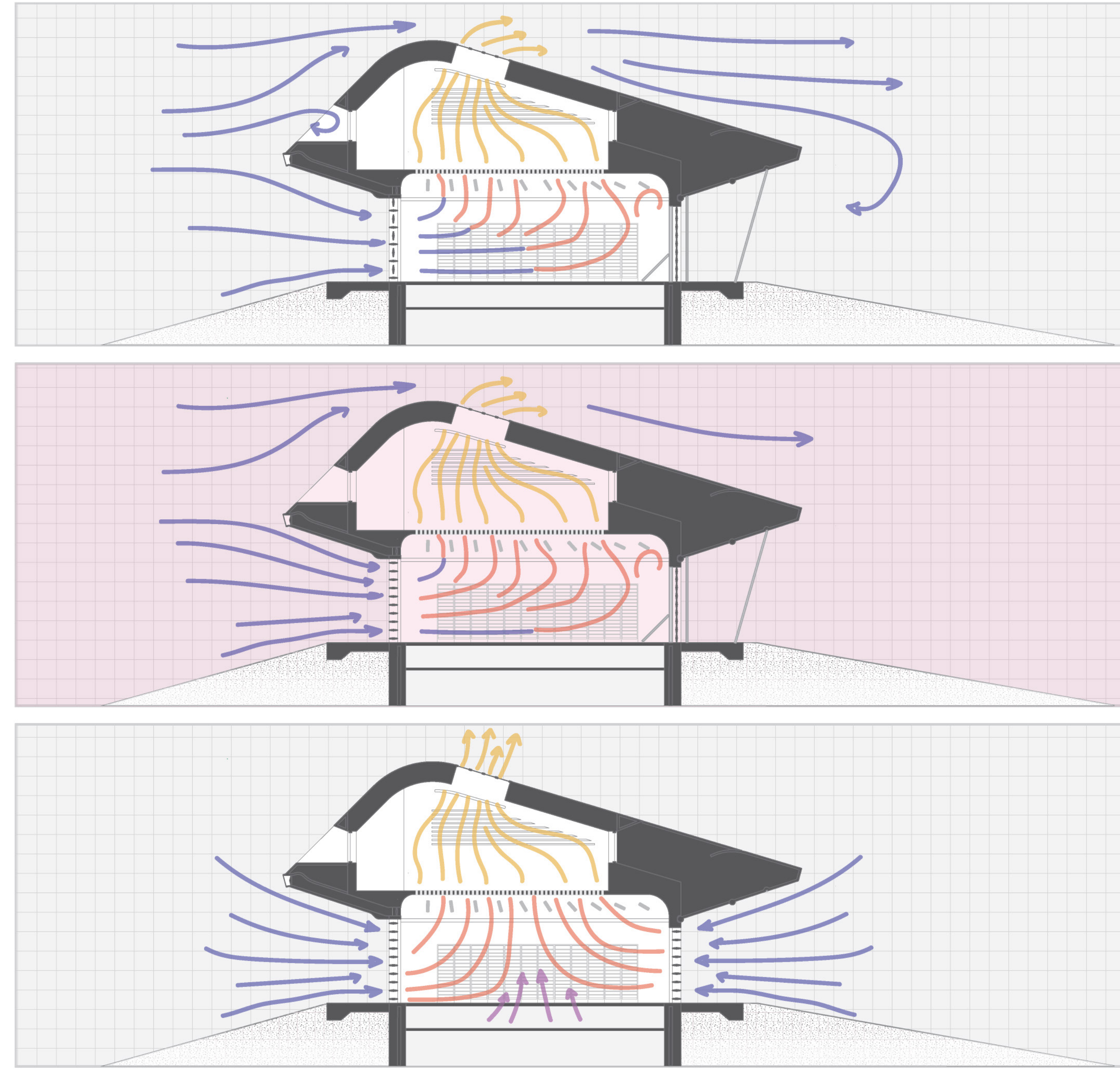


Fig. 18 | Sectional Permutations for Winter Operation

The figure above represents the changes in control systems for summer operation. From top to bottom, the building has been designed to account for airflow supply rates equal to or greater than the required airflow, airflow supply rates less than the required airflow, as well as negligible airflow scenarios. Summer operation requires maximizing cooling capabilities of the data center while relying on either cross ventilation or stack effect ventilation for internal cooling.

The figure above represents the changes in control systems for Winter operation. From top to bottom, the building has been designed to account for airflow supply rates equal to or greater than the required airflow, airflow supply rates less than the required airflow, as well as negligible airflow scenarios. Winter operations rely on the hot air produced from the data center to heat the occupied space. Air movement makes use of density driven buoyancy as a means to vent air. Due to time constraints, only the middle iteration will undergo CFD testing and further iteration in this thesis.

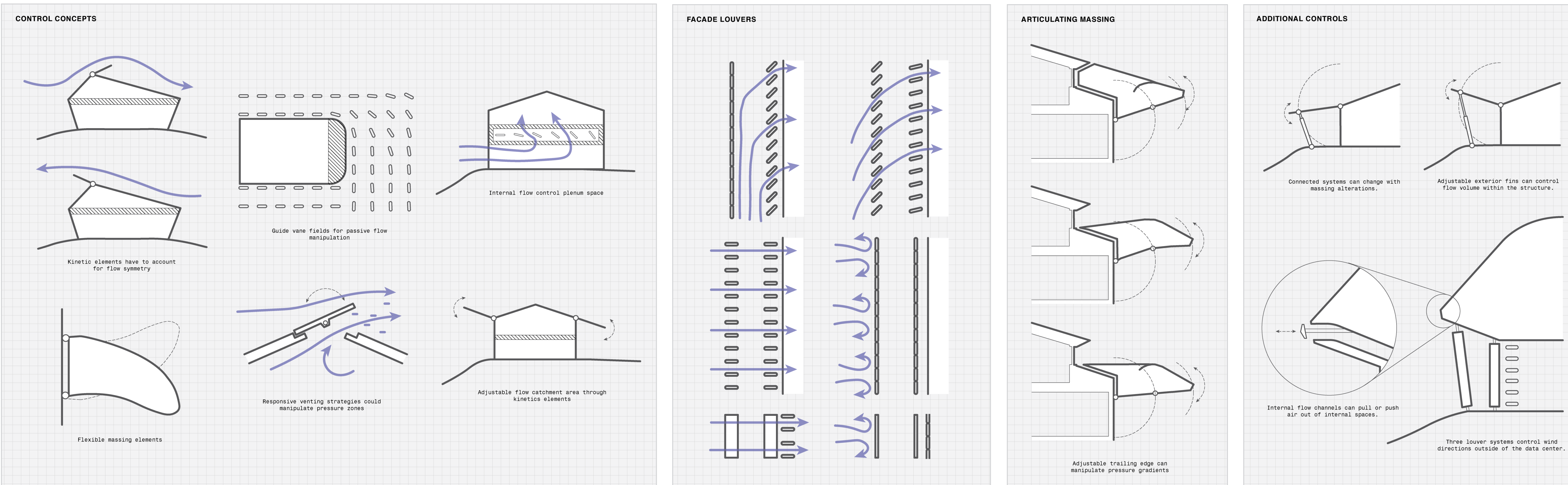


Fig. 19 | Control System Development

Control system concepts fundamentally rely on kinetic design elements to alter the buildings flow performance. The addition of fairing structures on the leading and trailing edges of the occupied space are built in a manner that promotes cost efficiency while informing architectural expression and fluid functionality. As these systems are separate from the occupied space, the lack of required structure and insulation means that they can take the form of expansive overhangs and even kinetic elements. In addition to the concept of building fairings, the extensive use of louvers, or guide vanes as they are referred to in flow design, are positioned around the building as a means to control airflow rates as well as flow direction.

CFD Iterations

While the initial design process relied heavily on intuitive understandings of flow mechanics, as an experiment in the application of CFD testing, a broad scope analysis of several massing iterations was conducted to provide insight on the benefits of using early-stage CFD simulations. Conducting these studies early on aims to provide a series of massing iterations to inform small scale design moves in the rest of the intuitive process. The objective of obtaining this type of iterative CFD results early in the design process is that it will reduce the severity of substantial design changes later in the project. Even though each of these iterative simulations took at a minimum 8 hours of total CFD processing time, they provide unique performative insight beyond intuitive capabilities. By using the pressure and velocity contours, a series of future design implementations were made possible by understanding how larger massing moves manipulate fluid flow.

Due to the bilateral symmetry imposed on the design from the site data, as well as the attempt to reduce the computational time of early stage CFD applications, the following analysis was conducted using two-dimensional CFD calculations. The variations in the section designs have been setup to determine an optimization between providing flow acceleration in the data center while reducing the wake effect for the downwind paragliding facility.

The first iteration explorers a sectional massing that resembles a traditional airfoil. Soft angles guide wind flow into the data center while making use of the velocity increase caused from the venturi effect. The upper portion of the building is designed to reduce the wake as much as possible by maintaining the adherence of flow to the buildings upper face. The second iteration increases the surface area of the flow intake to increase the flow velocity in this space. While the rooftop portion of this design achieves better performance regarding minimizing wake effects, the increased angle of attack of the intake surfaces ultimately reduces flow velocity within the data center region due to the destructive differences in flow directions. Thirdly, an iteration where nearly the entire facade of the building is used for air intake represents the maximum of this cross-sectional concept. Issues regarding the flow velocity reduction in the data center space are further developed in this iteration due to the increased angle of the facade. The reduction in velocity that occurs as a result is unfavorable for cooling performance of the electrical hardware. At the same time this negatively effects the performance of the upper surface in reducing wake effects and eddy formation.

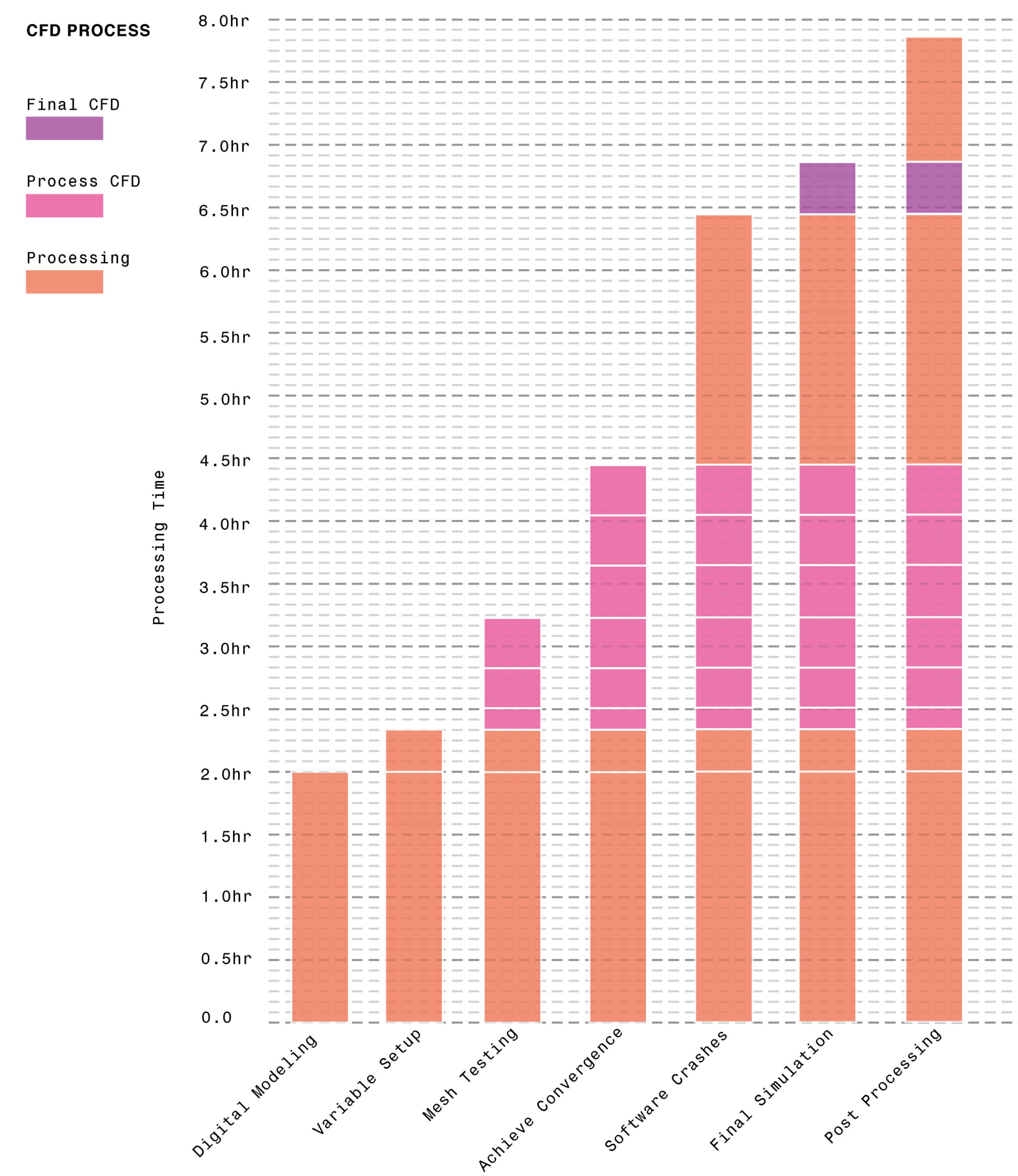


Fig. 20 | CFD Time Investment Breakdown

While these iterations are by no means an attempt at a final design massing, nor are they exhaustive in their accuracy and approach towards real world results, the trend of each mass presents several conclusions that were beneficial to the intuitive process. The following representations provide further conclusions taken from these studies and how their results may lead to intuitive design optimizations prior to a more detailed CFD analysis.

To quantify the magnitude of the time investment for these rapid studies, the figure above shows the approximate time allocation for each step of the CFD process. It should be noted that while a CFD solver may have a run time of 20 minutes, we can clearly see that the assortment of steps required to produce these results has approached an 8-hour time frame. While this is by no means a trivial process, these results produced data with an extremely high degree of performance utility.

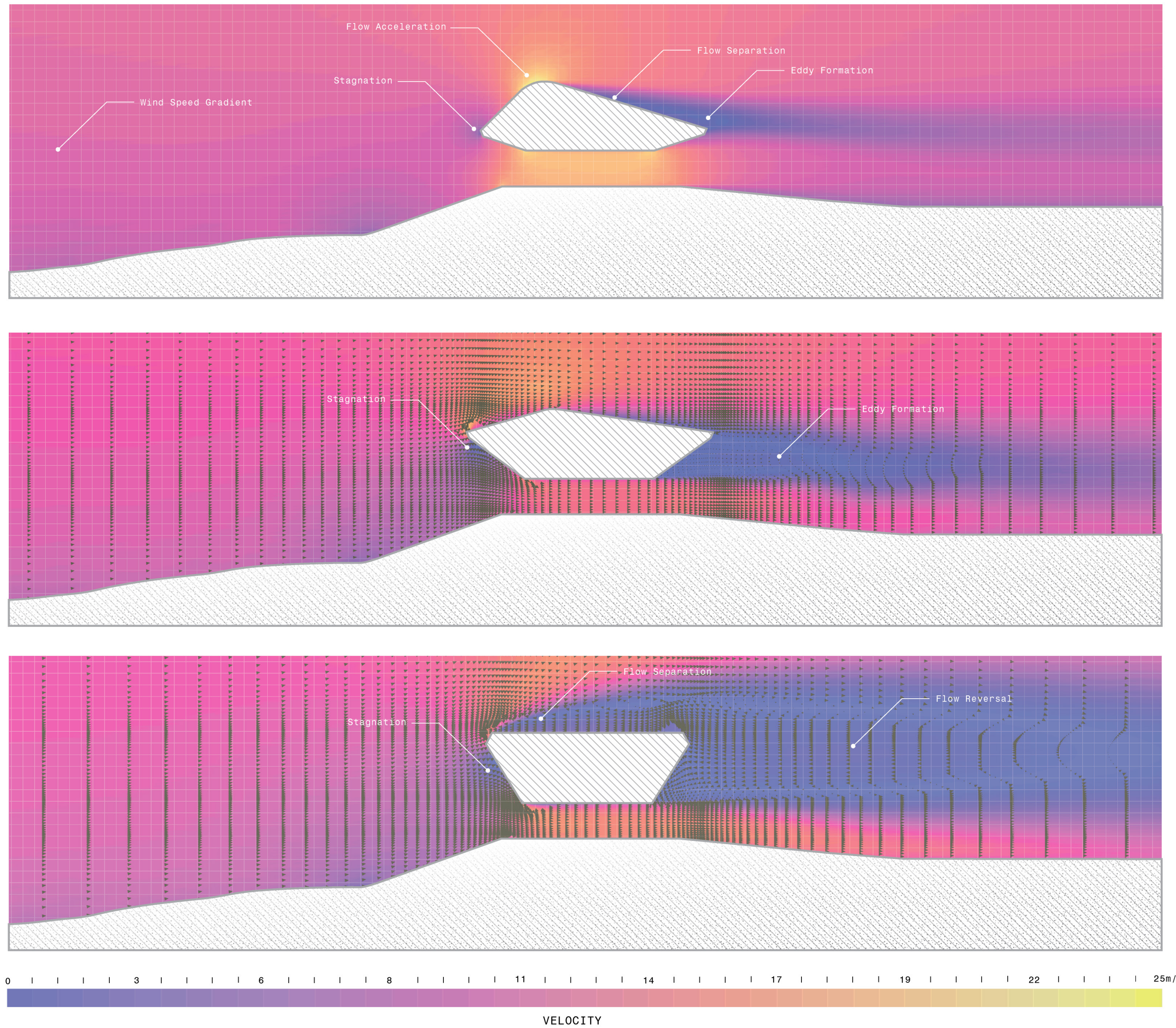


Fig. 21 | Massing Iteration CFD Velocity Results

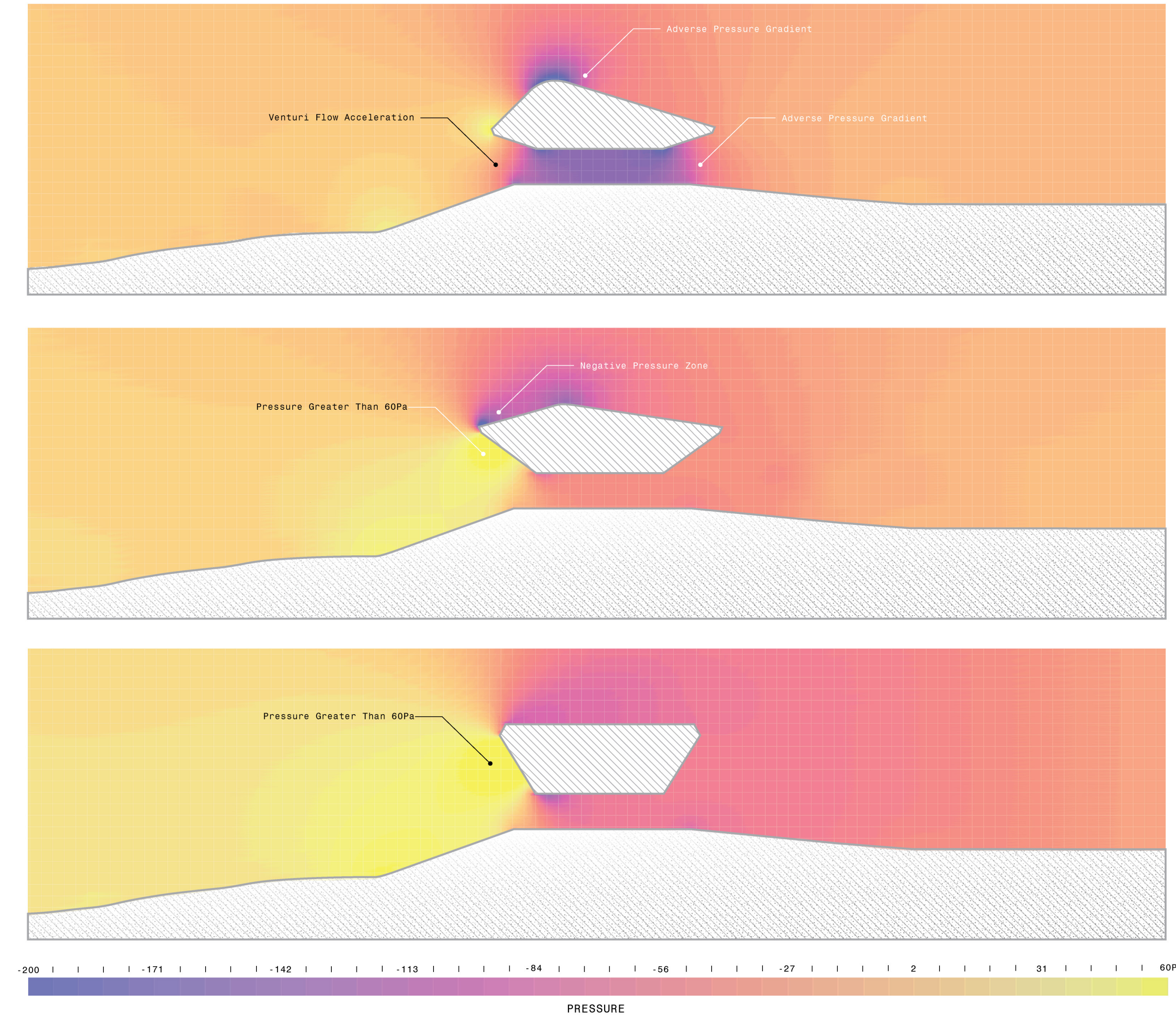


Fig. 22 | Massing Iteration CFD Pressure Results

Each iteration above was simulated with a 10m/s reference wind velocity. Minimum cell sizes ranged from 0.05mto 0.1m. As a result, the meshes consisted of approximately 16,000 cells. The computation time for each iteration lasted approximately 15 minutes. This of course excludes roughly 7 hours dedicated to modeling, meshing, finding convergence, and post processing. What we can see from the velocity profiles is the size and shape of the wake effect behind the massing. We can also identify the magnitude of the flow acceleration caused by the venturi effect in the data center space, which of course is the prime purpose of iterating these sections. Crucially we can also begin to identify areas of stagnation and acceleration on the upper surface of the massing that may indicate appropriate placements of intake and exhaust structures.

Several distinct conclusions arise from the depiction of these pressure contours. In general, areas of high pressure at the face of the building are cause by the impact of air particles on the building's face and the subsequent reduction in flow velocity. The first iteration reduces this effect which is why it experiences the largest acceleration of internal fluid flow. Perhaps the most informative results we can obtain from the pressure contour results, are regions of negative pressures that could be used for exhaust placement. Because the movement of airflow is driven by the process of moving air particles from high pressure regions to low pressure regions, being able to pinpoint areas that increase this pressure gradient will lead to improved flow properties within the building.

Design Development

From the numerous intuitive iterations, control system developments, and broad applications of CFD, we now arrive at the design intended for the final iteration of CFD testing. The approach to the project has been to utilize venturi acceleration to maximize cooling to the first-floor data center while using exhaust products to control occupant comfort above. The design can increase the passive ventilation operable range through the manipulation of control structures and the bilateral symmetry that promotes flow operation in two directions. In addition to maximizing flow velocity for the data center, the interior massing and positioning of critical fluid elements aims to increase the accessibility of passive ventilation to the occupied regions as well.

While this report will not serve as a comprehensive outline of every fluid and architectural trait instilled into the design, the following will outline several key performative design attributes crucial to the function of the project. In elevation we can see a clear distinction between a top and bottom massing. The upper portion is designed to guide fluid flow into the data center space by making use of venturi flow acceleration. The placement of the crest of the roof structure has been designed to reduce the wake effect for the downwind paragliding facility while providing regions of negative pressure to serve as air exhausts. Operable windows and a mechanically movable trailing edge fairing can optimize fluid flow and increase performative resilience in different environmental situations. The lower massing consists of several rotating guide vane structures with the sole intent of redirecting and conditioning air flow movement into the data center space. With the primary air intake being on this first floor, the guide vane structures are intended to autonomously respond to changes in wind flow direction to promote flow consistency within the building. In the wind West and wind East directions, this guide vein structure is intended to rotate to create a second skin for the building. This would trap incoming air within the bands of guide vanes to maintain an airflow pattern consistent with the building's internal workings.

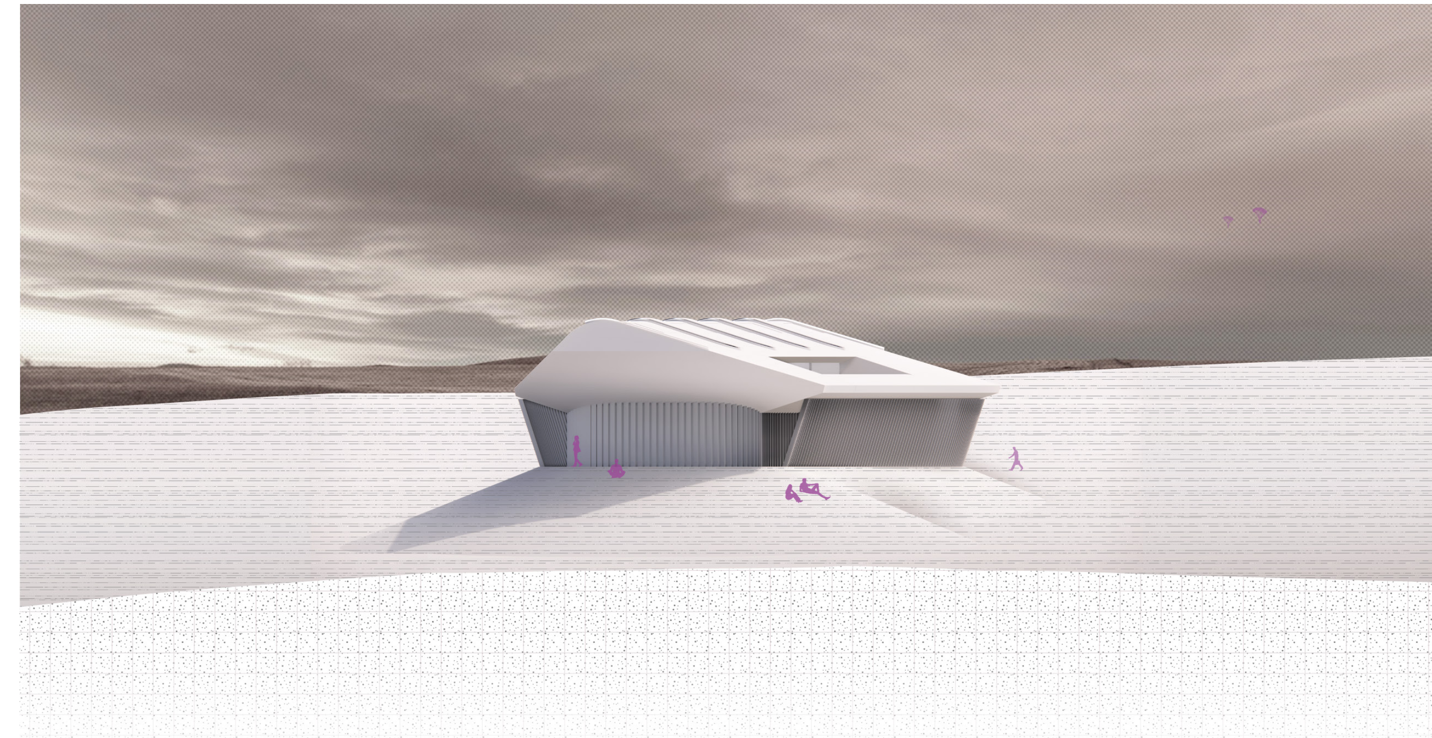


Fig. 23 | Wind West Elevation

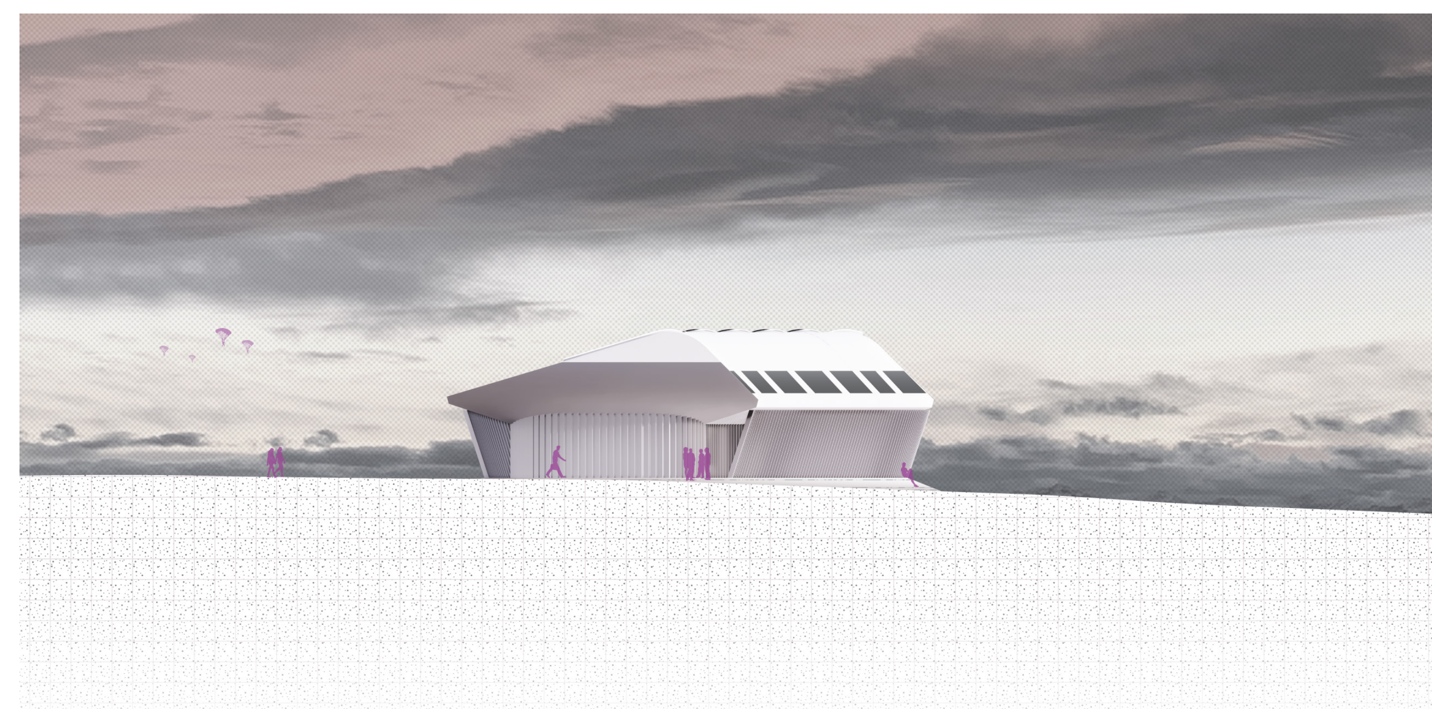


Fig. 24 | Wind East Elevation

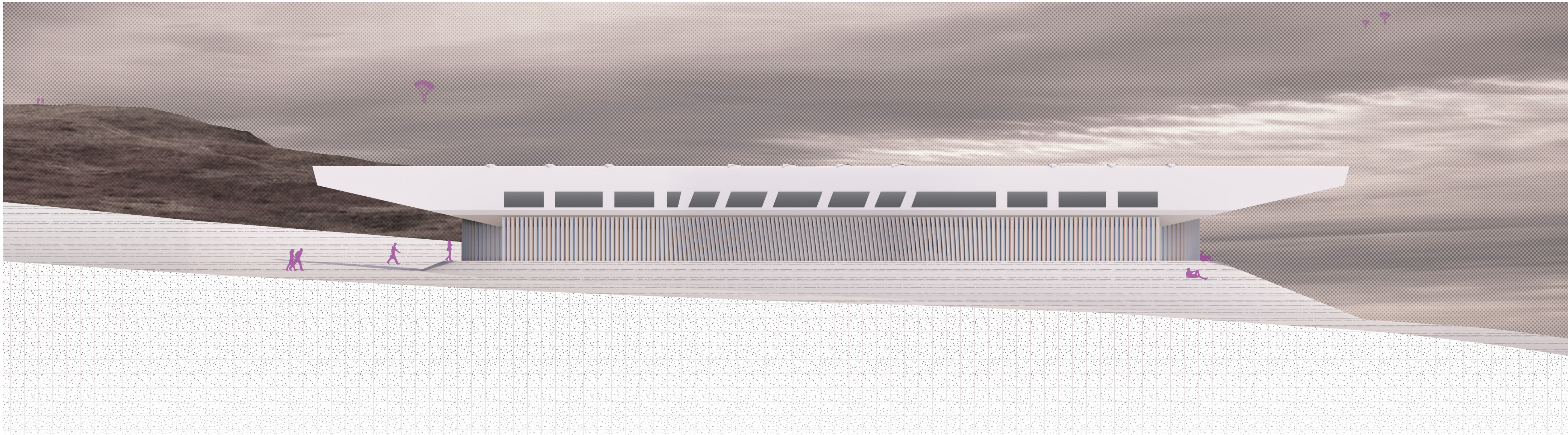


Fig. 25 | Wind North Elevation

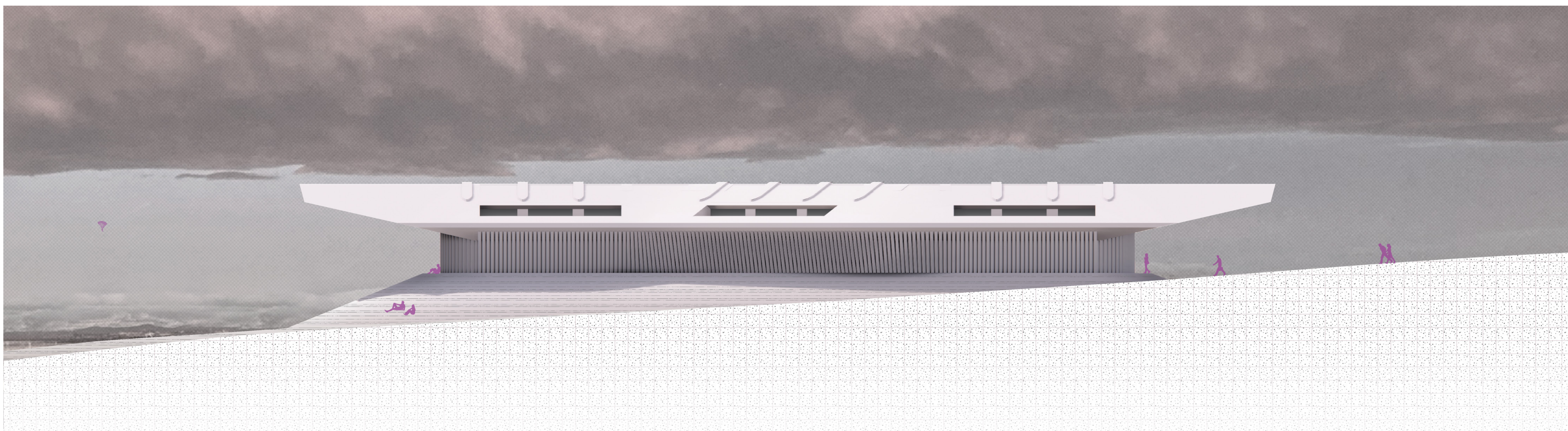


Fig. 26 | Wind South Elevation

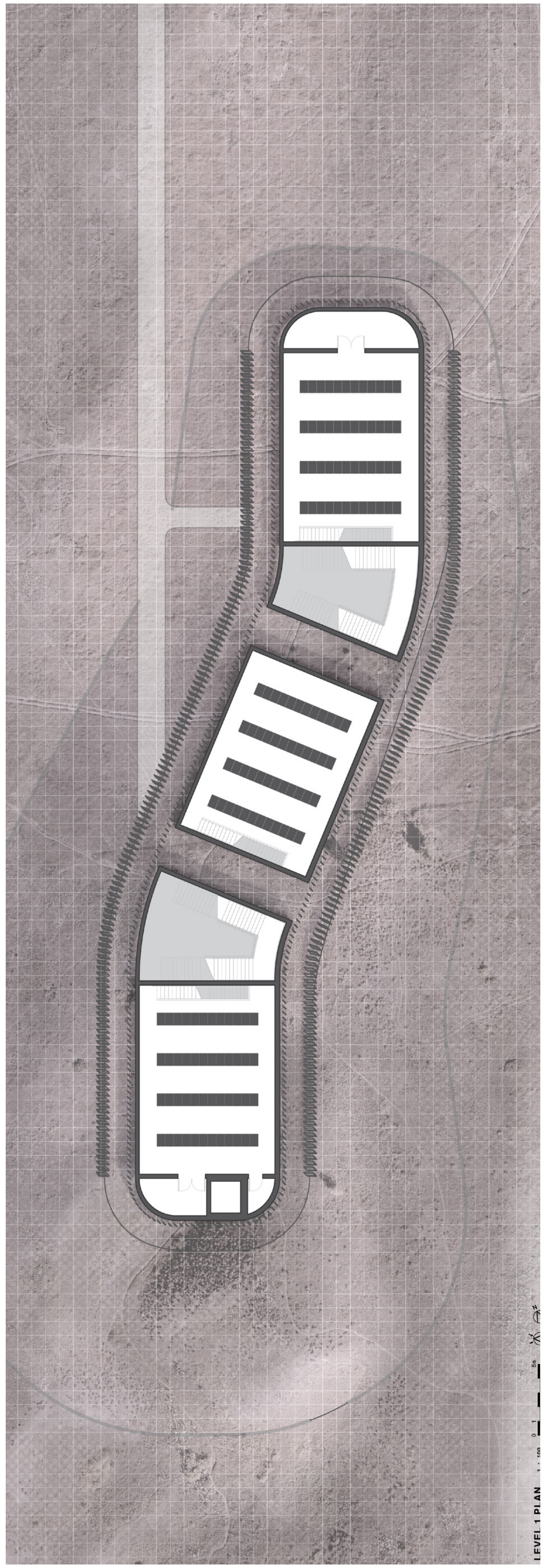


Fig. 27 | Level 1 Plan

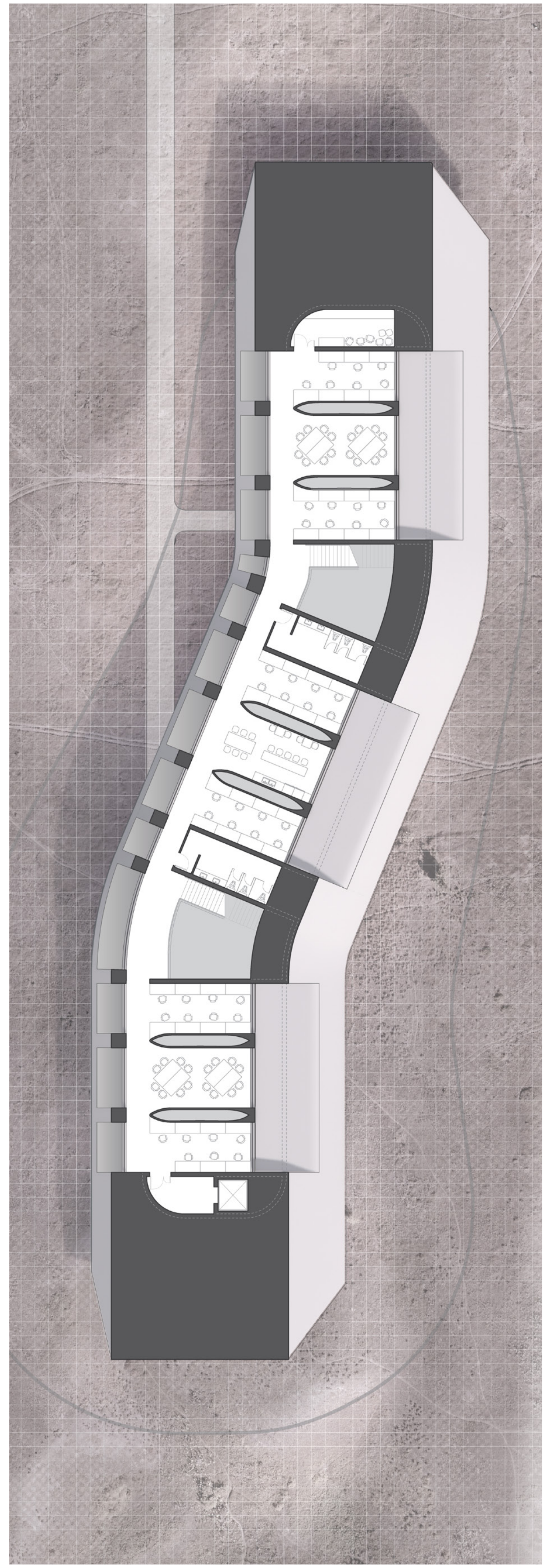


Fig. 28 | Level 2 Plan

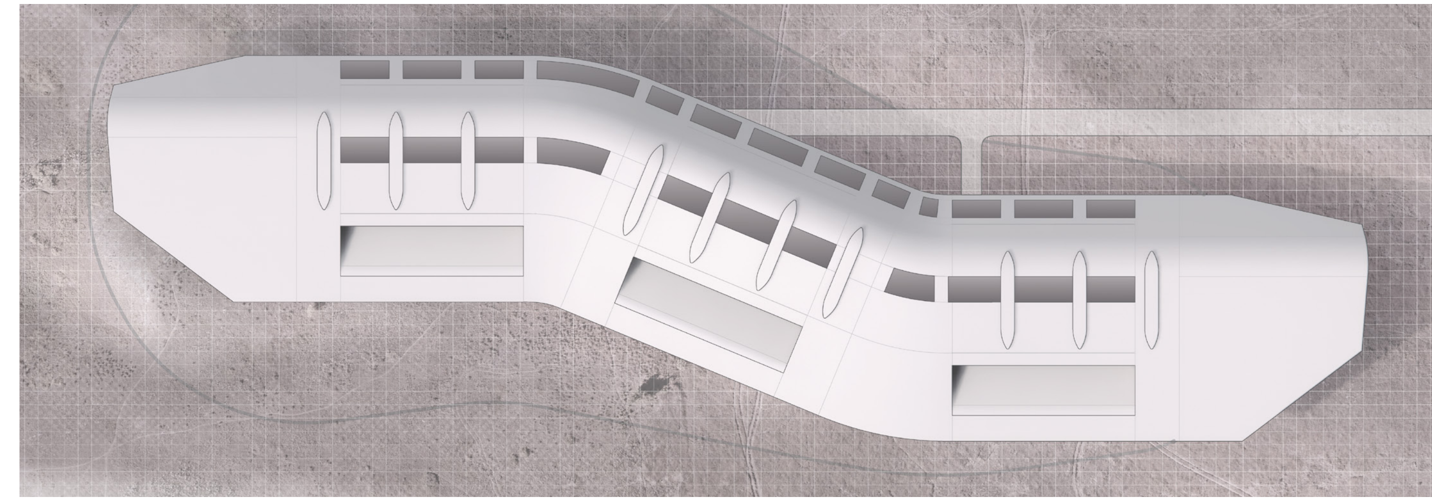


Fig. 29 | Roof Plan

The plan consists of a serpentine pattern with two perpendicular channels that establish a degree of porosity in the massing. This form uses the theory of pressure gradients and the Coanda effect to promote air flow perpendicular to the key section thereby reducing the weak airflow directions by promoting air to travel within the masses. The serpent pattern has been subdivided into three distinct operable modules. These operable modules consist of the data center on the 1st floor and the occupied office facilities on the 2nd. Rooms have been laid out based on the flow relationships that exist between the data center and the office spaces. Hallways and other circulation zones have been located offset from the data center facilities as these will see the lowest frequency of occupant interaction and therefore the least specific flow requirements.

In addition to the allocation of occupied spaces over the data center facility, the plan itself has been set up to make use of internal guide vane structures. On the first-floor, computer rows have been positioned parallel to the direction of airflow. Within the office space, laminar type airflow is promoted through the addition of guide vane separations that favor neither convergent nor divergent wind patterns. Unitizing the office space into smaller sections has the additional effect of restricting the variability of airflow in unconfined spaces. These hollow columns that exist within the occupied regions of the office, not only provide opportunities for structural support, but act as the primary venting system for warm air and buoyancy driven cooling.

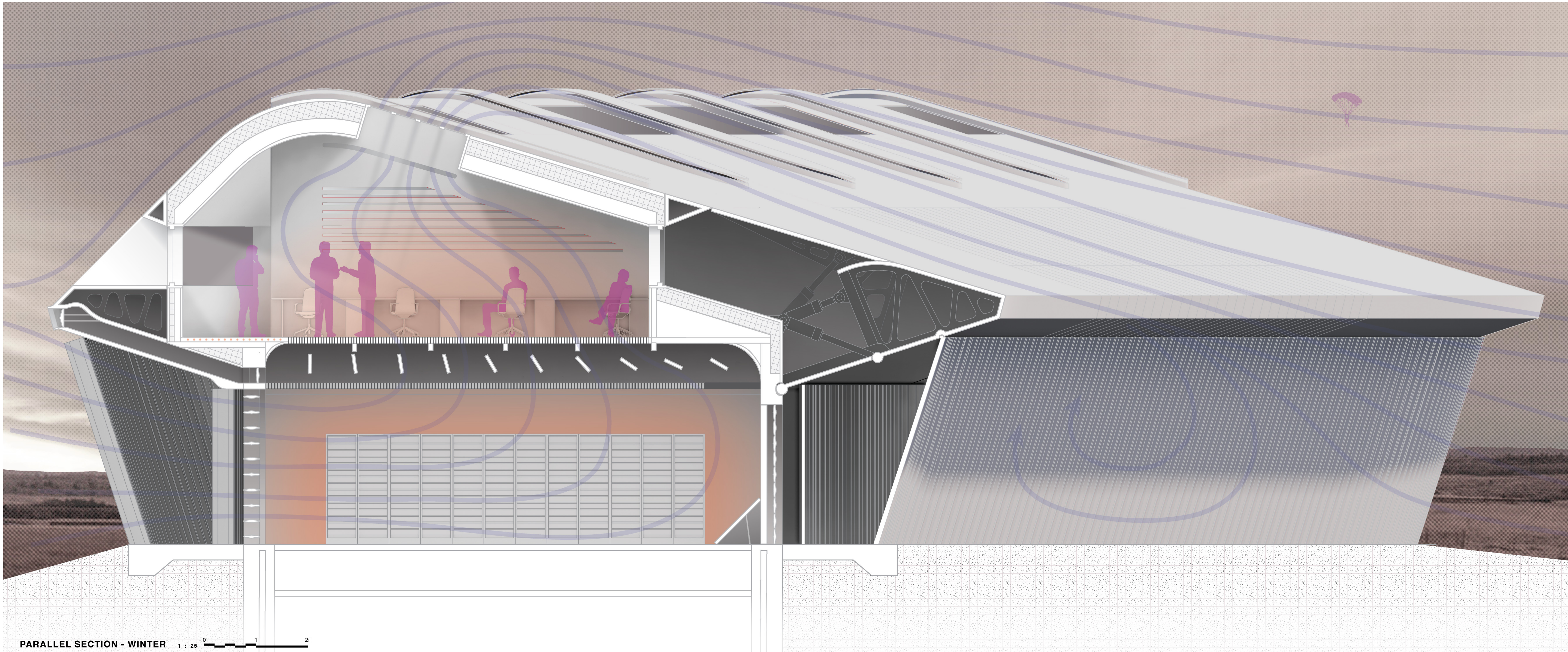


Fig. 30 | Parallel Section Winter Operation

As previously mentioned, it is the winter operation condition that will be analyzed in this thesis. The parallel wind flow direction has governed most of the design moves associated with the bilateral symmetry of the project. This diagram represents the intended heat and flow distribution through intuitively positioned flow lines. Airflow is first accelerated into the data center by the leading-edge fairing assembly and then redirected through the guide vane louvers to condition flow direction. As the air is heated by the data center it rises into a control plenum through a porous ceiling. Controllable guide vanes within this plenum space are positioned to direct air into the occupied zone and provide as even a distribution as possible. Through displacement ventilation the heated air will then rise into the occupied space. As seen in plan, the internal guide vane venting structures of the office space serve as the exhaust locations for the rising hot air. As identified in the pressure contours of early CFD iterations, the positioning of the outlet in this location should optimize the pressure gradient and promote consistent airflow.

Additionally, in this section we can see the hypothetical mechanism used to control the building's trailing edge through hydraulic actuation. We can also see the implementation of an exhaust channel originating from the plenum space and moving towards the leading edge of the facade. This channel has been designed in a manned that allows it to be opened to either provide either air intake or as an additional means of exhaust. While this section is largely designed in accordance with a major wind direction, it has also been laid out to operate in a similar capacity when wind comes from the minor wind direction as well.

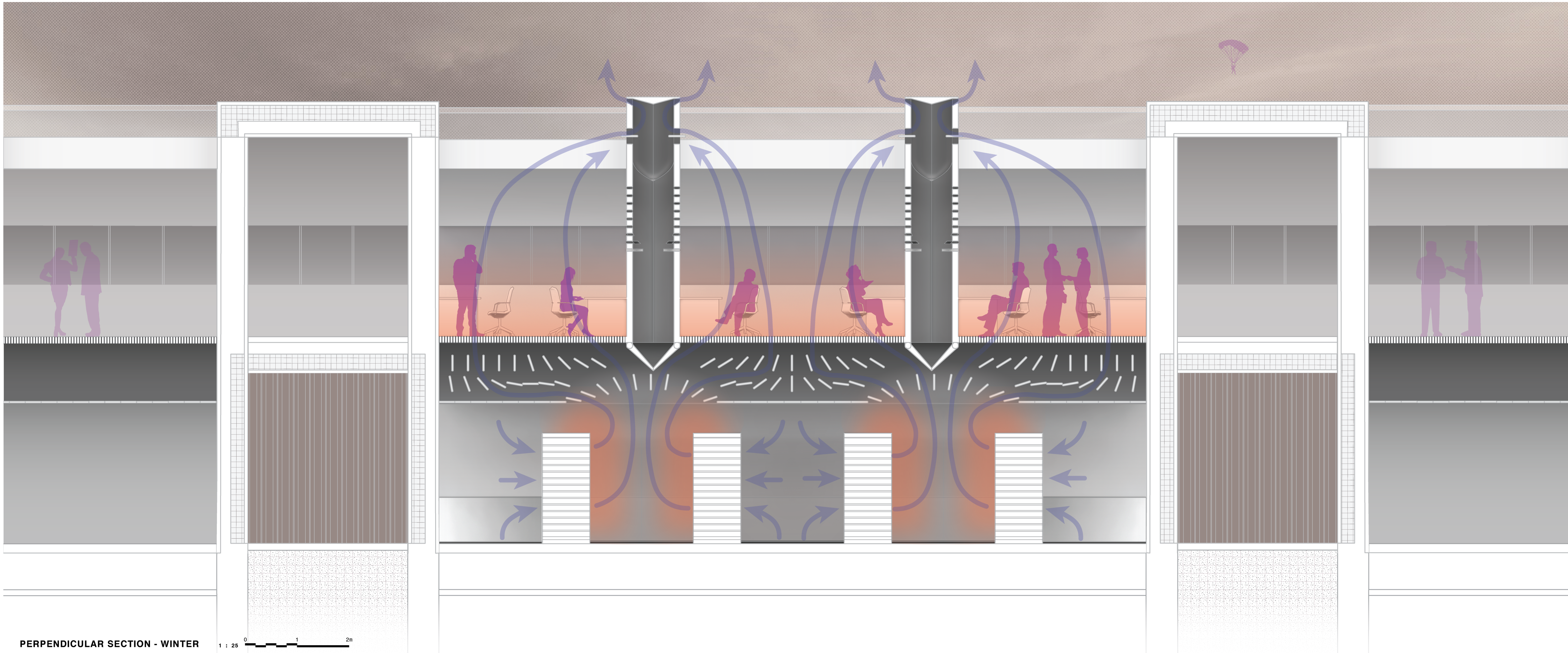


Fig. 31 | Perpendicular Section Winter Operation

While the parallel section governed initial design moves, as the design progressed the perpendicular section provided a substantial amount of flow insight. The placement of the hot air exhaust surfaces of the computer rows aligns with the venting structures of the office space. During winter operation cold air directed into the computer bays is heated and captured in two channels. The rising hot air flows through a permeable ceiling which itself is created from a series of controllable guide vane panels. As was the case in the parallel section, guide vanes in the plenum space help to promote an even distribution of flow reaching the occupied office space. While it is difficult to see in section, the floor of the office space would consist of a porous medium that uses displacement ventilation for direct and soft delivery of air and heat. The guide vane structures in this situation have been closed at the bottom but opened at the top as a means of allowing heat to exhaust from the space. While not represented in this diagram, during summer operation the guide vanes would capture rising hot air and promote stack effect cooling in the office space. As was the case in the parallel section, intuitive flow lines have been placed to represent intended airflow and heat distribution.

Results

CFD Testing

From this design iteration, the final step in process experimentation was to conduct a more detailed CFD simulation and observe if the intuitive design process matched what would be perceived as the as-built conditions. Unlike initial CFD testing, this round of iteration was focused on the internal environment, and as such, was carried out with a higher fidelity meshing structure. While early stage CFD iterations took approximately 8 hours per result, this final CFD simulation command a much more demanding time investment because of the complexity of the simulated environment. The following results used a wind velocity of 10m/s. The minimum cell size was set to 0.05m with the ambient temperature set to 5 degrees Celsius to represent winter operations. With a total cell count of 16335 the processing time for this simulation was approximately 25 minutes and 20 seconds. It should be noted that this CFD simulation was carried out in a two-dimensional environment and contains several assumptions used for simplifying the digital environment. While a three-dimensional analysis would undoubtedly provide a more accurate representation of flow phenomenon present inside the building, two-dimensional modeling was used primarily to reduce the time investment of the CFD study. Due to the size and scaling of the built environment, accurate results of CFD solvers rarely correlate to measured flow characteristics in as-built projects. As a result, the direct accuracy of simulations has less priority then achieving a fundamental understanding of flow patterns and approximate flow characteristic magnitudes.

As previously identified, we have obtained velocity and pressure contours. However, in this iteration we have turned on the energy equation solver and can now create informed decisions based on the thermodynamic behavior of air within the occupied space.

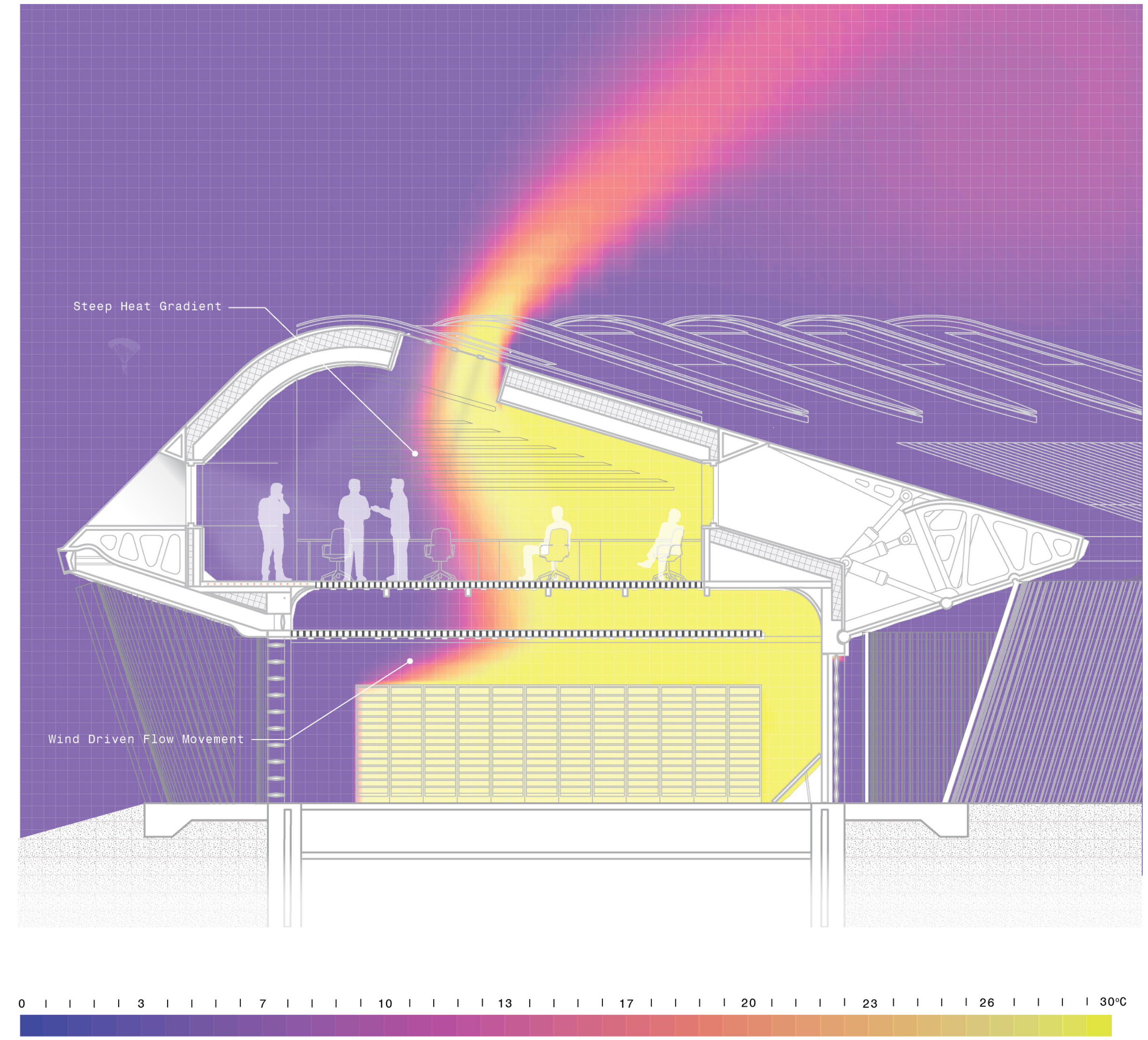


Fig. 32 | Parallel Section CFD Temperature Results

From this temperature contour we can see that due to the high wind velocity, hot air is being directed further into the interior than desired resulting in an undesirable temperature gradient within the office space. This result also provides a visualization of the buoyancy effects cause by the hot air. The noticeable plume of heated air exiting the building alludes to successful venting of the rising air.

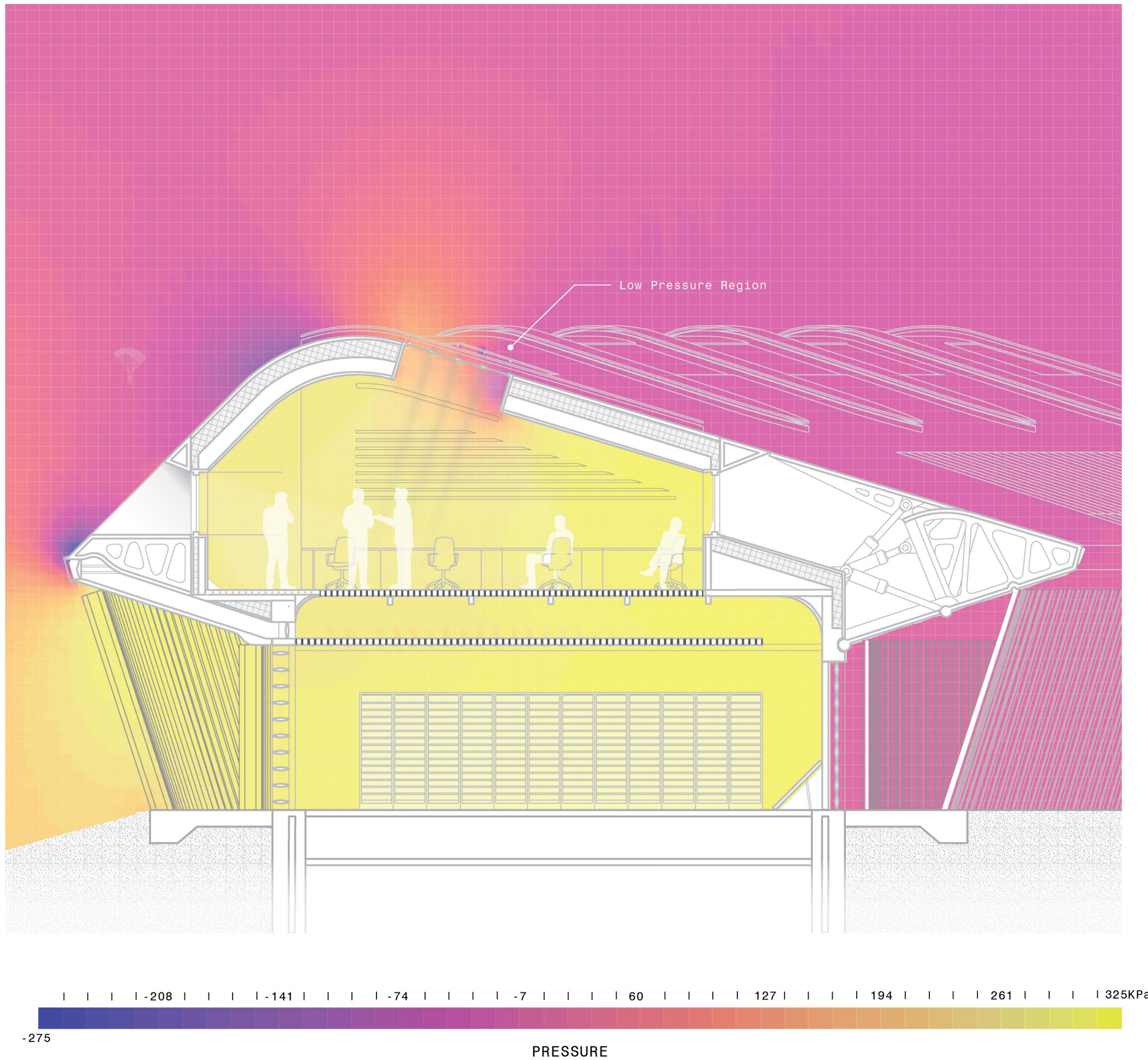


Fig. 33 | Parallel Section CFD Pressure Results

Compared to the earlier CFD iterations, the pressure contour has changed largely due to the addition and consideration of internal venting structures. Inside the building we see an expected increase in the pressure due to the contained environment, with reductions in pressures corresponding to stagnant zones on the building's leading edge. One important location to note is the point on the leading edge where a negative pressure region could be used as an exhaust. This result of potentially driving flow in the opposite direction of the wind due to the negative pressure in this region, is largely counter-intuitive, but observable when this type of CFD simulation is conducted.

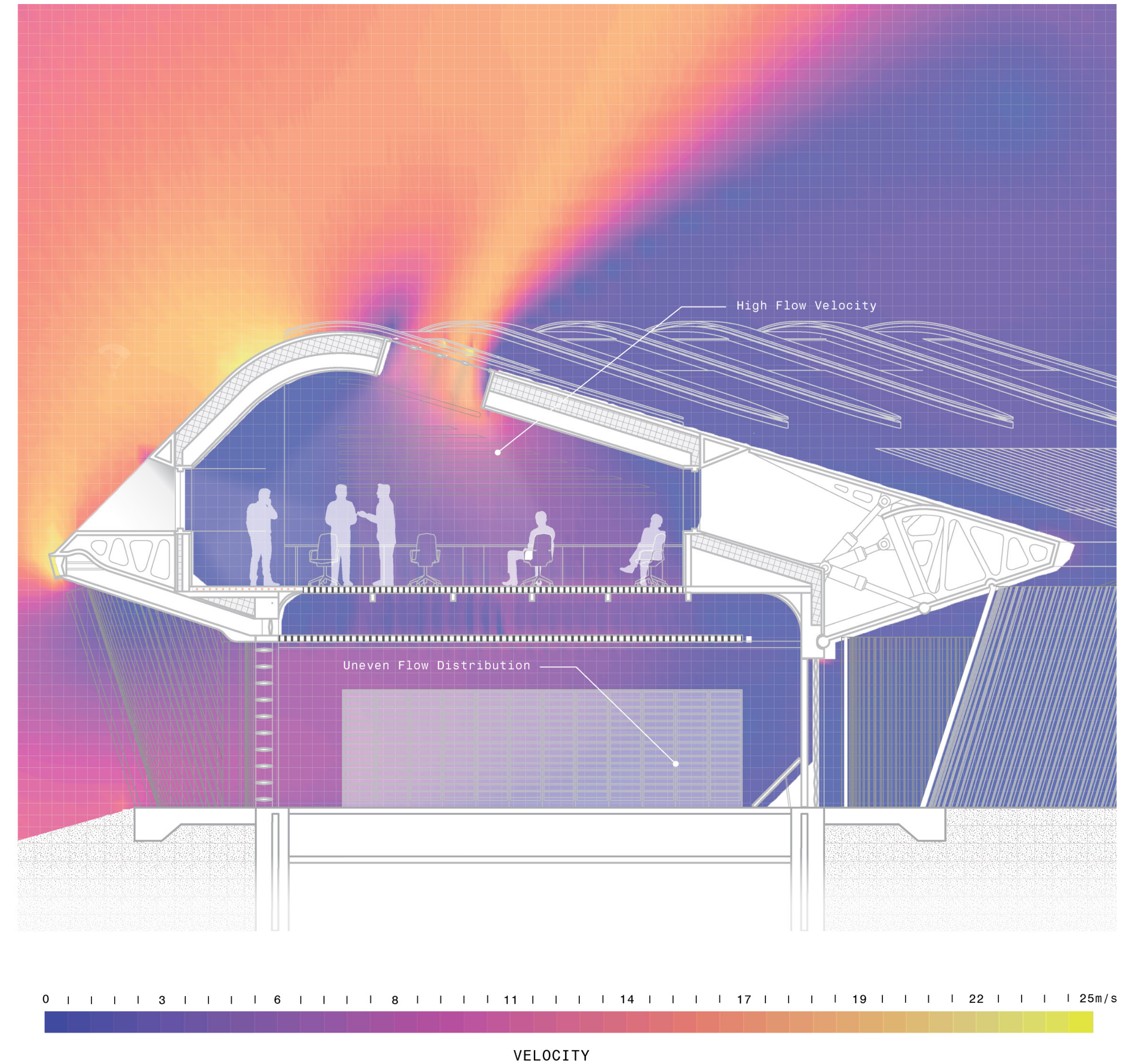


Fig. 34 | Parallel Section CFD Velocity Results

Lastly, the velocity contour indicates issues in the distribution of air flow within the data center itself. Faster air is only reaching approximately 60% of the computer units, with those set further into the structure receiving reduced flow rates. Additionally, the occupied space is encountering airspeeds higher than those outlined within occupant comfort standards.

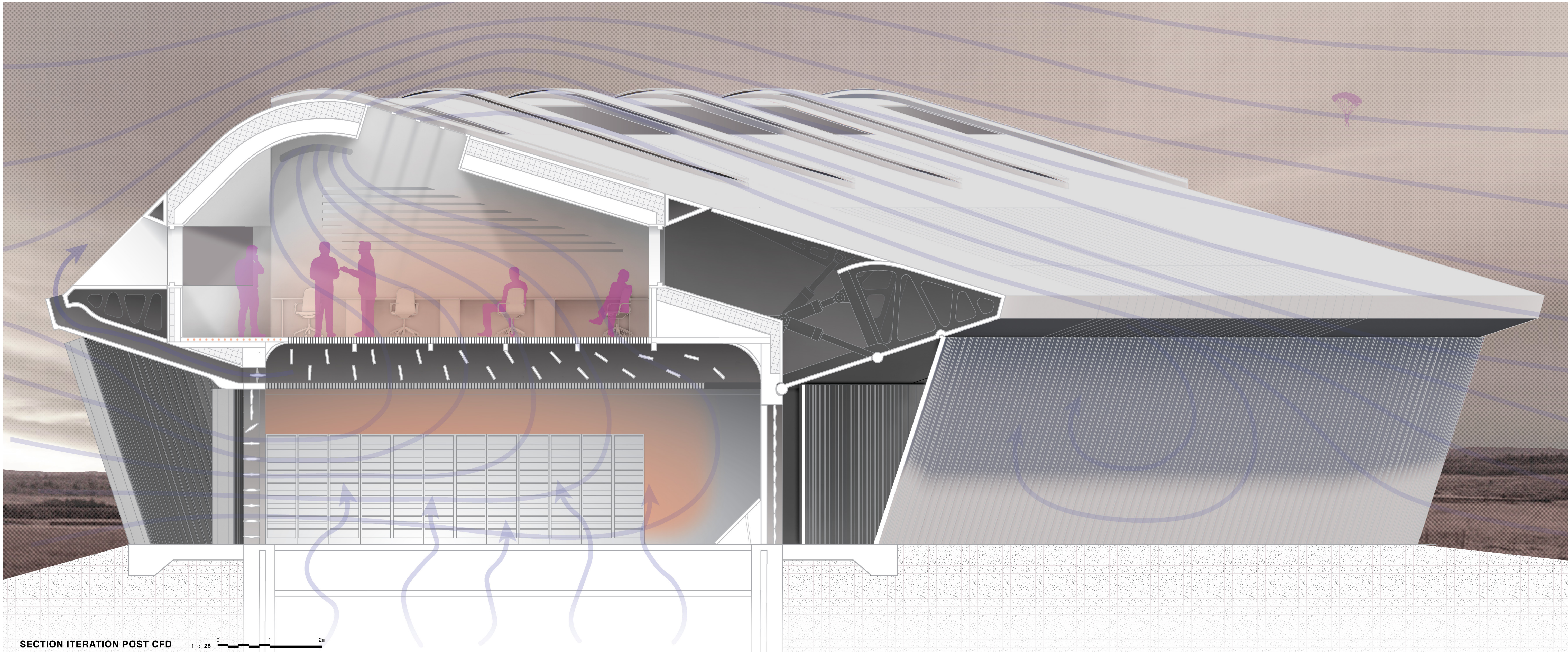


Fig. 35 | Parallel Section Iteration Post CFD

From the resulting CFD data, the above figure represents an intuitive iteration of design changes aimed to combat challenges highlighted in the CFD simulations. In practice this process of intuitive design informed by rapid CFD testing to produce a single design iteration which is then further analyzed through higher fidelity CFD analysis could be repeated as much as desired. The above figure is a depiction of the crucial parallel flow section with modifications informed from the CFD results. Due to the rapid CFD testing and intuitive capabilities of the initial design process, the recommended changes to the design required far less of a time investment then if a traditional design process disconnected with fluid mechanics had been employed. The various control systems put in place can be changed easily, with only a few structures requiring minor relocation and sizing.

Because the CFD data showed an undesirable positioning of hot air within the occupied space, the design changes have largely been implemented to redirect heated air for a more even distribution within the office. While flow velocities in the CFD results were higher than desired, porous ceiling and floor structures can be restricted to reduce this aspect of the airflow. Because the occupied space is slightly offset from the data center, hot air is reaching the office desks further back than desired. To combat this, design changes include shifting the data center forward and increasing the number of guide vanes to direct airflow as desired. Additionally, the upwind exhaust channel on the front of the building has been slightly reconfigured to make use of the pressure result. Exhaust air can be pulled through the plenum in an opposite direction to the wind direction. This would aid in redirecting error towards the front of the building. Lastly and most crucially, repositioning the exhaust location of the internal structure will substantially promote the movement of air flow to the front of the building.

Conclusion

The intuitive design continuum seen in Figure 36, was created as the result of the design process undertaken in this thesis. Iterative capacities to simultaneously work between plans, sections, massing, and control systems of the fluid vernacular, provide an environment that promotes rapid design testing. Within each of these design realms, a separate CFD process shows the potential to extend designs beyond intuitive understandings. While CFD can be applied to each of these realms of design thinking, the work done in the development of the data center has provided critical insight into the efficiencies of this process. Massing studies are often one of the earliest design challenges engaged by most projects. In the fluid vernacular, it is apparent that this stage of design shows significant potential for the application of rapid CFD testing. Establishing known performance qualities early in the design process was shown to reduce the level of required design interventions later on. Iterative CFD processes implemented at this stage of design, provided the highest utility to time investment ratio. This means that CFD results conducted at this stage will typically yield more productive outcomes while maintaining relatively low time investments. Plans and sections offer a similar level of utility but due to the elevated complexity of the modeling environment, these studies require far greater time investments. While these iterative pursuits are still incredibly relevant and applicable to designing with fluids, intuitive iteration should be undertaken as much as possible so that the number of required CFD simulations can be reduced. As the project developed it became increasingly more important to possess a careful awareness of the time investment for the simulation process. Lastly, due to the scale of the built environment, the control systems used in achieving the fluid flow, while incredibly important to design flexibility, show the lowest potential for utilizing CFD data.

As a conclusion of the hypothetical intuitive design continuum, I have differentiated the applicable scopes of CFD in Figure 37. CFD applied at the scale of external massing, offers the highest amount of performance and design benefit. Because we can simulate simplified forms, we reduce simulation time while maximizing the benefits of an iterative practice. As with traditional design processes, it is the ability to make effective decisions early in the design process that have the largest amount of value. Due to the uncertainties and scale of the built environment, as we narrow our window of design scope, CFD simulation provides increasingly less meaningful results. At the level of the interior, we still find substantial benefits from the application of CFD processes. However, at this scale, CFD testing should be done as a verification process as opposed to an iterative tool given the time requirement and modelling complexity of these studies.

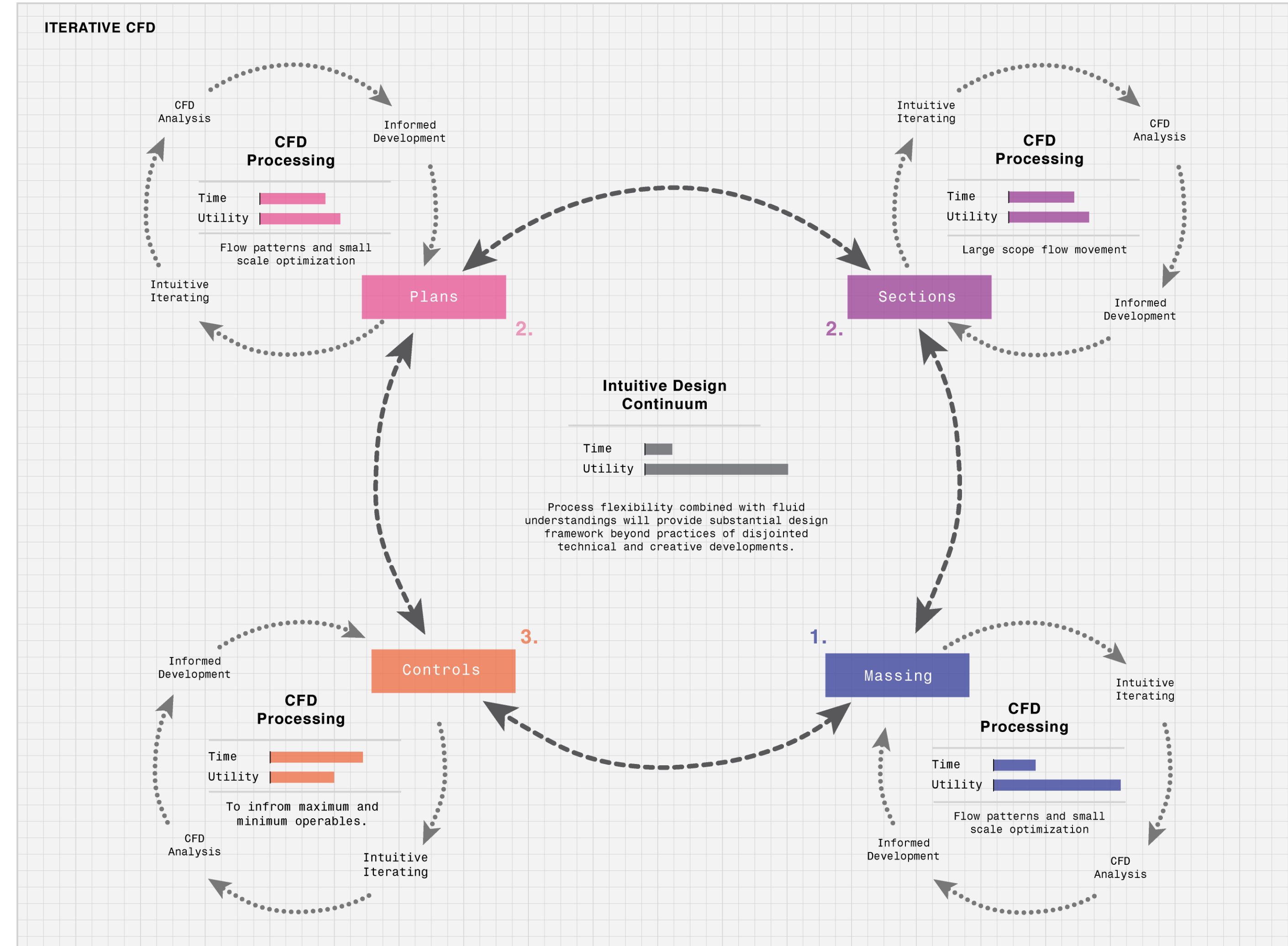


Fig. 36 | Integrated Intuitive Design Continuum

Due to the technical nature of the scope of design, excessive testing will perpetuate the challenges of incorporating CFD into architectural projects. Finally, while there would be benefits to modeling environments concerned with surface treatments and fine control structures, the reduction of the flow scales suggests that CFD results would often inadequately match the turbulent nature of human scale flow patterns. The amount of time to derive such specific simulation results is disconnected from the design benefit this would yield. Fundamentally, CFD in architectural design must account for the scale of the flow regime we are designing for. Large flows that exist within habitable regions are turbulent by nature and exist within a constantly changing and chaotic environment. No amount of CFD simulation will therefore be able to accurately account for real-world conditions. As this project demonstrates, it is the largest of design moves that have the greatest impact on fluid design. From this conclusion, a designer working in the fluid vernacular should be conscious of early design moves and how they impact fluid flow. There exists a balance between the investment of analysis and the benefits it yields. An educated designer must be capable of making these decisions to effectively implement CFD simulation into design.

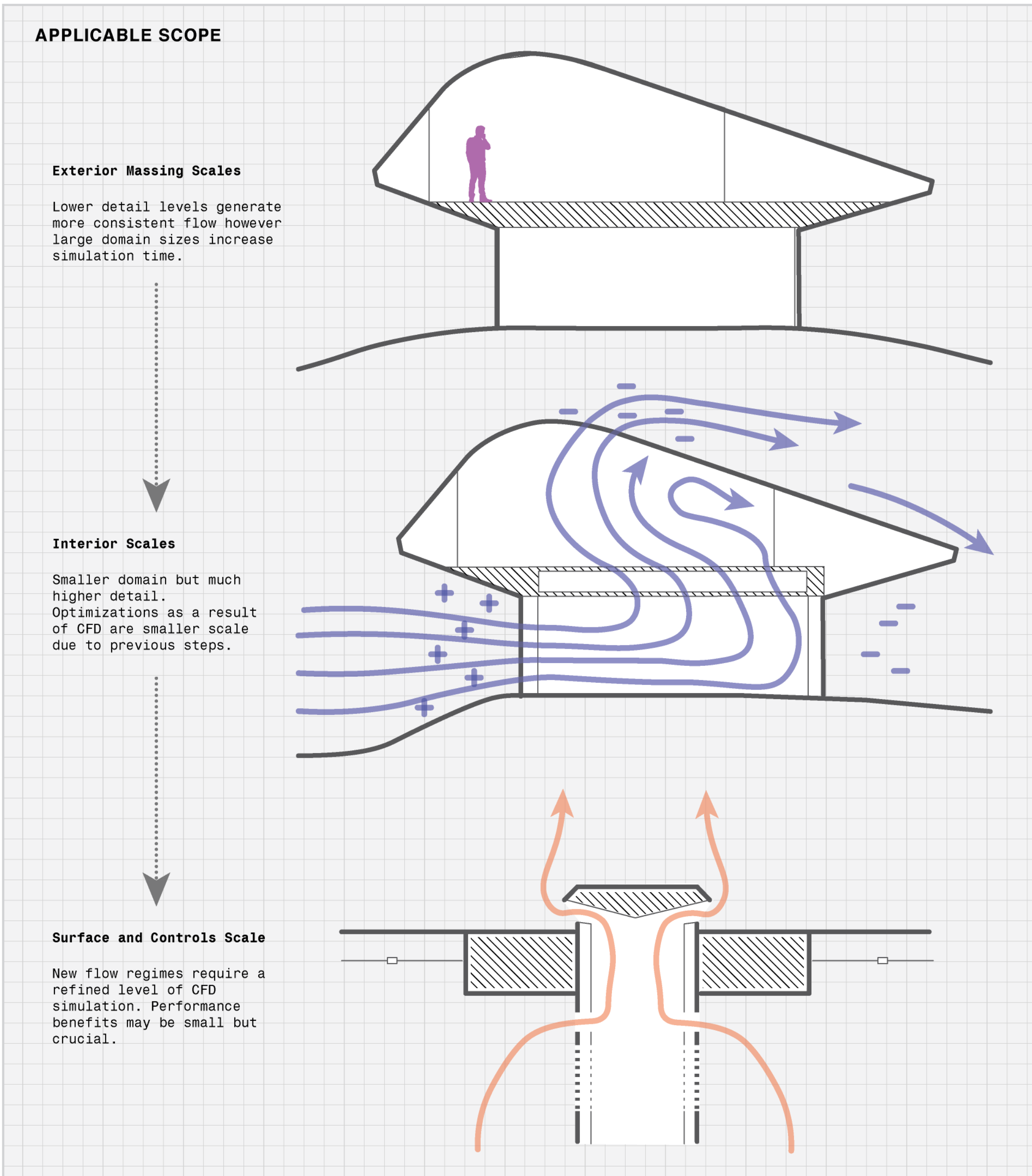


Fig. 37 | Applicable Scopes of CFD

As I reflect on the intuitive process, it is apparent that several design moves were carried out with the knowledge that CFD testing would be conducted later in the process. This undoubtably had an impact on the outcome of the final design. Many of the implemented control systems were designed to establish an ability to respond to multiple flow conditions. These systems were also the tools by which challenges highlighted through CFD testing could be easily resolved or optimized. Designing with lightweight fairing structures and guide vanes meant that any design interventions recommended by simulations could be easily adjusted with minimal impact to the occupied regions themselves. Not unlike parametric design, the ability to quickly manipulate just a few elements greatly increased the flexibility of a design in its ability to respond to CFD results. This method of design represents one way in which an intuitive design approach can be used to compliment an integrated process of simulation.

As previously alluded, this project highlights the concept of balancing simulation utility with time investments. There exists a relationship between the performative outcomes of CFD design and the resources required to obtain such a result. While a great emphasis has been placed on the designer to have an intuitive understand of flow mechanics, the effective designer should also be able to design with the knowledge of how to effectively position CFD in the design process. The intuitive process was successful in converging design performance to a point where CFD verification resulted in only minor changes to architectural design.

Another outcome of the research is the commentary it provides on how we currently structure design teaching. Responding to the lack of technical training in most architectural programs could see further efficiency improvements in the simulation process. As identified in this thesis, the ability to iterate and intuitively predict flow outcomes greatly reduced the reliance on CFD testing. While simulations provided further clarification to the design, it is not outside the realm of possibility that if architectural pedagogy was restructured to educate designers in the fluid vernacular, the separation between creative and technical disciplines could be reduced. Perhaps as more buildings are built in the fluid vernacular, the empirical data collected from these projects could also aid in reducing the reliance on CFD. Aerospace design relies heavily on the known development and testing of a wide range of airfoil shapes. Because such a large body of work exists in cataloguing the performance of airfoils, aircraft designers can readily converge new designs using past data without having to do ground-up simulation work. Perhaps a similar intervention could exist in the development of the fluid vernacular. The public sharing of performance from the development of different systems could inform the intuitive process to the extent that the utility provided from CFD fades away.

In summary, while this thesis is in no way a comprehensive analysis of the applications of CFD in design, the experimentation process used in the development of the data center project provides insight into useful applications of CFD in the architectural process. As the author of this thesis, I hope the work conducted here has inspired the reader to seek further integration of technical practices in creative pursuits. With a heightened understanding of technical tools, I hope the accessibility of technical design can be vastly increased. I believe a societal shift in designing with increased technical abilities will allow us to experience the mysterious that stands at the cradle of true art and science.

Bibliography

Aburamadan, Rania, and Claudia Trillo. “Applying Design Science Approach to Architectural Design Development.” Frontiers of Architectural Research 9, no. 1 (March 1, 2020): 216–35. https://doi.org/10.1016/j.foar.2019.07.008.

Ahmed, Noor A. Coanda Effect: Flow Phenomenon and Applications. Boca Raton: CRC Press, 2019. https://doi.org/10.1201/9780429441240.

Bere Semeredi, Iudit, Mihai Eugen Valceanu, Diana Mihaela Nica, Ella Anca Sipetan, and Romulus Corlan. “Indoor Air Quality Monitoring and Human Perception Survey on Air Quality in Public Buildings in Timisoara.” Edited by N.F. Cofaru and M. In. MATEC Web of Conferences 343 (2021): 10021. https://doi.org/10.1051/matecconf/202134310021.

Blake, Peter. “Conversation At 23 Beekman Place.” Paul Rudolph Heritage Foundation, 1996. https://www.paulrudolphheritagefoundation.org/interview-peter-blake.

Bufi, Nil, and Daniel Utges. “How to Measure the Indoor Air Quality of Your Buildings - DEXMA,” April 21, 2021. https://www.dexma.com/blog-en/how-to-measure-the-indoor-air-quality-of-your-buildings/.

Caetano, Inês, Luís Santos, and António Leitão. “Computational Design in Architecture: Defining Parametric, Generative, and Algorithmic Design.” Frontiers of Architectural Research 9, no. 2 (June 1, 2020): 287–300. https://doi.org/10.1016/j.foar.2019.12.008.

City of Cochrane. “Demographics | Cochrane, AB,” 2020. https://www.cochrane.ca/386/Demographics.

Clay Mathematics Institute. “Millennium Problems,” 2022. https://www.claymath.org/millennium-problems.

Dehghani Mohamadabadi, Hossein, Ali Akbar Dehghan, Abdul Hamid Ghanbaran, Alireza Movahedi, and Abolfazl Dehghani Mohamadabadi. “Numerical and Experimental Performance Analysis of a Four-Sided Wind Tower Adjoining Parlor and Courtyard at Different Wind Incident Angles.” Energy and Buildings 172 (August 1, 2018): 525–36. https://doi.org/10.1016/j.enbuild.2018.05.006.

Fairhursts Design Group. “The GSK Carbon Neutral Laboratories for Sustainable Chemistry,” 2018. https://www.architecture.com/awards-and-competitions-landing-page/awards/riba-regional-awards/riba-east-midlands-award-winners/2018/the-gsk-carbon-neutral-laboratories-for-sustainable-chemistry.

Gids, W de, and M Jicha. “Hybrid Ventilation,” 2010. https://www.aivc.org/sites/default/files/members_area/medias/pdf/VIP/VIP%2032%20Hybrid%20Vent.pdf.

Hooff, T. van, B. Blocken, and Y. Tominaga. “On the Accuracy of CFD Simulations of Cross-Ventilation Flows for a Generic Isolated Building: Comparison of RANS, LES and Experiments.” Building and Environment 114 (March 3, 2017): 148–65. https://doi.org/10.1016/j.buildenv.2016.12.019.

Howe, Marc. “The Promise of Generative Design -.” World-Architects, April 5, 2017. https://www.world-architects.com/en/architecture-news/insight/the-promise-of-generative-design.

Jenkins, Meg. “Building Aerodynamics 101 – Complete Guide.” SimScale, May 23, 2019. https://www.simscale.com/blog/2019/05/building-aerodynamics/.

Jomehzadeh, Fatemeh, Payam Nejat, John Kaiser Calautit, Mohd Badruddin Mohd Yusof, Sheikh Ahmad Zaki, Ben Richard Hughes, and Muhammad Noor Afiq Witri Muhammad Yazid. “A Review on Windcatcher for Passive Cooling and Natural Ventilation in Buildings, Part 1: Indoor Air Quality and Thermal Comfort Assessment.” Renewable and Sustainable Energy Reviews 70 (April 1, 2017): 736–56. https://doi.org/10.1016/j.rser.2016.11.254.

Kormaníková, Lenka, Henri Achten, Miloš Kopiva, and Stanislav Kme. "Parametric Wind Design." Frontiers of Architectural Research 7, no. 3 (September 1, 2018): 383–94. https://doi.org/10.1016/j.foar.2018.06.005.

Li, Biao, Zhiwen Luo, Mats Sandberg, and Jing Liu. "Revisiting the 'Venturi Effect' in Passage Ventilation between Two Non-Parallel Buildings." Building and Environment 94 (December 1, 2015): 714–22. https://doi.org/10.1016/j.buildenv.2015.10.023.

Melton, Paula. "Natural Ventilation: The Nine Biggest Obstacles and How Project Teams Are Beating Them." BuildingGreen, August 3, 2014. https://www.buildinggreen.com/feature/natural-ventilation-nine-biggest-obstacles-and-how-project-teams-are-beating-them.

Monceaux, Nina. "What Is Comfortable Air?" IKEUCHI (blog), 2020. https://www.ikeuchi.eu/news/what-is-comfortable-air/.

Nimlyat, Pontip, and Elizabeth Dassah. "Computer Simulations In Buildings: Implications For Building Energy Performance." IOSR Journal of Engineering 4 (March 1, 2014): 56–62. https://doi.org/10.9790/3021-04345662.

Papazoglou, Eleni, Konstantinos P. Moustris, Konstantinos-Stefanos P. Nikas, Panagiotis T. Nastos, and John C. Statharas. "Assessment of Human Thermal Comfort Perception in a Non-Air-Conditioned School Building in Athens, Greece." Energy Procedia, Technologies and Materials for Renewable Energy, Environment and Sustainability (TMREES), 157 (January 1, 2019): 1343–52. https://doi.org/10.1016/j.egypro.2018.11.299.

Rehm, Bill, and Jerome Schubert. "Reynolds' Number," 2008. https://www.sciencedirect.com/topics/engineering/reynolds-number.

Rezaei, Mahmud. Reviewing Design Process Theories: Discourses in Architecture, Urban Design and Planning Theories. SpringerBriefs in Architectural Design and Technology. Cham: Springer International Publishing, 2021. https://doi.org/10.1007/978-3-030-61916-9.

Robinson, Julia W. "Architectural Research: Incorporating Myth and Science." Journal of Architectural Education (1984-) 44, no. 1 (1990): 20–32. https://doi.org/10.2307/1424972.

Sampson, Ben. "The Future Role of Wind Tunnels in Test and Development." Aerospace Testing International (blog), March 15, 2018. https://www.aerospacetestinginternational.com/features/the-future-role-of-wind-tunnels-in-test-and-development.html.

Schlesinger, William H., and Emily S. Bernhardt. "The Atmosphere." Biogeochemistry, 2020, 51–97. https://doi.org/10.1016/B978-0-12-814608-8.00003-7.

Schulze, Tobias, and Ursula Eicker. "Controlled Natural Ventilation for Energy Efficient Buildings." Energy and Buildings 56 (2013): 221–32. https://doi.org/10.1016/j.enbuild.2012.07.044.

Short, C. Alan. "Introduction." In The Recovery of Natural Environments in Architecture. Routledge, 2017.

Stavridou, Anastasia D. "Breathing Architecture: Conceptual Architectural Design Based on the Investigation into the Natural Ventilation of Buildings." Frontiers of Architectural Research 4, no. 2 (June 1, 2015): 127–45. https://doi.org/10.1016/j.foar.2015.03.001.

Walker, Andy. "Natural Ventilation." WBDG, August 2, 2016. https://www.wbdg.org/resources/natural-ventilation.

Welch, Adrian. "GlaxoSmithKline Carbon Neutral Laboratory." e-architect, August 14, 2017. https://www.e-architect.com/birmingham/glaxosmithkline-carbon-neutral-laboratories-for-sustainable-chemistry.

Yi, Yong-Kyu, and Yun Yi. "Utilization of Scientific Method as a Tool of Architectural Design." Architectural Research 12 (December 30, 2010). https://doi.org/10.5659/AIKAR.2010.12.2.1.

Zhao, Weixin, Sami Lestinen, Simo Kilpeläinen, and Risto Kosonen. "An Experimental Study of the Influence of a Moving Person on Airflow Characteristics and Ther mal Conditions with Diffuse Ceiling Ventilation." Indoor and Built Environment 29, no. 6 (July 1, 2020): 860–80. https://doi.org/10.1177/1420326X20917202.