# Motion with Moisture

## Creating Passive Dynamic Envelope Systems Using the Hygroscopic Properties of Wood Veneer

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including my required final revisions, as accepted by my examiners.

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# ABSTRACT

This thesis presents research into the creation of an autonomously responsive envelope system capable of adaptation to variation in relative humidity through the use of wood veneer and its hygroscopic material properties. As an alternative strategy to the extensive, energy-intensive, technological systems characteristic of contemporary responsive envelopes, dynamic systems using hygroscopic materials are both low-cost and low-tech while also producing adaptation without consumable energy input or external control. Produced is a meteorosensitive, semi-permeable, passive facade that aims to enhance both the physical and physiological comfort of interior spaces through moderating airflow and light infiltration. The facade is an assemblage of expanding, hygroscopic tubes, formally based on the principles of fluid dynamics outlined by Bernoulli's principle and functionally implemented by the Venturi tube, to orchestrate airflow from exterior to interior. The performance of the hygroscopic facade is tested using computational fluid dynamics software and is compared against the performance of a standard Venturi tube assembled in the same manner. The results of this testing show that despite a cross sectional difference from the standard Venturi tube, the hygroscopic mechanism is capable of increasing airflow into interior spaces through the purposeful creation of a low pressure zone within the mechanism. Optimizing the performance of the mechanism is done through a biomimetic transfer of both formal and functional intelligence from the biological precedents of the Ipomoea flower and the conifer cone as found by Ross Koning, Wouter van Doorn et al., and Kahye Song et al. As well as, material studies performed by Steffen Reichert, and Artem Holstov et al. are traced to understand the performance and characteristics of the wood veneer as a bilayer composite that allows the mechanism to undergo repeated transformations and achieve variability of expansion from one end of the mechanism to the other. The direct integration of biological precedents within architecture asserts that building materials can be seen as productive entities, passively attuned to the natural rhythms and variability of the external environment, while maintaining flexibility for functional implementation as self-sufficient, adaptive facades.

# ACKNOWLEDGMENTS

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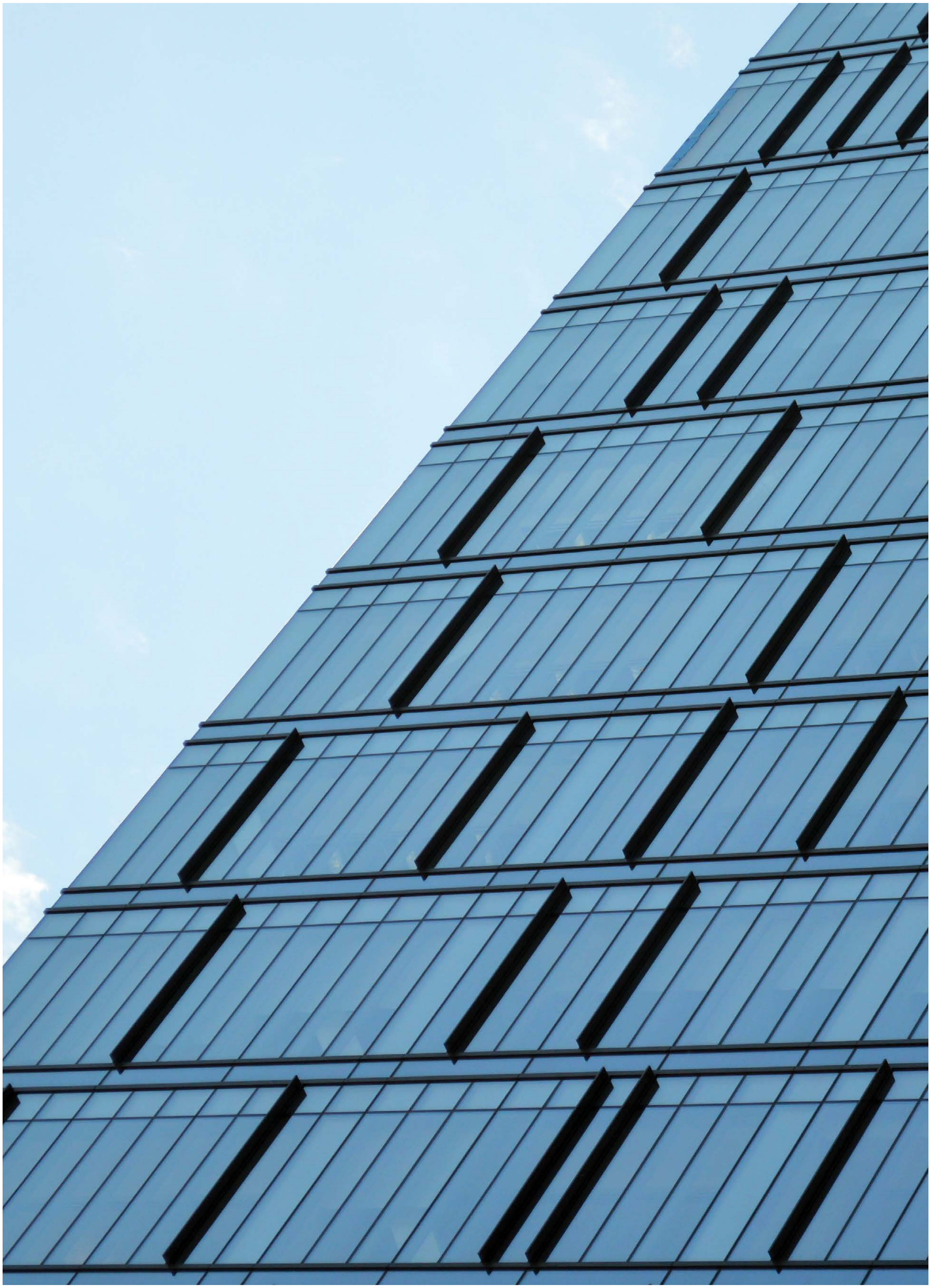


# INTRODUCTION

Human-driven alterations to environmental systems threaten the ability of these systems to produce and maintain conditions viable for life. Pervasive human activity at the onset of the industrial revolution has forced the world out of its natural geological epoch known as the Holocene and forced it into the Anthropocene, a new epoch where human activity has become a global geophysical force. Within this epoch, the earth is rapidly moving through and into a less biodiverse, less forested, much warmer and much wetter existence[1]. The most prominent factor causing environmental alteration is the global multi-decadal warming of the atmosphere due to the accumulation of greenhouse gas (GHG) emissions for which both economic and population growth are the largest contributors due to fossil fuel consumption[2]. Presently, an estimated 50 to 60% of the world's total GHG emissions is produced by cities, where more than half of the world's population resides and consumes approximately 75% of the world's primary energy[3]. With the current population set to increase by 2.5 billion people by 2050, and more than two-thirds of this population predicted to live in cities, the concentrated production of GHG emissions will only increase[4]. It is predicted that the global temperature resulting from the production of GHG emissions will increase by 1 to 4°C[5]. Where an increase of 1°C will only happen if strict action is taken to reduce carbon emissions significantly, and an increase of 4°C will take place if social behavior and environmental practices remain the same. Dense urban centers of future populations will experience even greater increases in temperature resulting from additional ambient heat accumulated through heat storage in urban fabrics[6].

Of the GHG emissions produced by cities, buildings alone produce an estimated 33-49%. The production of GHG emissions by buildings is a direct result of interactions between the building envelope and the external environment that surrounds it. Within urban centers, this emission production is expected to increase peak ambient temperatures by up to 10°C, reducing the general health of urban populations through reductions in livability and comfort. The environmental consequences of increasing temperatures over most land areas is a reduction in the demand for heating within a building and increasing the demand for cooling to maintain comfort and livability. The largest production of GHG emissions within a single building is a result of building operations focused on maintaining consistent comfortable internal environments[7].

[1] Steffen, Will, Paul J. Crutzen, and John R. McNeill. "The Anthropocene: are humans now overwhelming the great forces of nature." AMBIO: A Journal of the Human Environment 36, no. 8 (2007): 614-621.

[2] Pachauri, Rajendra K., Myles R. Allen, Vicente R. Barros, John Broome, Wolfgang Cramer, Renate Christ, John A. Church et al. "Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change." IPCC, 2014.

[3] "Energy." UN-Habitat. 2012. https://unhabitat.org/urban-themes/energy/.

[4] "World's population increasingly urban with more than half living in urban areas | UN DESA Department of Economic and Social Affairs." United Nations. July 10, 2014. http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html.

[5] Pachauri, Rajendra K., Myles R. Allen, Vicente R. Barros, John Broome, Wolfgang Cramer, Renate Christ, John A. Church et al. "Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change." IPCC, 2014.

[6] Fiorito, Francesco, and Mattheos Santamouris. "High Performance Technologies and the future of architectural design." TECHNE-Journal of Technology for Architecture and Environment 13 (2017): 72-76.

[7] La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.

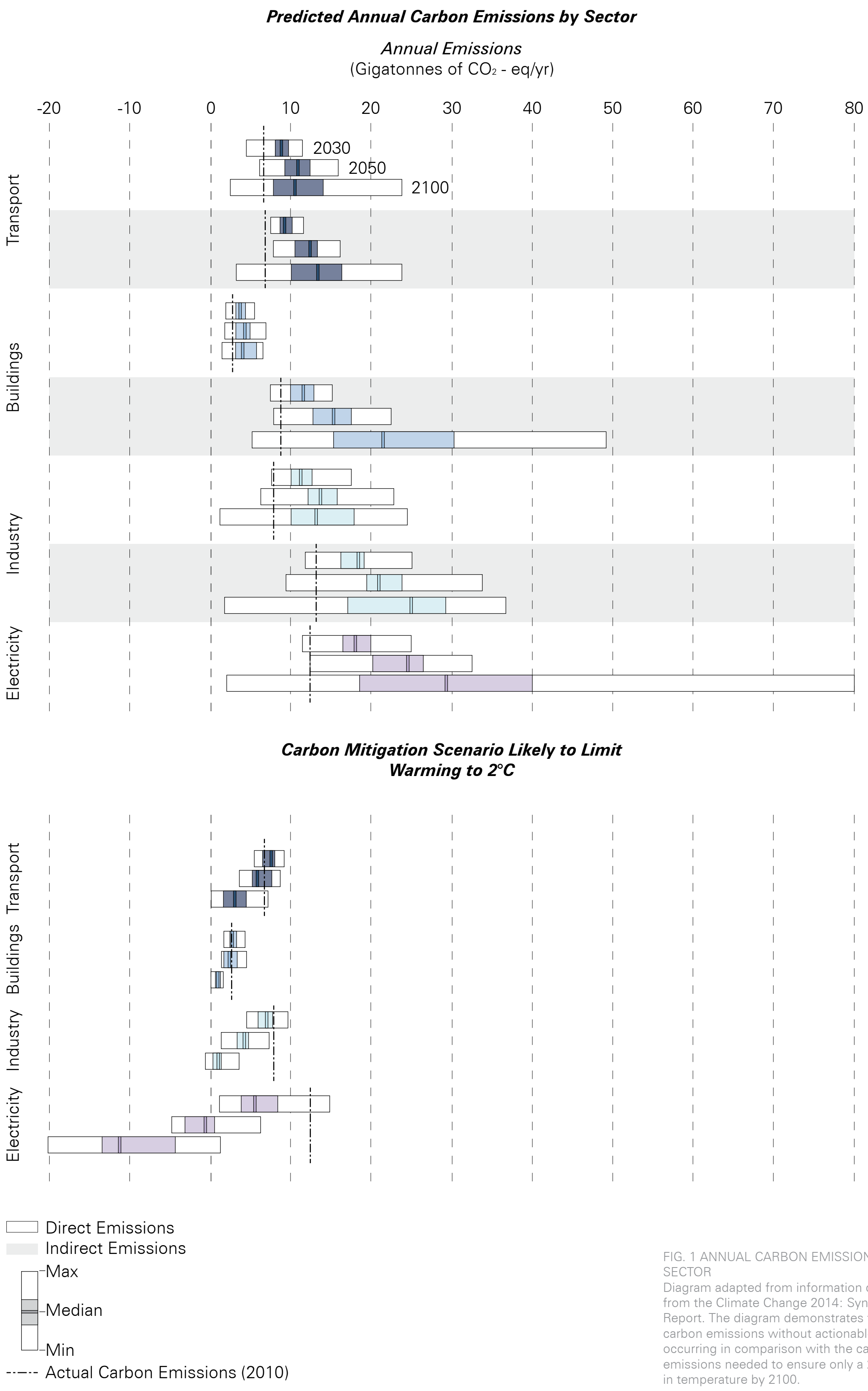


FIG. 1 ANNUAL CARBON EMISSIONS BY SECTOR
Diagram adapted from information collected from the Climate Change 2014: Synthesis Report. The diagram demonstrates the future carbon emissions without actionable change occurring in comparison with the carbon emissions needed to ensure only a 2°C increase in temperature by 2100.

*"The most efficient method to lessen energy use for mechanical cooling is to eliminate the need for it through climate-adaptive design." - Alison Kwok*[8]

Homeostasis is a term coined by the physician Walter Cannon in 1930 within his book, "The Wisdom of the Body", to describe the processes used by living organisms to actively maintain consistent conditions conducive to survival. Derived from the Greek words 'same' and 'steady', the stability achieved with homeostasis is maintained only if the organism is capable of modifying itself according to external stimuli[9,10]. In achieving local comfort of interior spaces, homeostatic principles can be applied to the built facade, thus enabling it through an adaptive capacity to passively mediate between exterior and interior domains. The implementation of biological strategies can be executed through the use of materials exhibiting inherent motion in response to changes in environmental conditions. Hygroscopic materials, which are those that experience physiological change as a result of variation in the relative humidity, offer a strategy for achieving adaptive envelope design that is also triggered through a variable of the thermal environment[11]. As such, this thesis explores how passive performance of dynamic envelope systems can be produced through amplifying and implementing the hygroscopic material property of wood veneer.

To analyze this topic, the first section of this thesis will briefly outline the historical development of the facade, arguing the separation of the envelope from the internal function was made possible through technological advancement that removed the burden of performance from the envelope and allowed interior environments to be artificially produced through energy-intensive mechanical systems[12]. Following this will be an analysis of the three environments for which the facade must navigate to maintain comfort as well as a study to understand the relationship between the human body, the body's recognition of comfort, and the role of both the facade and the skin in maintaining this condition. This will establish how the building envelope is not only capable of interaction with both interior and exterior environments, but through the manipulation of these elements into adaptive strategies, can also control the comfort of the occupant.

Within the following section is an argument for the relevancy of biomimetics in design. Through the evaluation of motion principles found in nature, specifically the movement principles deployed by plants, such as taxi movement, tropic movement, and nastic movement[13], multiple biological precedents are discussed to reveal the mechanisms responsible for motion. This section will also demonstrate how form is inherently tied to function in order to achieve passive adaptive qualities for maintaining a homeostatic condition. Within this section, proof-of-concept architectural precedents including those developed by Achim Menges, Oliver David Krieg and Steffen Reichert, are discussed to illustrate the potential translation of biological mechanisms into functional hygroscopic facades.

The third section studies principles and methods of passive ventilation used for the control of thermal comfort, based on the law of conservation of energy. The first method is Bernoulli's principle, which states that an increase in the speed of a fluid is simultaneously coupled with a decrease in pressure. The second principle discussed is the Venturi effect, which applies Bernoulli's principle to a tube with a constricted segment thereby decreasing pressure and increasing flow[14]. This chapter aims to outline that the purposeful creation of positive

[8] Kwok, Alison G., and Walter T. Grondzik. "The green studio handbook: environmental strategies for schematic design." Enquiry: A Journal for Architectural Research 4, no. 2 (2007).

[9] Fiorito, Francesco, and Mattheos Santamouris. "High Performance Technologies and the future of architectural design." TECHNE-Journal of Technology for Architecture and Environment 13 (2017): 72-76.

[10] Cannon, Walter Bradford. "The wisdom of the body." 1939.

[11] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[12] Straube, John . "BSD-042: Historical Development of the Building Enclosure." Building Science Corporation. November 15, (2010)

[13] Sonnewald, Uwe. "Physiology of Movement." In Strasburger's Plant Sciences, pp. 531-568. Springer Berlin Heidelberg, 2013.

[14] "Stack Ventilation and Bernoulli's Principle." Stack Ventilation and Bernoulli's Principle | Sustainability Workshop. 2017. https://sustainabilityworkshop.autodesk.com/buildings/stack-ventilation-and-bernoullis-principle.

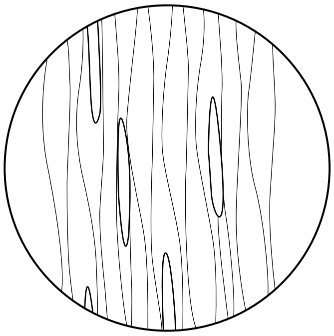
and negative pressure zones across the threshold of the facade will passively increase airflow. Additionally, this airflow, due to the use of wood veneer as a smart material, will be capable of increasing or decreasing in response to relative humidity variation. The shape of the final prototype is comparatively tested against the standard Venturi tube to demonstrate airflow using computational fluid dynamics software run on the Rhinoceros 3D modeling platform.

The following series of sections will begin with the study of wood and research into its motion properties resulting from its preparation process. The main objective is to understand how wood is capable of passive motion and how this can be amplified for use as a responsive material. Through the implementation of the methods of functionality demonstrated in the biological precedents, an artificial bilayer configuration, necessary for repeatable deformation, is constructed. Methods and procedures of material selection, preparation, assemblage, and actuation are all studied for achieving the greatest dimensional transformation. Following this is the documentation of the design and experimentation process. Through coupling the functional principles studied within the biological precedents with those described by Bernoulli's principle and the Venturi tube, a mechanism capable of passively manipulating air and light is developed. Through further refinement of the prototype, it is assembled into a facade that is responsive to changes in relative humidity.

The final section of this thesis will focus on the application of the passive facade into the specific site of 480/488 University Avenue in downtown Toronto. The site, which was previously host to an 18-story commercial office tower, is currently being re-clad. The original concrete grille facade has been removed and the building re-skinned in a combination of both glass curtain wall and window wall systems with an additional 37 stories of residential floors above the existing tower. This thesis uses the re-skinning of 480/488 University Ave. as a site for speculating the ways in which environmentally responsive facades can mediate between the warming microclimates of the city and the need for comfort within interior environments. The specific positioning of the responsive facade is interacting with an office occupancy, which offers high activity levels during the day when thermal pressure from the environment is at its peak.

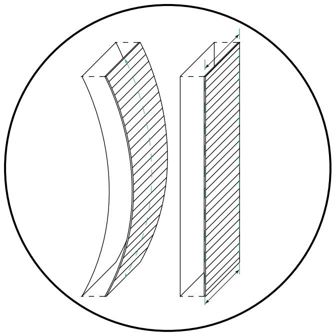
The responsive design strategy investigated within this thesis is studied at numerous scales, from the molecular configuration of wood to the scale of the structure where the mechanism is speculatively placed. The aim of this thesis is to study and understand ways in which materials with inherent behavioral properties can be implemented more strategically within the building envelope so adaptation to change in environmental conditions can occur. The scope of the thesis studies the creation of varying thermal zones, the biomimetic transfer of functional capacity, and the principles of air motion first, to understand the ways in which formal assembly of the mechanism can impact the performance of the facade assembly. The additional study of the hygrmorphic materials of wood, engages these elements to produce a climatically responsive, semi-permeable, passive facade that is both low-tech and capable of achieving change without external input. The purpose is to achieve comfort of internal spaces through an adaptive cooling strategy capable of altering the allowance of air across the facade in alignment with changes in relative humidity. Architectural systems deploying materials with embedded responsive behavior allows the built form to be passively attuned to natural rhythms and variables of its greater environmental context.

Microscale



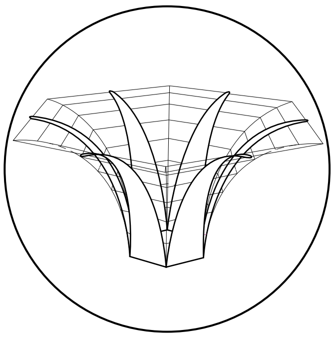
Function of the material: Hygroscopic expansion of wood cells due to uptake of moisture from humidity in atmosphere

Mesoscale



Application of Function: Coupling the material with a restrictive passive layer forming a bilayer composite

Macroscale



Generation of Performance: global expansion of the bilayer is coupled with additional materials to create a mechanism responsive to environmental changes

FIG. 2 FUNCTIONAL PERFORMANCE
Diagram demonstrates the translation of material performance into adaptive performance of the mechanism through amplification of natural material properties.

# THE ENVELOPE

## *Historical Context of Thermal Internal Spaces*

To control internal occupant comfort through the implementation of passive cooling strategies within the envelope, it is important to understand the role of the envelope throughout its development and its relationship to both the environment and the body of the occupant. This will establish how the envelope is capable of moderating comfort through meteorosensitive adaptation.

Within the building, the envelope serves two primary functions; to enclose and make sense of an internal volume, and to achieve comfort for occupants within the delineated space[1]. The development of the contemporary facade, in both form and function, was the result of an evolutionary process originating from the dualistic forms of human existence; the settled and the nomadic. Through the relationship between lifestyle and climate, two principles of envelope development came into fruition; the solid wall and the temporary structure. The solid wall provided for comfort within cold climates and settled populations where the vernacular is characterized by the use of readily available local materials and an understanding of climate and site[2,3]. The success of such structures is attributed to their relation to larger contextual environmental processes through orientation, exposure, ground conditions, adjacencies, and climate in order to implement material properties more strategically[4]. The development of more sophisticated designs resulted from the identification of more suitable materials, increased craftsmanship skills, and building techniques[5]. These evolving systems additionally began including openings in the facade, which moved from the single purpose of smoke exhalation to light infiltration with the use of lintels for structural integrity. The solid walls seen in the Romanesque era were quickly replaced by the refined structural elements of Gothic architecture, seen as a precursor to the contemporary skeletons of today. At the structural limits of lintels emerged arches, allowing for larger openings and increased day lighting. Infilling the openings with glass allowed for both lighting and views to the exterior while maintaining a thermally independent interior. Alternatively, the temporary structures, due to nomadic lifestyles, were made of lightweight supporting skeletons and additionally lightweight outer coverings. The conceptual basis of the solid wall and the temporary structure combined to form the contemporary facade[6]. Isolation of the facade from its

[1] Lovel, Jenny. “Building envelopes: an integrated approach.” Princeton Architectural Press, 2013.

[2] Straube, John . “BSD-042: Historical Development of the Building Enclosure.” Building Science Corporation. November 15, 2010

[3] Knaack, Ulrich, Tillmann Klein, Marcel Bilow, and Thomas Auer. Façades: principles of construction. Birkhäuser, 2014.

[4] Lovel, Jenny. “Building envelopes: an integrated approach.” Princeton Architectural Press, 2013.

[5] Straube, John . “BSD-042: Historical Development of the Building Enclosure.” Building Science Corporation. November 15, 2010

[6] Knaack, Ulrich, Tillmann Klein, Marcel Bilow, and Thomas Auer. Façades: principles of construction. Birkhäuser, 2014.

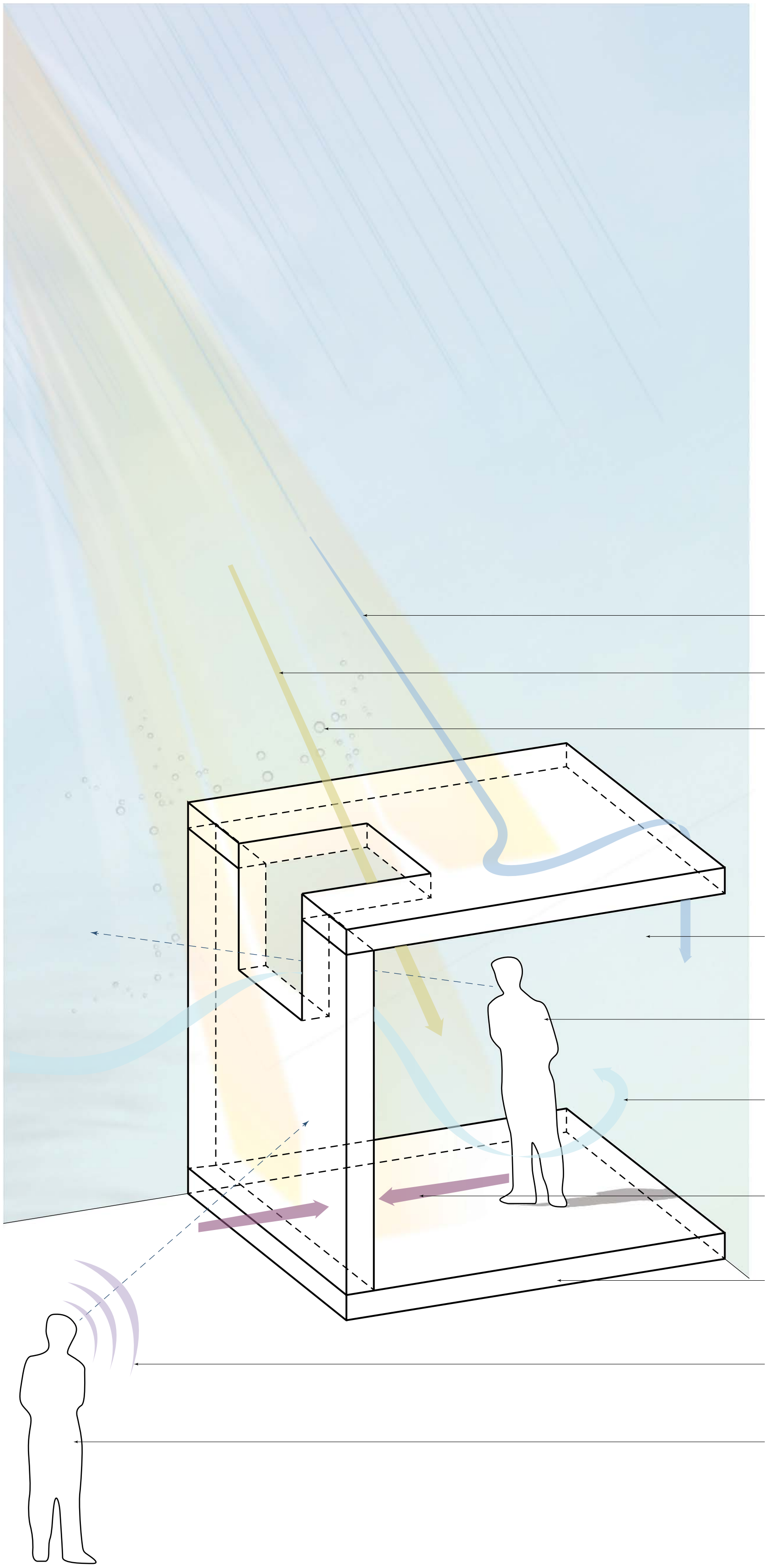


FIG. 1 FUNCTION OF THE ENVELOPE
The diagram demonstrates the foundational functions of the building envelope. For both the temporary structure and the solid wall the purpose of the envelope is to create a private space protected from adverse or harsh environmental conditions that the body cannot directly protect against without additional assistance.
The diagram was created from information retrieved from: Knaack, Ulrich, Tillmann Klein, Marcel Bilow, and Thomas Auer. Façades: principles of construction. Birkhäuser, 2014.

Prevent the passage of moisture, keeping out adverse atmospheric precipitation

Allow the transmittance of natural lighting

Mediate the diffusion of vapor into the interior space

Maintain structural stability against both lateral and gravitational forces

Allow occupants of interior spaces to maintin a visual connection to the exterior

Allow for ventilation or air exchange to maintin the quality of the interior atmosphere

Prevent temperature transmittance across the envelope from both exterior to interior and interior to exterior

Delineate and create a protected environment

Prevent noise transmittance across the envelope from both exterior to interior and interior to exterior

Maintain privacy by preventing people exterior to the envelope views in traditional roles began at the onset of the Industrial revolution, where rapid development of new materials, products, techniques, and new forms of energy generation and equipment were introduced. During this time, the development of mechanical equipment that could artificially condition spaces extended the human thermal environment into less hospitable climates. As a result of this new technology, the responsibility of maintaining internal thermal conditions was removed from the envelope and buildings evolved into structural endo-skeletons with enclosing skins[7]. With the functional duties of the envelope reallocated to technological equipment, the modern envelope is not only removed from its obligation to directly interact with climate and geographical cause and effect but also results in a homogeneous environmental expectation from its users. Ignoring the atmospheric variability beyond the surface of the envelope is a failure of modern architecture and is a result of consistently underestimating the environmental forces that play upon the building while also persistently overestimating the capabilities of deployed technologies used to maintain interior environments. This reliance on mechanical systems has enabled an approach of, "material as visual artifact" where a material palette can be freely applied on a visual basis and the creation of complex forms is possible with little regard for environmental impact on either side of the envelope[8,9]. Paolo Portoghesi, an architect and theorist, argues that it is this Promethean attitude towards technology; the conception of technological development as the salvation in exchange for the defeat and servitude of nature, that is responsible for today's ecological disaster. Rather than pursuing a conception of the envelope as a thermal threshold and its interior space as an "artificial second nature"[10], the envelope should be conceptualized as a selective filter, working in dialogue with both the interior occupied environment and its terrestrial surroundings[11]. In essence, the building envelope must relate to the scale and comfort of the human body, at the same time it relates to the dynamic nature of climate to regain responsibility of thermal performance and the production of interior comfort[12].

In controlling the thermal environment, architect James Marston Fitch, author of, "American Building 2: The Environmental Forces That Shape It," argues there are three thermal zones with which the envelope of the building must acknowledge. The first is the macroenvironment, which consists of the thermal conditions governed by environmental forces, the second is the microenvironment, which is the internal thermal maintenance governed by the human body, and the third, which acknowledges the limitations of the human body to navigate all thermal environments found in the natural world, is regarded as the mesoenvironment. The mesoenvironment is created by the envelope (and additionally by clothing) through the function of a semi-permeable threshold to lessen the severity of the macroenvironment on the microenvironment.

FIG. 2 (FACING PAGE) TYPICAL ENVELOPE SYSTEM
The diagram demonstrates the execution of functional parameters of the facade for moderating the thermal environment in a typical example of an envelope commonly used in todays architectural practice.

### *The Macroenvironment*

The macroenvironment refers to the large-scale and long-term environmental processes that shape global and regional thermal zones. The relationship between the energy received from the sun and the shape of the earth turns an otherwise inert body of solids, liquids, and gases, into a variety of different climates and thermal landscapes. The two most important factors for the production of different thermal environments include insolation; which is the amount of solar radiation reaching the earth's surface at any given point, and

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[7] Straube, John . "BSD-042: Historical Development of the Building Enclosure." Building Science Corporation. November 15, 2010

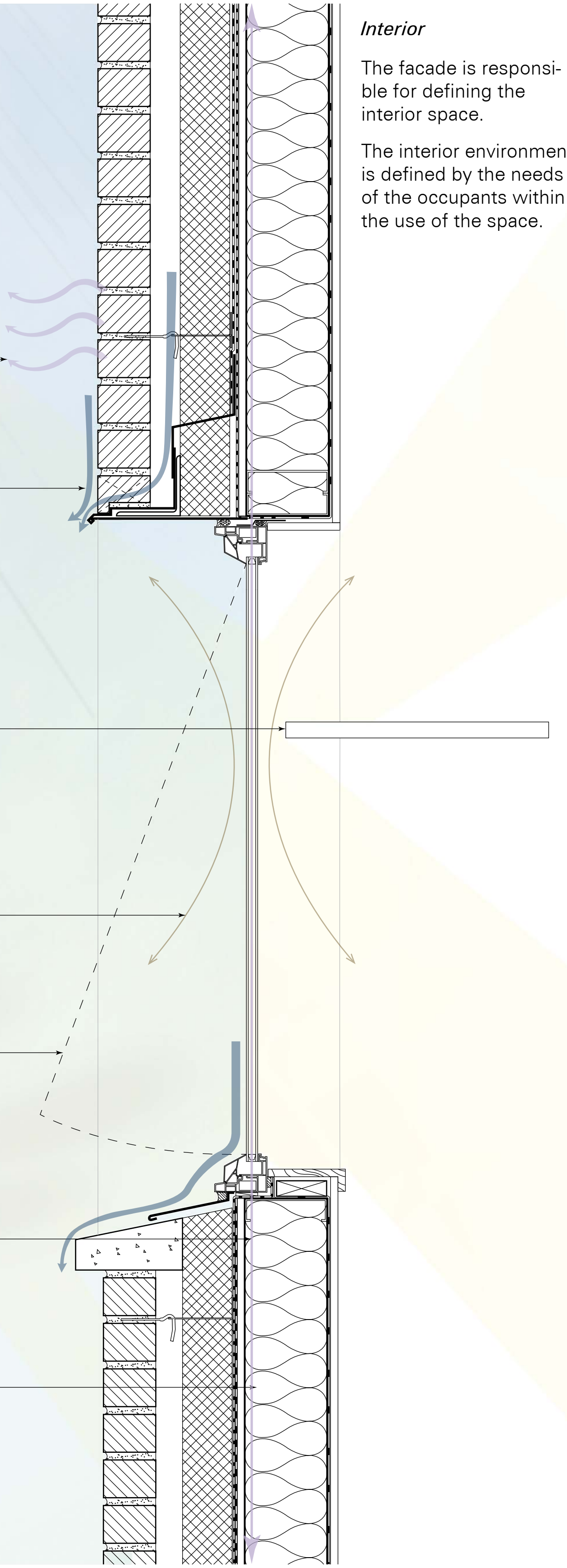
[8] Lovel, Jenny. "Building envelopes: an integrated approach." Princeton Architectural Press, 2013.

[9] Fitch, James Marston, and Daniel P. Branch. "Primitive architecture and climate." Scientific American 203, no. 6 (1960): 134-144.

[10] Portoghesi, Paolo. "Nature and architecture." (2000).

[11] Fitch, James Marston, and Daniel P. Branch. "Primitive architecture and climate." Scientific American 203, no. 6 (1960): 134-144.

[12] Lovel, Jenny. "Building envelopes: an integrated approach." Princeton Architectural Press, 2013.



*Exterior*

The external environment is the three dimensional space of varying mass and energy properties. Adjacent portions of the external environment are affected by the building creating a mesoenvironment.

External environment and its interaction with the envelope is dependent on the weather patterns, time of day, week of month, and the season.

Envelope design can take advantage of heat retention for passive heating and cooling using materials with high solar capacities

Envelope prevents water penetration through a series of barriers and a rain screen system, draining water out of the envelope before it reaches the interior spaces through a cavity

Lighting of interior spaces and the allowance of solar gain can be controlled through light shelves and appropriatly high windows that are concious of solar angles

Design of the envelope is to maintain a separation between the interior and exterior

Provision of air and control of interior thermal climates can be provided through operable portions of the envelope

Thermal control provided by continuous insulation within the entire envelope used to prevent heat and cold transfer through the envelope

Envelope provides structural stability to resist and transfer loads inflicted by the macroenvironment

*Interior*

The facade is responsible for defining the interior space.

The interior environment is defined by the needs of the occupants within the use of the space.

latitude; which is the distance from the equator that determines the amount of solar energy a given point will receive. The interaction of insolation and latitude with the materials that make up the surface of the earth results in varying climatic regions. This is a consequence of varying heat capacities within the material assembly of the earth's surface. Water has the highest heat capacity of all surface materials and therefore accumulates and dissipates heat much slower than other surface materials. The slow release of heat causes landmasses surrounded by large bodies of water to have reduced diurnal and seasonal temperature extremes. Additionally, landmasses experience varying heat capacities depending on their material structure and ground cover (Fig. 3). Though ground cover does not have a heat capacity high enough to produce substantial climatic variation, these materials affect regional climate through the creation of secondary climate characteristics (for example: sand is a proficient absorber of heat while snow is highly reflective, both of these ground cover materials are a result of direct solar radiation, however snow appears where there is little insolation, and sand is seen where there is plenty of insolation. The secondary characteristics are seen as both of these ground cover materials exacerbate further the terrestrial systems causing them)[13].

> *"We live not on the summit of a solid earth, but rather at the bottom of an ocean of air" - Sean Lally*

### *The Microenvironment*

The microenvironment is produced through the interaction of the human skin with its immediate thermal surroundings, and is the climate region within which the human body perceives comfort. As a state of physical ease, the body achieves the perception of comfort when the mind expresses satisfaction with the thermal environment. This satisfaction is produced when the internal thermal temperature of the body is maintained within a specific range (36.5 - 37.5°C), the moisture of the skins surface is low, and the physiological effort needed to sustain this condition is at a minimum[14]. Any biological organism, including the human body, deploys mechanisms for maintaining comfort that both perceive changes in the environment as well as respond to those changes. Organisms are capable of existing harmoniously within their surroundings, only by continuously perceiving and balancing their internal operations with the constant flux of external conditions. This homeostatic balancing is the body's way of maintaining thermostatic consistency of its internal environment. Mediation of this condition is performed by the hypothalamus in the brain, which deploys thermal control mechanisms during periods of overheating and engages thermodetectors in the skin during period of under heating to accelerate all muscular activity for metabolic heat production[15]. The results of this, for warm temperatures, include vasodilation, which is the expansion of blood vessels near the surface of the skin in order to increase blood supply and heat dissipation. If this response is not enough to decrease internal temperatures, the body will begin to sweat in an effort to increase cooling through evaporation of water off the skins surface. Alternatively, in cold temperatures, the body will respond through vasoconstriction, or the reduction of blood circulation to the skin to decrease heat loss. Again, if this response is not enough to reach a comfortable state, the pores of the skin will close to reduce the surface area of the body and shivering will begin so as to increase the production of heat (Fig. 4)[16].

FIG. 3 (FACING PAGE) GLOBAL THERMAL ENVIRONMENT
Adapted diagrams from James Marston Fitch: Solar energy received by the earth from the sun is a function of the angle of incidence and the duration of the exposure. This, accompanied with the varying heat capacities of earth's materials, and the patterns of resulting atmospheric motion produce numerous thermal landscapes in which the envelope must navigate on a local level.

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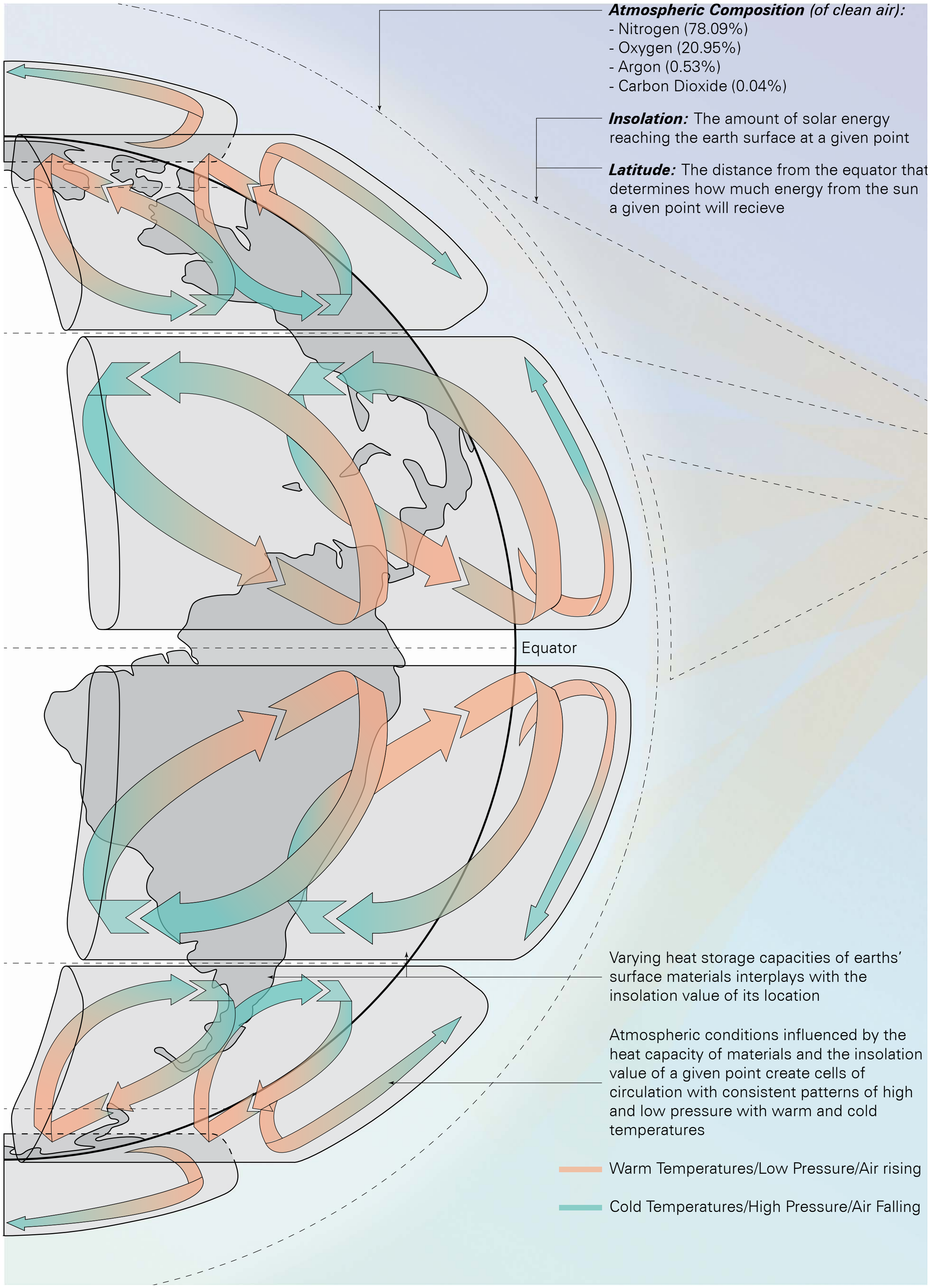
[13] Fitch, James Marston. American Building: 2, the Environmental Forces that Shape it. Vol. 2. Houghton Mifflin, (1972) 239 - 241

[14] La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.

[15] Fitch, James Marston. "American Building: 2, the Environmental Forces that Shape it." Vol. 2. Houghton Mifflin, 1972.

[16] La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.



***Atmospheric Composition** (of clean air):*
- Nitrogen (78.09%)
- Oxygen (20.95%)
- Argon (0.53%)
- Carbon Dioxide (0.04%)

***Insolation:*** The amount of solar energy reaching the earth surface at a given point

***Latitude:*** The distance from the equator that determines how much energy from the sun a given point will recieve

Varying heat storage capacities of earths' surface materials interplays with the insolation value of its location

Atmospheric conditions influenced by the heat capacity of materials and the insolation value of a given point create cells of circulation with consistent patterns of high and low pressure with warm and cold temperatures

🟧 Warm Temperatures/Low Pressure/Air rising

🟩 Cold Temperatures/High Pressure/Air Falling

The human metabolism, which allows the body to both produce and absorb energy, is a continuous process of combustion that generates heat as a byproduct of energy production. While heat is always being created through this process, the body is capable of accelerating or decelerating its generation based on its' perception of the thermal environment of its immediate physical surroundings. As such, the management of internal thermal comfort of the body is determined by the body's interaction with surfaces surrounding it as well as the air it is immersed in. Within the environment external to the human body, the perception of heat by the body is based on three atmospheric parameters. The first is as ambient and/or radiant temperatures, the second is air movement and the third is humidity. While the facade cannot control the production of heat within the human body, it can control the dissipation of heat from the body's surface by understanding and manipulating these three parameters to control the thermal comfort of a space. Heat dissipation off the body can be accomplished through convection, evaporation, conduction, and radiation. However the degree to which each of these methods can be used effectively to manipulate environmental conditions at a given time is dependent on the external thermal factors of the macroenvironment. The efficiency of dissipation is based on the varying sum of the radiant temperature of the immediate environment, the ambient air temperature, the moisture content of the air, and the rate of air movement over the skin (Fig. 5)[17]. Therefore, because the facade is conceived as a semi-permeable barrier, it has the capacity to control both the conditioning of the interior environment as well as the individual and collective comfort of the occupants with an acute understanding of these interacting elements. Through purposefully increasing air movement within interior spaces by allowing its passage through the facade, occupant comfort in warm temperatures can be achieved through the evaporation of moisture off the skin. This method of cooling also provides relief in humid climates where evaporation would take place more slowly because of the high moisture content already present in the air; the increased motion of air across the skin would result in increased evaporation[18].

### *The Mesoenvironment*

Through the interaction of larger forces within the terrestrial macroenvironment, local thermal landscapes are produced. Described by Fitch as the third element between the macro and microenvironments, the mesoenvironment is the thermal scale where both building envelopes and human bodies interact[19, 20]. Though larger terrestrial air masses determine regional weather patterns, the air masses are manipulated locally based on the particular configuration of the land along with the built objects poised upon it. The interaction of local air masses with a given site results in small scale variations of the thermal environment based on changes in elevation, sun and wind exposure, proximity to bodies of water, soil structure, local vegetation, and other neighboring structures. Every change to the site, whether produced by cultural development or biological systems, will have an affect on the characteristics of local air masses. The clustering of built objects into the urban form results in a much more significant alteration to local thermal environments. Due to heat absorption and retention within masonry materials, and the widespread use of these materials throughout urban spaces, cities distort the normal thermal cycle of local environments[21]. As a collection of buildings, urbanization manipulates local external thermal environments through casting shadows, the reflection of light and heat off of glazed surfaces, the exfiltration of heat through the building facade, and the

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[17] Fitch, James Marston. "American Building: 2, the Environmental Forces that Shape it." Vol. 2. Houghton Mifflin, 1972.

[18] La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.

[19] Fitch, James Marston. American Building: 2, the Environmental Forces that Shape it. Vol. 2. Houghton Mifflin, (1972) 244 - 245

[20] Lally, Sean. Air from Other Planets: A Brief History of Architecture to Come. Lars Muller Publishers, 2013.

[21] Fitch, James Marston. American Building: 2, the Environmental Forces that Shape it. Vol. 2. Houghton Mifflin, (1972) 249

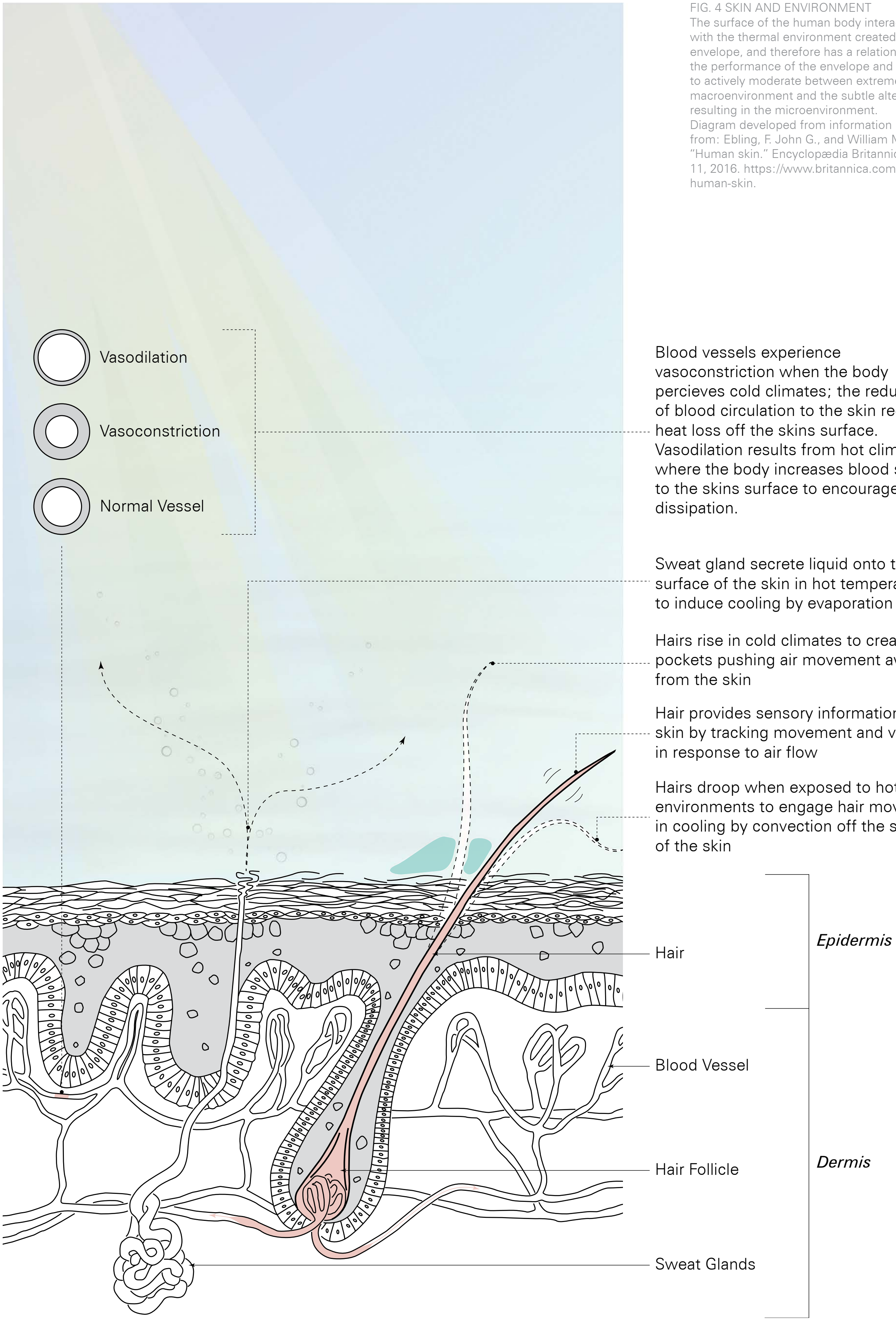

FIG. 4 SKIN AND ENVIRONMENT
The surface of the human body interacts with the thermal environment created by the envelope, and therefore has a relationship with the performance of the envelope and its ability to actively moderate between extremes of the macroenvironment and the subtle alterations resulting in the microenvironment.
Diagram developed from information retrieved from: Ebling, F. John G., and William Montagna. "Human skin." Encyclopædia Britannica. April 11, 2016. https://www.britannica.com/science/human-skin.

Blood vessels experience vasoconstriction when the body percieves cold climates; the reduction of blood circulation to the skin reduces heat loss off the skins surface. Vasodilation results from hot climates, where the body increases blood supply to the skins surface to encourage heat dissipation.

Sweat gland secrete liquid onto the surface of the skin in hot temperatures to induce cooling by evaporation

Hairs rise in cold climates to create air pockets pushing air movement away from the skin

Hair provides sensory information to the skin by tracking movement and vibration in response to air flow

Hairs droop when exposed to hot environments to engage hair movement in cooling by convection off the surface of the skin dumping of conditioned air from mechanical systems[22]. Both the heat retained by the materials of the city as well as the heat accumulated by the use of the city is kept within its local environment by atmospheric pollution (Fig. 6)[23].

In navigating the terrestrial thermal environment, the envelope has the unique position of being the threshold between interior and exterior conditions. Having the ability to act as an interface, between the macroenvironment of terrestrial systems and the microclimate of the human body, the mesoenvironment can be tailored based on the design of the envelope, to accommodate occupant needs[24]. As such, the building envelope can take on the form of a selectively permeable membrane, or an open system with the capacity to transfer energy to and from the environment in order to regain the responsibility of, and control over, thermal comfort[25]. This definition and functional understanding of the facade is demonstrated within vernacular architecture whose, "primitive practice reflects a precise and detailed understanding of local climate, on one hand; and a remarkable grasp of the performance characteristics of local building materials, on the other"[26]. Within the development of vernacular architecture, the materials afforded by the environment were the absolute limitation of construction[27]. While achieving thermal comfort was the largest challenge facing the design of vernacular architecture, both theory and practice of design development were focused on controlling the envelopes surface response to environment; controlling the buildings homeostatic relationship to the macroenvironment[28].

The igloo is an example of achieving thermal performance based on form and choice of material within a cold climate. The dome of the igloo minimizes the external surface area while maximizing internal volume and, in doing so; the envelope of the igloo has the least exposure to winter temperatures as well as maintaining an interior volume that can be easily heated by a single point source. The specific use of snow as the material of the igloo is vital to its thermal performance. Attempting to achieve thermal comfort within extremely cold environments dictates a material with the lowest possible heat capacity, which is a property of dry snow. The use of point source heating on the interior, coupled with the body heat of occupants, not only increases the temperature of the internal thermal environment, but also increases the insulation value of the snow envelope. This is a result of a thin layer of ice, which forms on the interior side of the dome that seals any pores and reflects light and heat back into the space. Lining the interior of the igloo with fabrics or other insulating materials also minimizes heat transfer out of occupant bodies. Alternatively, adobe is a material used within vernacular architecture of hot climates with large temperature swings between day and night. A material successful at maintaining thermal comfort within this type of climate has a high heat capacity. This allows for the absorption of solar radiation during the day and the release of it at night when the temperature is lower, thus flattening the internal thermal diurnal variation between day and night[29]. An example of this material in use can be seen within beehive homes found in hot climates such as Syria. The high dome shape collects hot air so as to maintain cooler temperatures at the bottom for occupants, thick walls absorb heat during the day for release at night thus delaying internal temperature shifts, and the material is both locally sourced and readily available[30]. The igloo, as well as the adobe beehive house, demonstrates the envelope is not an inert object, but can successfully maintain control over the internal thermal environment and achieve passive occupant comfort when the design has an acute understanding of both material and local environment.

[22] Lally, Sean. Air from Other Planets: A Brief History of Architecture to Come. Lars Muller Publishers, 2013.

[23] Fitch, James Marston. American Building: 2, the Environmental Forces that Shape it. Vol. 2. Houghton Mifflin, (1972) 9

[24] Fitch, James Marston. American Building: 2, the Environmental Forces that Shape it. Vol. 2. Houghton Mifflin, (1972) 9

[25] Hensel, Michael. Performance-oriented architecture: rethinking architectural design and the built environment. John Wiley & Sons, 2013.

[26] Fitch, James Marston. American Building: 2, the Environmental Forces that Shape it. Vol. 2. Houghton Mifflin, (1972) 265

[27] Fitch, James Marston, and Daniel P. Branch. "Primitive architecture and climate." Scientific American 203, no. 6 (1960): 134-144.

[28] Fitch, James Marston. American Building: 2, the Environmental Forces that Shape it. Vol. 2. Houghton Mifflin, (1972) 270

[29] Fitch, James Marston, and Daniel P. Branch. "Primitive architecture and climate." Scientific American 203, no. 6 (1960): 134-144.

[30] "The History of Beehive-Shaped Homes ." Earthbag Building , www.earthbagbuilding.com/articles/beehive.htm.

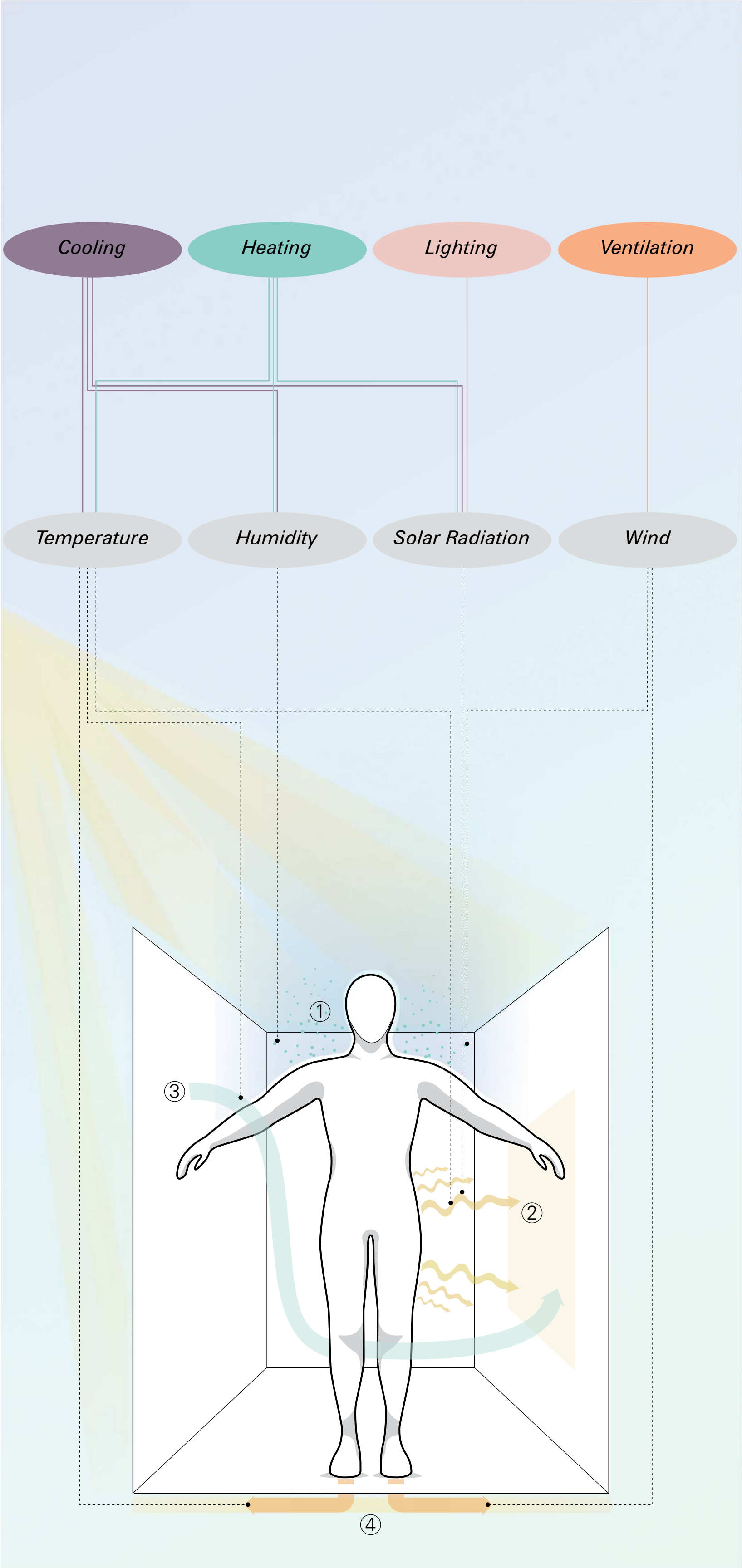

FIG. 5 BODY AND ENVIRONMENT
The creation of comfortable interior environments begins with the interaction of the body with the microclimate. This microclimate is then maintained by the interaction of the facade with the parameters of the terrestrial thermal environment.
Diagram developed from information retrieved from: La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.

① ***Evaporation:*** the dissipation of heat by the vaporization of moisture off the surface of the skin

② ***Radiation:*** the transfer of thermal conditions to and from the body through electromagnetic waves

③ ***Convection:*** the dissipation of heat by the motion of air

④ ***Conduction:*** the transfer of thermal conditions through direct molecular contact between the body and a surface

Through the facade, architecture is continuously participating in all atmospheric processes, however the way in which it interacts can be strategized in a more cohesive manner. An expanded understanding of building performance and envelope design should acknowledge that the forces acting on and with the building including climate, energy, and human agents, are all non-static conditions. As such, the envelope design must transcend a role that has been largely regarded as merely a protective wrap to separate inside from outside, and must become involved in the variability of its environment. Conceiving the macro to microenvironments as one continuous space of constant interaction allows for an understanding of the envelope and its enclosed spaces as more than simply nested objects, but rather a means of negotiating and participating in the perceived world[31].

FIG. 6 (FACING PAGE) ENVELOPE AND ENVIRONMENT
Diagram illustrates the main ways a typical envelopes such as standard curtain wall systems can distort the external thermal environment while maintaining the comfort of interior spaces.

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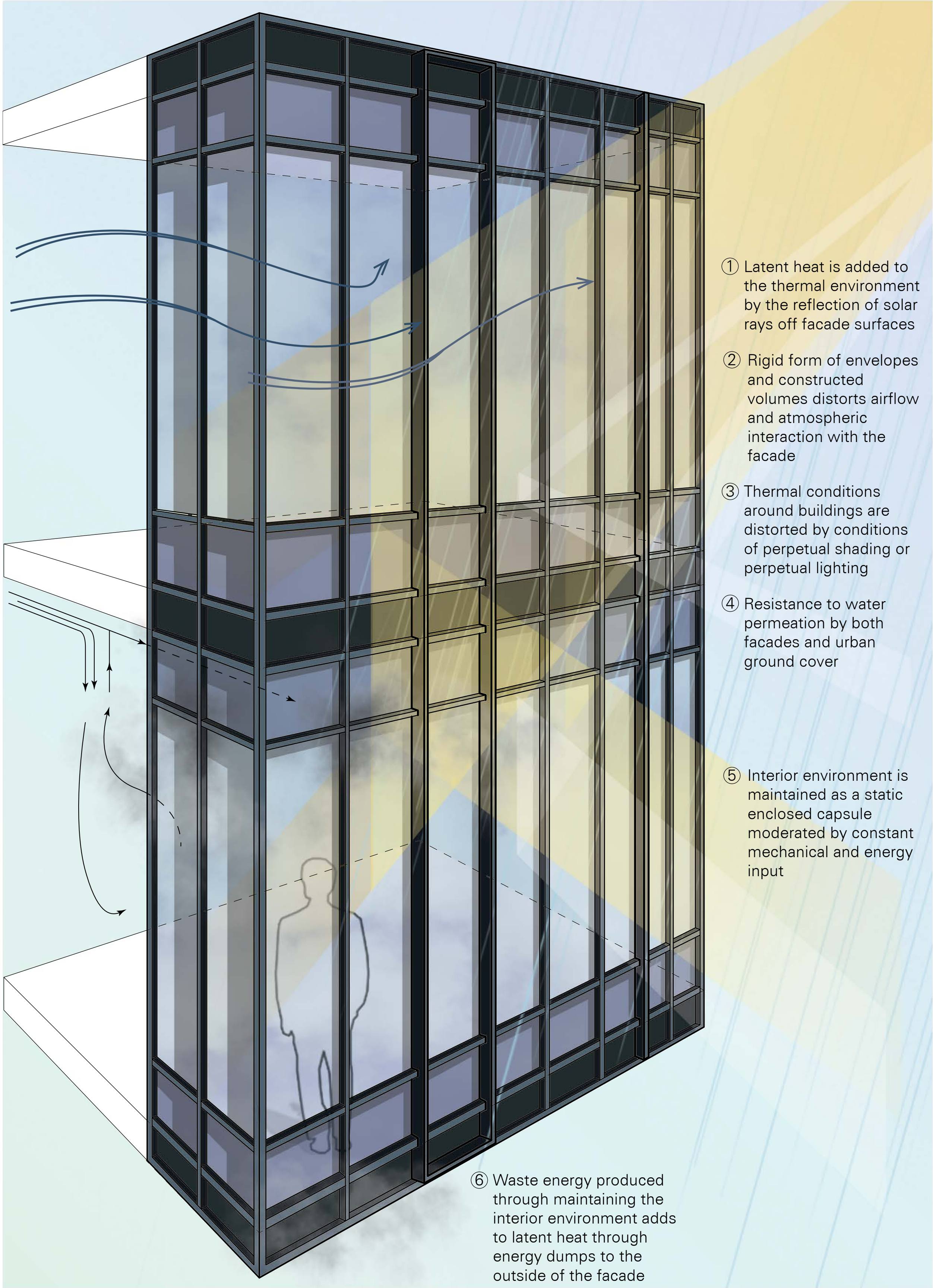
[31] Lally, Sean. "Air from Other Planets: A Brief History of Architecture to Come." Lars Muller Publishers, 2013.



① Latent heat is added to the thermal environment by the reflection of solar rays off facade surfaces

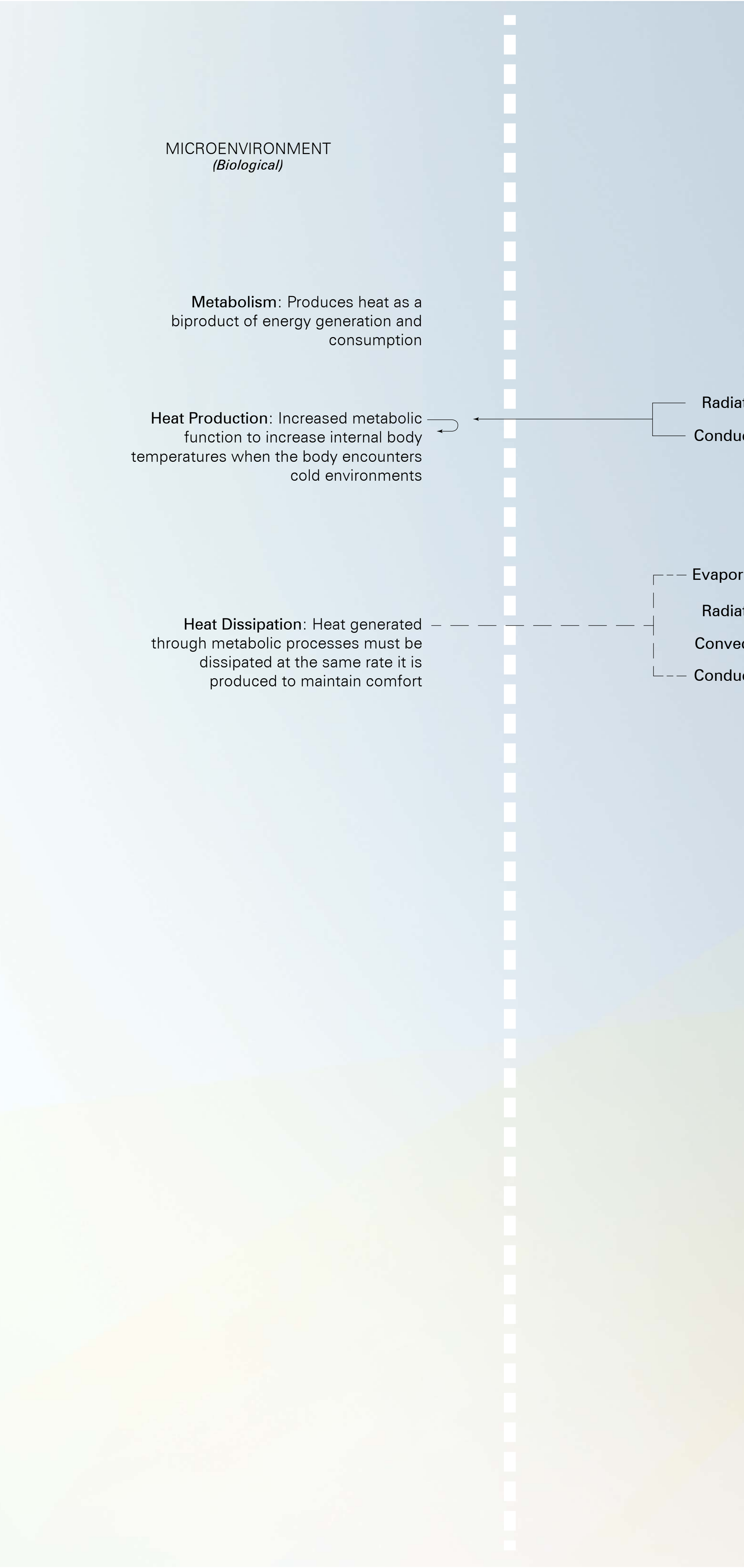
② Rigid form of envelopes and constructed volumes distorts airflow and atmospheric interaction with the facade

③ Thermal conditions around buildings are distorted by conditions of perpetual shading or perpetual lighting

④ Resistance to water permeation by both facades and urban ground cover

⑤ Interior environment is maintained as a static enclosed capsule moderated by constant mechanical and energy input

⑥ Waste energy produced through maintaining the interior environment adds to latent heat through energy dumps to the outside of the facade



MICROENVIRONMENT
*(Biological)*

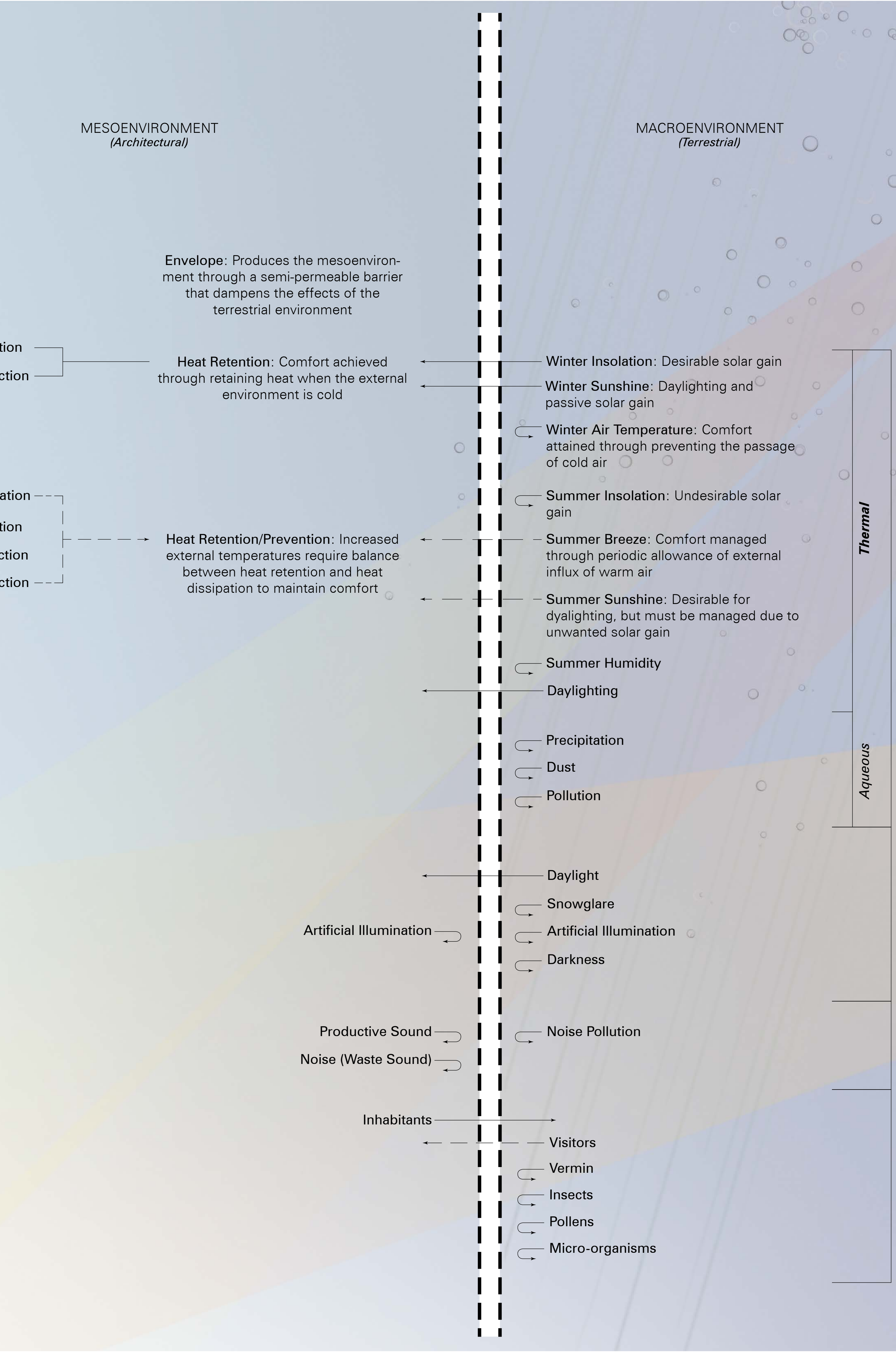
**Metabolism**: Produces heat as a biproduct of energy generation and consumption

**Heat Production**: Increased metabolic function to increase internal body temperatures when the body encounters cold environments

**Heat Dissipation**: Heat generated through metabolic processes must be dissipated at the same rate it is produced to maintain comfort

FIG. 7 ENVELOPE AS A SEMIPERMEABLE MEMBRANE
Adapted diagram by James Marston Fitch

“The wall [is] conceptualized as a selective filter, acting as interface between natural macro-environment and man-made meso-environment” - James Marston Fitch



MESOENVIRONMENT
*(Architectural)*

MACROENVIRONMENT
*(Terrestrial)*

**Envelope**: Produces the mesoenvironment through a semi-permeable barrier that dampens the effects of the terrestrial environment

tion

ction

**Heat Retention**: Comfort achieved through retaining heat when the external environment is cold

ation

tion

ction

ction

**Heat Retention/Prevention**: Increased external temperatures require balance between heat retention and heat dissipation to maintain comfort

**Winter Insolation**: Desirable solar gain

**Winter Sunshine**: Daylighting and passive solar gain

**Winter Air Temperature**: Comfort attained through preventing the passage of cold air

**Summer Insolation**: Undesirable solar gain

**Summer Breeze**: Comfort managed through periodic allowance of external influx of warm air

**Summer Sunshine**: Desirable for dyalighting, but must be managed due to unwanted solar gain

Summer Humidity

Daylighting

Precipitation

Dust

Pollution

Daylight

Snowglare

Artificial Illumination

Darkness

Noise Pollution

Artificial Illumination

Productive Sound

Noise (Waste Sound)

Inhabitants

Visitors

Vermin

Insects

Pollens

Micro-organisms

***Thermal***

*Aqueous*

***Atmospheric***

*Luminous*

*Sonic*

*Biological*

# PASSIVE MOTION

## *Biomimetics in Design*

*"Adaptation is the evolutionary process whereby a population becomes better suited to its habitat. This process takes place over many generations, and is one of the basic phenomena of biology." - Charles Darwin*

As a response to global challenges created by increasing populations, such as global energy scarcity and increasing temperatures, the built form must alter its practices and look for new ways of designing that can navigate through fluctuating conditions[1]. The ability to participate with changing environmental conditions with agency so as to maintain a steady internal condition viable for comfortable living is an ability demonstrated by biological systems. Organisms are open systems permanently interacting with their surroundings, and are therefore examples of functional designs that exist in equilibrium with the environment, able to navigate as an interconnected system between the macro to microenvironments[2]. The systems deployed by biological organisms can be implemented within the architectural field to help create the same meteorosensitive behavior within the built environment as is demonstrated by organisms. The transfer of functional morphology from the biological world into architectural systems is known as biomimicry, and is not an unfamiliar concept to systems design. Historical examples of biomimicry in systems and product design include modern paper; originally made from cotton linen fibers, Antoine Reaumur, in 1719, noted the use of wood pulp by wasps and suggested it as an alternative material. Additionally, dolphins were studied by George Cayley in 1809 to streamline ship hulls in an effort to reduce drag, and lastly, George de Mestral studied burrs in 1949 to invent Velcro by combining two strips of fabric, one with tiny hooks and the other with tiny loops, for a material that gripped together while still allowing easy release[3].

The term 'biomimicry' was coined by the American inventor, engineer and biophysicist Otto Schmitt, in 1957 and first appeared in scientific literature in 1962[4]. However, it was popularized by the American science writer, innovation consultant and author, Janine Benyus in her book, "Biomimicry: Innovation inspired by nature", first published in 1997[5]. The intent of biomimicry is to understand the principles of natural forms and systems so as to translate

[1] Armstrong, Rachel. "How Do the Origins of Life Sciences Infuence 21st Century Design Thinking?" PDF. Proceedings of the European Conference on Artificial Life, (2015): 2-11 DOI: http://dx.doi.org/10.7551/978-0-262-33027-5-ch002

[2] Gruber, P. "Biomimetics in architecture: architecture of life and buildings." Wien: Springer. (2010)

[3] Pawlyn, Michael. "Biomimicry in architecture." Vol. 15. Riba Publishing, (2011).

[4] Pawlyn, Michael. "Biomimicry in architecture." Vol. 15. Riba Publishing, (2011).

[5] Benyus, Janine M. "Biomimicry: Innovation inspired by nature." (2002).

them into architectural solutions. While there are several definitions of the term biomimicry, this thesis will be referring to biomimicry as, "mimicking the functional basis of biological forms, processes, and systems to produce sustainable solutions"[6].

The development of biomimicry in architectural practice has been through the reevaluation of nature as a necessary part of humanity, and the realization that biological organisms provide graceful solutions to nearly all anthropogenic problems[7]. The importance of biomimetics in architectural practice is highlighted by Janine Benyus, who critics western society for the cultural customs of dominating or attempting to improve upon nature. Benyus argues that humanity has only recently learned both humans and biological organisms are subject to the same environmental laws. The most important of which is also the one that humanity has ignored the most, which states that any singular species cannot occupy a niche that appropriates all resources and that any species who ignores this destroys its supporting environmental community in its efforts of self expansion. Benyus refers to anthropologist Loren Eisley, to further argue that the real survivors are the inhabitant that have subsisted for millions of years without consuming their ecological capitol[8]. In agreement with Benyus is Donna Haraway, a prominent figure in science and technology studies and the author of, "The Cyborg Manifesto". Haraway asserts in her work that the cultural appropriation and domination of nature is an indirect product of capitalism, and the creation of the 'cyborg', as the hybrid of machine and organism, insists in the coupling of people with other living entities. Haraways argues that through biomimicry, the relationship between nature and culture can be redeveloped so one can no longer be the resource for misuse of the other[9]. In this sense, architecture should be seen as part of a given environment, where application of biological problem solving can be used to solve functional imbalances within the anthropogenic realm. This argument is made by Paolo Portoghesi, an architect, theorist, and historian, who refers to John Ruskin when he argues, "no form or set of forms [can] be conceived without there being an example somewhere in the universe"[10]. Furthering the idea of systems translation is Michael Pawlyn in his work, "Biomimicry in Architecture", where he aims to look at nature as a sources for translating biological adaptation in architectural solutions. Pawlyn speculates the biomimicry in architecture could create regenerative buildings that are no longer static consumers, but autonomous producers[11].

### *Passive and Active Biomimetic Strategies*

Despite the more rapid involvement of biomimetics strategies in other fields of industrial design and medicine, rather than architecture[12], many examples of biological precedents can be found in both active and passive building skin designs. Petra Gruber first addresses this in her book, "Biomimetics in Architecture of Life and Building", where she asserts that architecture should assume more than a passive role in future environments, discussing reaction to environment by the building as implying architecture must signal, regulate, and actuate in response to climate changes. Gruber argues that the incorporation of active systems offers the possibility of setting up reactive behaviors[13]. Branko Kolarevic and Vera Parlac in their work, "Adaptive Building Skins", investigate the generation of a two-way relationship between environment and user through space using active envelope systems. The focus of the study is on mechanically controlled architecture capable of transformation in shape,

[6] Pawlyn, Michael. "Biomimicry in architecture." Vol. 15. Riba Publishing, (2011).

[7] Pawlyn, Michael. "Biomimicry in architecture." Vol. 15. Riba Publishing, (2011).

[8] Benyus, Janine M. "Biomimicry: Innovation inspired by nature." (2002).

[9] Haraway, Donna. "A Cyborg Manifesto: Science, technology, and socialist-feminism in the late 20th century." In the international handbook of virtual learning environments. Springer Netherlands. (2006) 117-158.

[10] Portoghesi, Paolo. "Nature and architecture." (2000).

[11] Pawlyn, Michael. "Biomimicry in Architecture." Vol. 15. Riba Publishing, (2011).

[12] Pawlyn, Michael. "Biomimicry in Architecture." Vol. 15. Riba Publishing, (2011).

[13] Gruber, P. "Biomimetics in architecture: architecture of life and buildings." Wien: Springer. (2010)

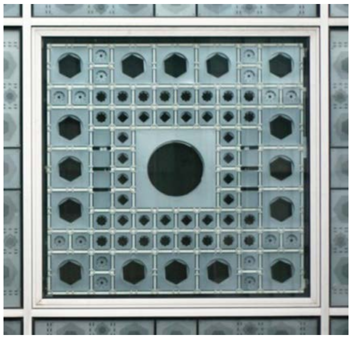


FIG. 1 SINGLE OCULUS - OPEN
Image shows a single oculus within the solar wall of the Institut du Monde Arabe when it is fully actuated.
Image retrieved from: http://www.anarchitectabroad.com/blog/most-instagram-worthy-places-in-paris/

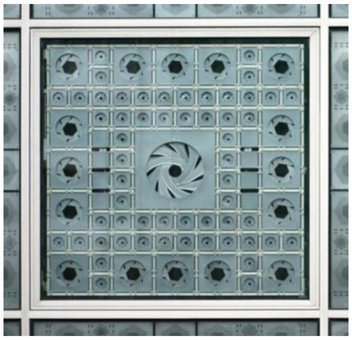


FIG. 2 SINGLE OCULUS - CLOSED
Image shows a single oculus within the solar wall of the Institut du Monde Arabe when it is fully closed.
Image retrieved from: http://www.anarchitectabroad.com/blog/most-instagram-worthy-places-in-paris/

form and configuration. Kolarevic and Parlac define the primary goal of responsive, adaptive architecture to be the provision of agency to interact with both environment and user within the built form. This is accomplished through the creation of technical systems that create, simulate, and are stimulated by changing environments. Despite the productivity provided by mechanized systems, Kolarevic and Parlac conclude that active systems should not be blindly implemented without consideration of a low or no-tech alternative. This is due to several challenges of active systems including the complexity of hardware, cancellation of the system due to annoyance with automation, and the necessity for a complete rethinking of how a building can perform typical functions alongside adaptation[14]. The solar facade within the Institut du Monde Arabe by architect Jean Nouvel, is an example of a system performing active adaptation to environmental changes. The design of the facade takes precedent from traditional Arab lattice screens called 'mashrabiya' and is composed of 30,000 photosensitive diaphragms that control light infiltration through alternating opacity of the facade (Fig. 1 and 2). While the facade was completed in 1989 and marked for the significant and large-scale implementation of adaptive facade systems, it is presently inoperable due to mechanical problems[15].

As an alternative to mechanized strategies for adaptive behavior, reaction of the built form on a material level can be used as a passive regulation process, capable of performing the role of both sensor and actuator. This can be done through the use of materials with chemical change behavior, where differentiating physical condition can be directly initiated by changes in the environment. Chuck Hoberman, an artist, engineer, architect, and inventor of toys, most notable for the invention of the Hoberman Sphere, argues within his work, "Transformation in Architecture and Design", that transformation in architecture refers to a structure that transforms itself by itself. Hoberman asserts that this principle can be identified in biological organisms where the behavior of the object emerges from the geometry of the object, and this can be functionally applied to architectural design through the ability to fold, retract, or shape shift to perform responsiveness in reaction to environment[16]. For biomimetics in architecture, the study of plant adaptation is most notable because they share a common characteristic; most are immobile, dependent on and subject to local environmental conditions and natural forces[17].

Responsive behavior in plants can be produced from both active and passive systems. Active movements are powered through systems deployed by the plant itself, usually involving excessive growth on one side over the other, or the purposeful influx of fluids into the cells to force expansion and generate motion. Alternatively, passive movements within plants are produced by the physical composition of the organism, and the interaction of that configuration with an environmental trigger. This could result in cell elongation as a result of moisture uptake or through external actuation to produce an elastic deformation. The first categorical method of motion is active taxis movement, which is the motion of a plant or organism demonstrating motility and guided movement away or towards a stimulus (Fig. 3). This type of movement is continuous and does not have to follow a repeatable motion. The second category of motion is tropic movement, which is an active, direction dependent and non-repeatable movement towards a directional stimulus. This method of motion is incapable of repeated cycles because it involves irreversible growth of the plant to produce motion (Fig. 4). Typical examples of tropisms include movements toward a light source, referred to as phototropism, directional growth in response to gravity, known as gravitropism, and touch sensitive growth referred to as thigmotropism.

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[14] Kolarevic, Branko, and Vera Parlac. "Adaptive Building Skins." The Routledge Companion for Architecture Design and Practice: Established and Emerging Trends (2015).

[15] Kolarevic, Branko, and Vera Parlac, eds. Building dynamics: exploring architecture of change. Routledge, 2015.

[16] Hoberman, Chuck. "Transformation in architecture and design." Transportable Environments 3 (2006): 70-73.

[17] Gruber, P. "Biomimetics in architecture: architecture of life and buildings." Wien: Springer. (2010)

The third category of motion is nastic movement, which is a repeatable and independent movement occurring in response to environmental stimulus. This category of movement also takes place in response to individual environmental factors. For example, the terms photonasty, thermonasty, and thigmonasty refer to independent movement resulting from interaction with light, heat and touch. As this motion is most commonly produced within dead tissue and is a result of morphological structural characteristics of the plant, it is a completely passive motion[18]. Within this thesis, biological organisms are studied to understand ways in which both form and physiological configuration of a material affect the performance of the organism as a whole. The performance of these organisms is then functionally transferred to the design of an architectural mechanism for adaptive cooling (Fig. 5). The first biological precedent studied is the Ipomoea, which forms a conical shape when fully in bloom and gains strength through double curvature. The Ipomoea performs multiple transformations of shape change from start to finish of the blooming process and while this motion is not a passive system, it shows how a larger surface can be deployed using localized actuation. The second biological precedent is the conifer cone, which demonstrates a functional assembly capable of passive, repeatable motion. The material configuration of the conifer cone is applied directly to that of the wood veneer composite for the creation of a hygroscopic mechanism.

FIG. 3 TAXI MOVEMENT
As an example of taxis movement within plants, mycelium shows guided movement toward nutrients. If nutrients are not found, the movement of the plant redirects to continue searching.
Photo retrieved from: Leland, Beau. October 28, 2015. http://jarofgrasshoppers.com/mycelium-running/.

FIG. 4 PHOTOTROPISM
Tropic behavior, as is shown by the phototropic plant in the above image, is growth of a plant towards an environmental stimuli.
Photo retrieved from: Tropism. In Plant Life. http://lifeofplant.blogspot.ca/2011/01/tropisms.html.

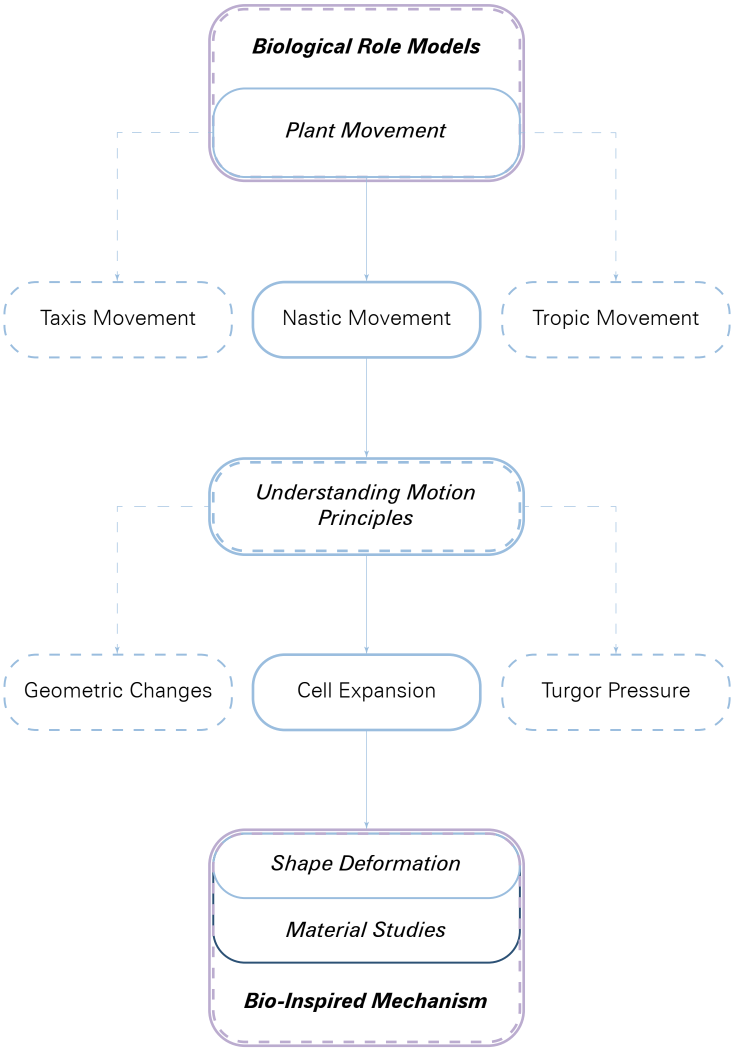

FIG. 5 BIOMIMETICS TO ARCHITECTURE
The diagram demonstrates the methodological translation of performance qualities shown by biological organisms into an architectural mechanism.

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[18] Guo, Qiaohang, Eric Dai, Xiaomin Han, Stephen Xie, Eric Chao, and Zi Chen. "Fast nastic motion of plants and bioinspired structures." Journal of the Royal Society Interface 12, no. 110 (2015): 20150598.

## Case Study 1: IPOMOEA

### *Introduction*

Ipomoea occupy the largest genus of the Convolvulaceae family of flowering plants. They are known by a number of common names including morning glory, water convolvulus, sweet potato, bindweed, and moonflower. This genus is native to tropical and subtropical regions of the world and produces both annual and perennial herbaceous climbing plants. Incorporating a number of different species, all Ipomoea plants are characterized by funnel shaped, tubular flower buds, ranging from 4 - 6cm in length, and are distinguishable by their uniquely formed corolla, which merges the five lobes along their margins to form the symmetrical tube visible when the flower is in full bloom. The total blooming process of the Ipomoea flower begins in the morning, and is completed by mid-afternoon, thus demonstrating a cycle of transformation that takes place on a rapid time scale, in combination with multiple transformative stages during maturation and deployment of the bud[19].

### *Morphology and Shape Change*

The stages of deformation are a result of this singular corolla surface, which requires numerous stages of folding and bending to fully bloom. These multiple stages suggest that the flower is a highly refined mechanism that incorporates both locally adapted stiffness and varying cell orientation specific to location within the flower. This physiological structure of bud is composed of a thin layer of organic tissue known as the lamina, which makes up the structure of the corolla, and five thick, leathery, mid-petaline bands. The development of the bud during blooming begins with the bud-state. In this state the flower is helically curled into a tight package protecting the interior organs. While bound in this bud-state, the mid-petaline bands are wrapped clockwise around the exterior of the folded corolla, increasing in rotation angle as they extend from the base of the bud to the tip to maintain a continuous barrier of protection[20].

The start of the blooming process is triggered by growth of the corolla resulting in a sudden burst of the ribs wrapped around the bud. This process is knows as bud popping and begins the unfolding process at the start of blooming. During

FIG. 6 (FACING PAGE) IPOMOEA
Image of Ipomoea 'morning glory' when fully in bloom.

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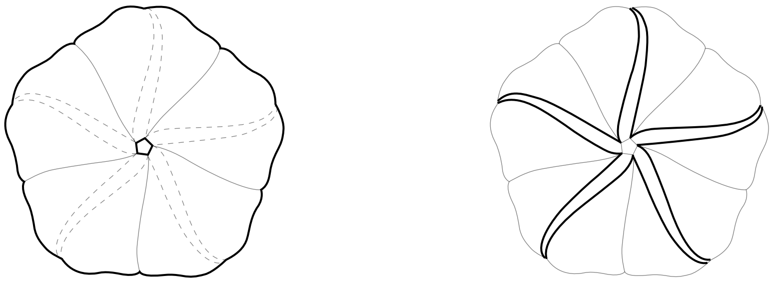
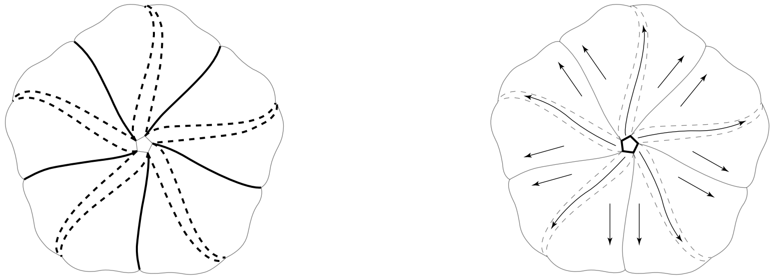
[19] "Ipomoea." Fine Gardening. Accessed December 26, 2017. http://www.finegardening.com/morning-glory-ipomoea.

[20] van Doorn, Wouter G., and Uulke van Meeteren. "Flower opening and closure: a review." Journal of experimental botany 54, no. 389 (2003): 1801-1812.



Corolla

Mid-petaline Bands



Mountain Ridge Fold —
Valley Ridge Fold - - -

Cell Orientation

FIG. 7 ANATOMY OF THE IPOMOEA
Diagrams demonstrate the anatomy of the Ipomoea bud when fully in bloom. Diagrams adapted from information retrieved from: Schleicher, Simon. Bio-inspired compliant mechanisms for architectural design: transferring bending and folding principles of plant leaves to flexible kinetic structures. 2015.

this intermediate state, the bands unfold outward in a slow helical rotation, made possible by rapid and significant loss of turgor pressure along the edges of the bands, releasing stored elastic potential energy. The specific orientation of cells also plays an important role in the multi-transformative behavior of the Ipomoea. Within the bands, the cells orient themselves along the slight ‘s’ shape, while the cells in the corolla are oriented parallel to the crease. These morphological characteristics allow for the folded bud to deploy in a helix without tearing or other damage. Once fully blossomed, the conical shape develops into double curvature around the brim of the flower. The slightly rolled brim allows the flower to gain structural stability and support the weight of pollinators. The final transformation of the bud takes plays during its decay. The corolla and midribs fold the flower in on itself so the result is a decayed curl[21, 22, 23].

Overall, this biological structure provides a precedent for morphological changes that undergo multiple stages of deformation from start to finish of the transformation. This precedent is also an example of morphological configurations that utilizes local motion to produce physical changes across a larger surface, though these are triggered by active systems within the organism. The case study of the Ipomoea influenced both the formal and functional outcome of the hygroscopic mechanism produced in this thesis by providing a means of generating an intermittently expanding conical shape for the manipulation of airflow. The following precedent of the conifer cone more directly influences the performance of the wood veneer composite itself, demonstrating a way in which bilayer configurations can be used to amplify the dimensional expansion of the wood veneer when in the presence of moisture.

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[21] Koning, Ross E. “The role of ethylene in corolla unfolding in Ipomoea nil (Convolvulaceae).” American journal of botany (1986): 152-155.

[22] Ma, Ying, and Junqi Sun. “Humido-and thermo-responsive free-standing films mimicking the petals of the morning glory flower.” Chemistry of Materials 21, no. 5 (2009): 898-902.

[23] van Doorn, Wouter G., and Uulke van Meeteren. “Flower opening and closure: a review.” Journal of experimental botany 54, no. 389 (2003): 1801-1812.

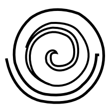


FIG. 8 PLAN VIEW OF BUD-STATE
Diagram demonstrates tight helical curl of the Ipomoea in its bud-state prior to bud-popping.

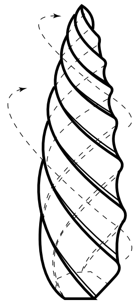


FIG. 9 IPOMOEA BUD-STATE
Diagram demonstrates tight helical curl of the Ipomoea in its bud-state prior to bud-popping.

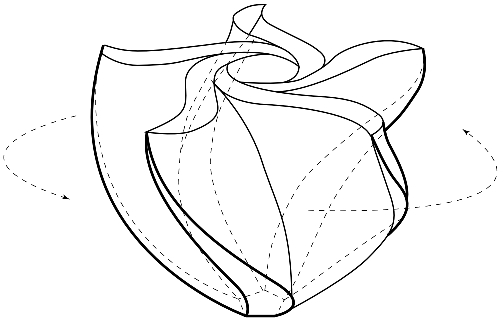


FIG. 10 IPOMOEA PARTIAL BLOSSOM
Diagram demonstrates the helical unwinding of the Ipomoea after bud-popping as elastic potential energy is released from the bands.

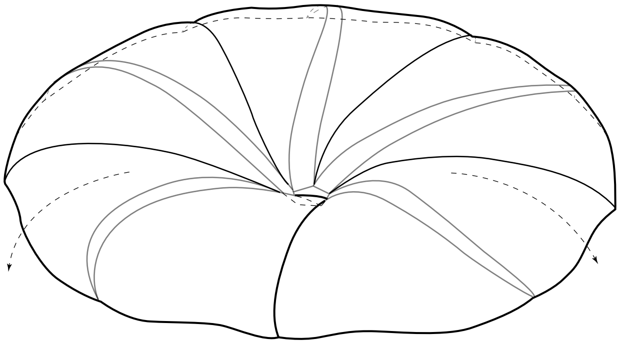


FIG. 11 IPOMOEA FULL BLOSSOM
Diagram demonstrates the ipomoea in its fully blossomed state with double curvature providing structural stability along the outer edge.

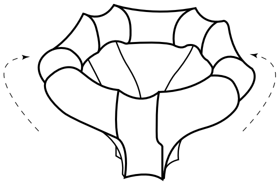


FIG. 12 IPOMOEA DECAY
Diagram demonstrate the ipomoea decay of the bud, where the corolla and mid-petaline bands fold to inward.

## Case Study 2: CONIFER CONE

### *Introduction*

Unlike the Ipomoea flower, which uses active systems to perform physical transformations, the biological material of the mature conifer cone is made up of dead cells, thus the structural transformations are demonstrative of nastic plant movement and are both repeatable and passive. The conifer cone is an organ that contains the reproductive structures of their larger plant hosts. Seed production involves the fertilization of female conifer cones by their male counterparts. For this process to take place, the female cone first opens to allow for fertilization, and then re-closes to allow the fertilized ovule to develop into a seed. Upon maturation of the seed, the female cone exhibits unique behavior of specific ecological adaptation that allows for distribution of the seeds to take place in optimal environmental conditions. The environmental trigger of the conifer cone is the presence of humidity, which causes the cone to close

FIG. 13 CONFIER CONE IN AN OPEN vs CLOSED STATE
Images demonstrate the change of the conifer cone in both a closed (humid) and open (dry) state.

FIG. 14 (FACING PAGE) CONIFER CONE
Image retrieved from: https://commons.wikimedia.org/wiki/File:Pine_cone_on_pine_tree.jpg

in wet weather and open in dry weather. The purpose of which is to ensure long-range seed dispersal for continued species growth. The ability to exhibit transformative behavior within dead tissue as a result of water absorption makes the conifer cone a precedent for passive, independent actuation in response to environmental stimuli[24].

### *Morphology and Shape Change*

The repeatable deformations of the cone scales, which are made of only dead tissue, are demonstrative of motion produced from a morphological relationship between structural composition and water. As such, the passive motion completed by the individual scales of the cone is driven by a humidity gradient between the cells at the tissue level and the ambient air. As water is absorbed and expelled at a local cellular level, the scale experiences global dimensional changes[25]. This global motion is made possible due to the structural morphology of the individual scale. The inner surface of the scale is composed of bundled sclerenchyma fibers, which are a hard woody fibrous material that forms the structural support of the cone. Alternatively, the outer surface of the scale is composed of sclerid cells, which are a reduced form of the sclerenchyma cells of the inner layer. Having thick cellular walls, the sclerid cells also bundle together to form durable structures[26]. The mechanics of bending are a result of alternating orientation of these fibers into two distinct layers, where the sclerenchyma fibers are oriented along the cells to restrict elongation under wet conditions, while the sclerid cells are oriented around the cells, promote expansion. This structural assembly is known as a bilayer configuration, where the inner fibers resist cellular expansion, while the outer fibers allow it. Swelling of the outer layer applies pressure to the inner layer, restricting its planar expansions and forcing the scales inward for a global closure of the cone. The sequence of deformation begins with water falling toward the center of the cone, where an inner portion of the cone called the bract scale absorbs it. Water absorbed into the bract scale is then distributed into the internal fibers, where cellular expansion results in structural transformation. Length and breadth of the scale when wet can increase by 5.5% as compared to the length and breadth of the scale when dry[27].

The nastic motion of the conifer cone provides a precedent for a structural assembly of materials capable of achieving repeatable transformations without damage or loss of functionality, that are additionally triggered by environmental stimuli. The bilayer configuration presented within the morphology of the cone scale is replicated within the hygroscopic mechanism produced in this thesis. The active layer of the conifer scale, is replicated using wood veneer, while the passive/restrictive layer is replicated using a non-hygroscopic plastic PET material. The hygroscopic mechanism produced using this configuration is capable of multiple transformations without degradation of the material or its responsive performance to environmental stimuli.

[24] Song, Kahye, Eunseop Yeom, Seung-Jun Seo, Kiwoong Kim, Hyejeong Kim, Jae-Hong Lim, and Sang Joon Lee. "Journey of water in pine cones." Scientific reports 5 (2015): 9963.

[25] Song, Kahye, Eunseop Yeom, Seung-Jun Seo, Kiwoong Kim, Hyejeong Kim, Jae-Hong Lim, and Sang Joon Lee. "Journey of water in pine cones." Scientific reports 5 (2015): 9963.

[26] Dawson, Colin, Julian FV Vincent, and Anne-Marie Rocca. "How pine cones open." Nature 390, no. 6661 (1997): 668-668.

[27] Song, Kahye, Eunseop Yeom, Seung-Jun Seo, Kiwoong Kim, Hyejeong Kim, Jae-Hong Lim, and Sang Joon Lee. "Journey of water in pine cones." Scientific reports 5 (2015): 9963.

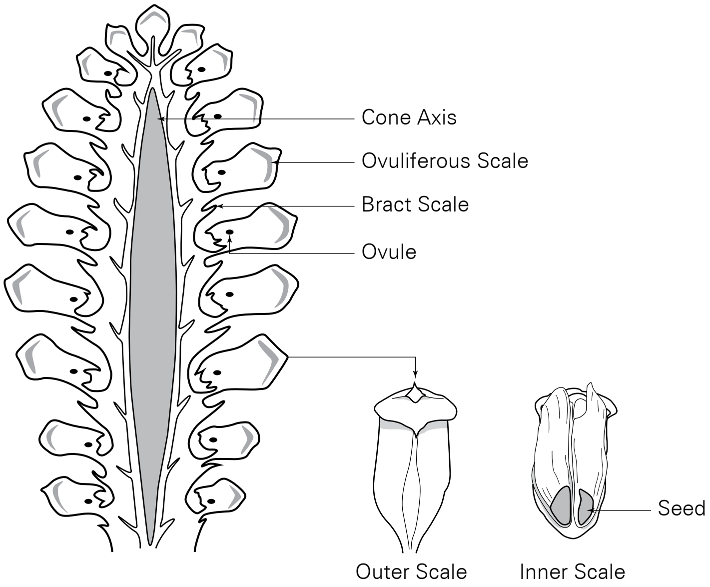


FIG. 15 CONIFER CONE ANATOMY
Diagram demonstrates the morphological structure of the conifer cone in section, as well as the location of the seeds in relation to a single scale.
Diagram developed from information retrieved from: “Common Pine Tree Features.” Pine Characteristics. https://projects.ncsu.edu/project/dendrology/index/plantae/vascular/seedplants/gymnosperms/conifers/pine/pinus/generic/generic.html.

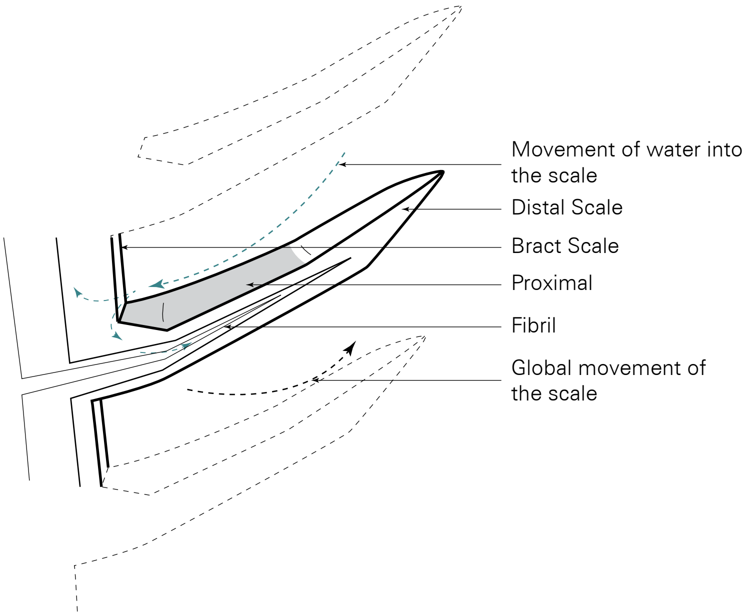


FIG. 16 MOVEMENT OF WATER WITHIN THE SCALE
The diagram demonstrates the flow of water and its absorption pattern into the scale.
The global movement within the diagram demonstrates the direction of the global movement of the scale.
Diagram adapted from information retrieved from: Song, Kahye, Eunseop Yeom, Seung-Jun Seo, Kiwoong Kim, Hyejeong Kim, Jae-Hong Lim, and Sang Joon Lee. “Journey of water in pine cones.” Scientific reports 5 (2015): 9963.

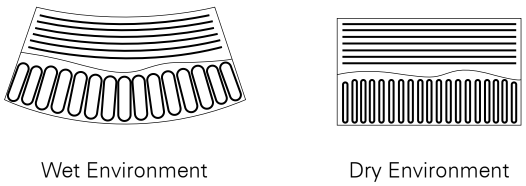


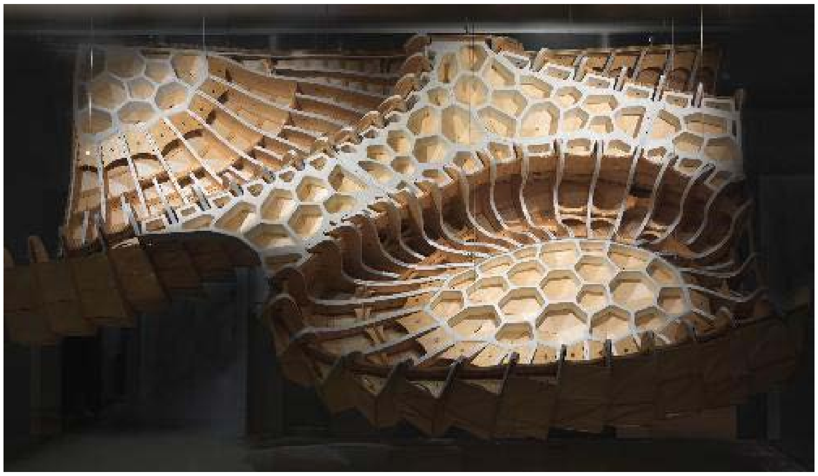
FIG. 17 CELLULAR EXPANSION
The diagram demonstrates the expansion of the microfibrils within a single scale as a result of moisture uptake resulting in the global closure of the conifer cone to protect the plants seeds.

FIG. 18 A) HYGROSCOPE: METEOROSENSITIVE MORPHOLOGY
Completed installation with open apertures.

FIG. 18 B) HYGROSCOPE: METEOROSENSITIVE MORPHOLOGY
Completed installation with closed apertures.
Images retrieved from: "HygroScope: Meteorosensitive Morphology." Achimmenges.net, www.achimmenges.net/?p=5083.

The creation of functional mechanisms, inspired by the conifer cone, and the assembly of these systems into a passive adaptive design has been demonstrated by Achim Menges, founding director of the Institute for Computational Design, and Steffen Reichert in their installation of the, "HygroScope: Meteorosensitive Morphology" designed in 2012 at the Centre Pompidou in Paris (Fig. 18 through 19). The design deploys the strategies of the conifer cone to allow for physical programming of a material system that produces responsive change without the requirement of mechanical or electronic input. While the design is permanently fixed within the Centre Pompidou, the structure is enclosed within a glass case and the materials movement is demonstrated through humidifiers programmed with an accelerated database of the relative humidity of Paris. The responsive capacity of the material is embedded within the wood, and is the product of a functional relationship between the materials physical properties and the directionality of the grain. The system is composed of a combination of quarter sliced maple veneer and synthetic composites. To produce the apertures, the composite layers are manufactured to shape and assembled into four to seven sided polygons that open and close to a central point. Alongside these are rectangular apertures mounted on one side to allow for a flap-like motion. The movement of the composites is calibrated to open when there is an increase in relative humidity within the display case and close when there is a decrease. This constant passive motion and attainment of equilibrium by the material suggests how an architecture based on behavior intrinsic to

FIG. 19 HYGROSCOPE: METEOROSENSITIVE MORPHOLOGY
Complete installation of the performative system within the Centre Pompidou, showing front (top) and back (bottom).
Images retrieved from: Meguerditchian, Georges , and Achim Menges. HygroScope - Meteorosensitive Morphology, National museum of modern art/ Industrial Design Centre. 2012. https://www.centrepompidou.fr/cpv/resource/c7GpBeA/r4KMoM.



the material can mediate between interior and exterior conditions rather than separating them. The overall performance of the wood composites to relative humidity connects the observer to environmental phenomena that is always present but usually remains unnoticed through daily interaction of body with environment. Therefore, work such as this can promote a renewed sense of awareness and provide an example for new kinds of interaction that can be created between the built form and the natural environment[28]. This method of bioinspired application has been additionally demonstrated by Achim Menges, Oliver David Krieg, and Steffen Reichert, in their production of the "HygroSkin - Meteorosensitive Pavilion" in 2013 for the ArchiLab exhibition located at the FRAC (Fonds Regional d'Art Contemporain) Centre in France (Fig. 20 through 21). The project demonstrates how the structure of the conifer cone can be applied to create an artificial composite for application as a highly adaptive architectural system. The assembly of conical panels, which have been produced through the use of plywood sheets and foam, form the overall volume of the pavilion while the hygroscopic elements, arranged into clusters at the center of each panel, are calibrated to operate within the atmospheric conditions local to the location of the pavilion. The assembly of the mechanisms within each panel demonstrates how an architectural facade can respond to changes in both the interior and exterior environments. This is seen through behavior of the facade changing as a result of changes to local atmospheric conditions, including relative humidity and temperature as affected by radiation and obstructions[29]. Both the "Hygroscope: Meteorosensitive Morphology" installation and the "Hygroskin - Meteorosensitive Pavilion" provide this thesis

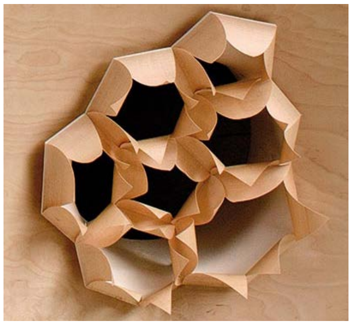


FIG. 20 A) HYGROSKIN: METEOROSENSITIVE PAVILION
Completed installation with open apertures.

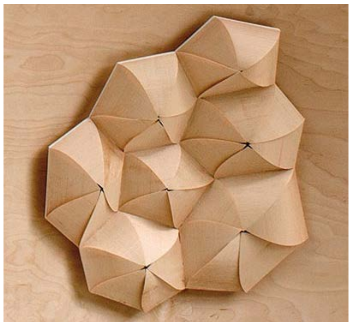


FIG. 20 B) HYGROSKIN: METEOROSENSITIVE PAVILION
Completed installation with closed apertures.

FIG. 21 HYGROSKIN: METEOROSENSITIVE PAVILION
Complete installation of the performative system, showing exterior (top) and interior (bottom).
Images retrieved from: "HygroSkin-Meteorosensitive Pavilion / Achim Menges Architect + Oliver David Krieg + Steffen Reichert" 09 Sep 2013. ArchDaily. Accessed 7 Dec 2017. https://www.archdaily.com/424911/hygroskin-meteorosensitive-pavilion-achim-menges-architect-in-collaboration-with-oliver-david-krieg-and-steffen-reichert/. ISSN 0719-8884

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[28] Menges, Achim, and Steffen Reichert. "Performative Wood: Physically Programming the Responsive Architecture of the HygroScope and HygroSkin Projects." Architectural Design 85, no. 5 (2015): 66-73.

[29] Reichert, Steffen, Achim Menges, and David Correa. "Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness." Computer-Aided Design 60 (2015): 50-69.

with directly applicable demonstrations of how the extrapolation of biological structure into the bilayer composite can be assembled into architectural systems for the moderation of environment. However, the "Hygroskin - Meteorosensitive Pavilion" resounds more with the research of this thesis as it applies the hygroscopic elements to a formal envelope, which can be occupied and whose envelope is directly impacted by the cross section of interior and exterior environments. Where the work of this thesis branches apart from this precedent is in the formal coupling of the hygroscopic elements with additional materials to produce a mechanism that can induce forced airflow across the facade through the introduction of Venturi tube principles. Coupling of additional materials for increased functionality is seen more explicitly within the prototype, "Hygro" completed in 2013 by Efilena Baseta, an Architect Engineer who holds a masters degree in Advanced Architecture from the Institute for Advanced Architecture of Catalonia (IAAC) (Fig. 22 through 23). This prototype, which is also made from a wood veneer composite, was developed to explore the kinetic energy produced by nature without mechanical assistance. The additional functionality is provided by the inclusion of plastic mesh between the two layers of veneer inspired by fog collectors. As the relative humidity of the prototypes environment increases, the movement of the wood stretches the mesh, which then condenses the humid air to subsequently collect water. Through this design, a smart component has been created that can both respond to environmental changes as well as draw utility from the triggering environmental condition[30]. While this precedent did not formally apply to the adaptive mechanism produced within this thesis, the way in which additional materials, as well as a structural latticework was applied to the design was informative to the overall assembly of the final system completed within this study.

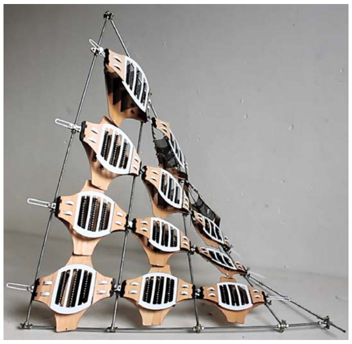

FIG. 22 A) HYGRO
Completed installation with open apertures.

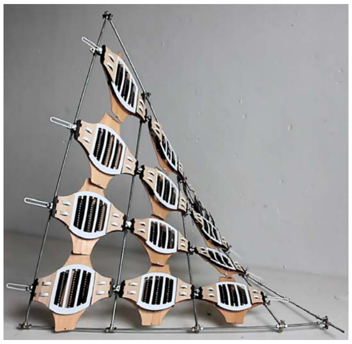

FIG. 22 B) HYGRO
Completed installation with closed apertures.

FIG. 23 HYGRO
Image demonstrating the incorporation of materials within the completed responsive system.

Photos retrieved from: Baseta, Efilena . "Hygro." Accessed November 2017. http://cargocollective.com/efilenabaseta/Hygro.

Hygroscopic motion and the formation of a composite system is also not exclusive to the material of wood. Hygromorphic response is also prevalent in bacteria spores as demonstrated by Carolina Ramirez-Figueroa, Luis Hernan, Aurelie Guyet, and Martyn Dade-Robertson from Newcastle University in their work titled, "Bacterial Hygromorphs: Experiments into the integration of soft

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[30] Baseta, Efilena . "Hygro." Accessed November 2017. http://cargocollective.com/efilenabaseta/Hygro.

technologies into building skins" (Fig. 24). In their work they demonstrate how a hygromorphic material composite can be constructed from the attachment of bacterial spores to an environmentally passive layer. Using this method, the authors speculate how low complexity actuators, which convert energy held within evaporating water, can be translated into mechanical work. The spore, which is a dormant and resistant stage of development that allows the bacteria to preserve its biological integrity and genetic material to survive adverse environmental conditions, expands or shrinks in response to relative humidity through an uptake of moisture into the cell membrane. While the overall configuration into a bilayer composite may be the same as a timber hygromorph, the bacterial spores provide unique challenges and opportunities for use. Significant challenges include the production of the spores themselves, which require a specialized understanding of their properties for productive manipulation, and the production process must take place within laboratory conditions. An additional challenge is the scale discrepancy between the

FIG. 24 BIOLOGICAL HYGROMORPHS
Application of bacterial spores onto passive plastic strips result in a contraction of the strip when in the presence of moisture.
Photo retrieved from:Ramirez-Figueroa, C., L. Hernan, A. Gnyet, and M. Dade-Robertson. "Bacterial Hygromorphs: Experiments into the integration of soft technologies into building skins." 2016.

FIG. 25 BLOOM
Using thermobimetals, rather than hygroscopic materials, the installation passively responds to the thermal environment through differentiating coefficients of heat expansion.
Photo retrieved from: Alison Furuto. "Bloom / DO|SU Studio Architecture" 11 Mar 2012. ArchDaily. Accessed 7 Dec 2017. <https://www.archdaily.com/215280/bloom-dosu-studio-architecture/> ISSN 0719-8884

[31] Ramirez-Figueroa, C., L. Hernan, A. Gnyet, and M. Dade-Robertson. "Bacterial Hygromorphs: Experiments into the integration of soft technologies into building skins." Proceedings of ACADIA 2016 - Posthuman Frittiert: Data, Designers and Cognitive Machines, Michigan, Ann Arbor. Association for Computer Aided Design in Architecture, (2016). 244-253.

spore actuator and the intended architectural application. However, despite these problems, bacterial spores are much more responsive than their timber counterparts and respond to both relative humidity and ambient humidity on a much faster time scale. Additionally, the spores offer enhanced programmability in terms of their ability to be patterned within the active layer to act against the passive layer. The prototypes explored within this paper provide useful approaches to the design of living and semi-living materials that could allow for highly programmable, soft, low-maintenance, architectural components[31].

As there are biological organisms that passively respond to different environmental stimuli, there are materials that respond to other parameters of the thermal environment. An example of this is found within thermobimetal composites, which are the lamination of two metals together with different coefficients of thermal expansion so that the produced combination deforms when heated or cooled. Due to the varying expansion coefficients, as the material composite is heated, one side will expand more than the other, producing a curved or curled metal segment. Current applications of thermobimetals can be found in thermostats, ventilation flaps, and fire protection flaps, but this system also offers potential for application within adaptive building skins[32]. DOSU Studio Architecture demonstrated the potential application of thermobimetals in the architectural installation, "Bloom" at the Materials and Application Gallery in Los Angeles (Fig. 25). The project combined material experimentation, structural innovation, and computational form and pattern making into an environmentally responsive installation with a surface of 14,000 thermobimetal tiles. The tiles curl away to expose perforations in the sculptural element when exposed to changes in ambient temperature of heat from the sun. This project aimed to demonstrate that although a thermobimetal composite can be generated from any two compatible sheet metals, the combination of different coefficients of expansion, and material thickness can produce a wide variety of different deflections[33]. Through the two precedents of the bacterial hygromorphs and the thermobimetal actuators, it is demonstrated that passive performance is not limited to a singular material, and other materials may respond to other parameters of the environment. As such, while this thesis focuses only on the motion produced by wood veneer in response to environmental humidity, coupling of responsive materials could produce a system capable of multiple changes to a wider range of environmental variability.

The aforementioned precedents all demonstrates ways in which the passive mechanisms of motion used by biological organisms can be transferred into an architectural application with the intent to improve performance. Further work within this thesis traces the steps taken by Steffen Reichert for the functional translation of morphological structure from the conifer cone into a wood veneer composite for architectural application. Following this is an exploration, through the design of a mechanism, into the ways in which the utility of hygroscopicity can be used to produce a responsive facade capable of mediating between the interior and exterior conditions passively.

### *Critics*

Though the continual investigation of natural systems will provide an increased awareness of the environment and will provide a better understanding of its interrelations, biomimetics as a tool and nature as a source of knowledge will not automatically produce good architecture. Rather the same process of testing

[32] Sung, Doris Kim. "Skin Deep: Breathing Life into the Layer between Man and Nature." AIA Report of University Research 3 (2007).

[33] Furuto, Alison. "Bloom / DO|SU Studio Architecture". ArchDaily (2012). <https://www.archdaily.com/215280/bloom-dosu-studio-architecture/> ISSN 0719-8884

[34] Pawlyn, Michael. "Biomimicry in architecture." Vol. 15. London: Riba Publishing, 2011.

and experimentation, which took place through the evolutionary process, will be necessary for proper intellectual transfer. Michael Pawlyn, as an architect noted for his work in biomimetics, warns against the dangers of romanticizing nature in his work, “Biomimicry in Architecture”. Pawlyn argues that the vast array of productivity found in nature was the result of selection, refinement, and genetic variability where the fittest are selected over time, and this process should not be extrapolated to literally into cultural development. Additionally, Pawlyn asserts that while the word ‘natural’ often implies correctness, certain aspects of nature, such as parasitic characteristics, shouldn’t be emulated, and this requires a critical understanding of biomimetic implications[34]. Additional criticisms of the biomimetic field can be found within the work of architect Petra Gruber, who criticizes the field for its lack of underlying design theory. This, Gruber states, leads to inconsistencies in the degree to which biological methods and strategies are transferred to the architectural discipline. This is evident within approaches to environmental design such as biomorphology, a field often grouped with biomimetics, but is in actuality the translation of only biological form rather than the communication of systems processes and functionality[35]. This is also found within the field of geomorphism, which is the use of greenery in combination with analogy between urban and natural spaces. The problem with this approach is that it lacks real consciousness towards nature as a precedent for design, but is often included within the field of biomimetics[36]. In order to increase the proficiency of biomimetics in architecture, research into the peripheries of both architecture and biology is necessary to identify overlapping content. Gruber Argues that in addition to this, increased regional freedom and stronger global environmental regulation would allow biomimetics to grow as a developing field. Experimentation without building constraint, as asserted by Gruber, could allow for further innovation and better overall awareness of natural and built environments[37]. Improved design theory should also include philosophical principles, which govern not only our systems of production but also out socio-cultural desires. The viability of biomimetics requires the reorganized and more complete establishment of biomimetic principles within both design and culture if the outcome is to be social and physical integration with nature[38].

[35] Gruber, Petra. “Biomimetics in Architecture.” Springer Wien, (2010).

[36] Portoghesi, Paolo. “Nature and architecture.” (2000).

[37] Gruber, Petra. “Biomimetics in Architecture.” Springer Wien, (2010).

[38] Mathews, F. “Towards a Deeper Philosophy of Biomimicry.” Organization & Environment 24, no. 4 (2011): 364-87. doi:10.1177/1086026611425689.

# PASSIVE ENVIRONMENTS

## *Comfort Models*

In developing a facade that is capable of controlling comfort through articulation of both the internal and external thermal environments, it is important to understand how comfort is measured within typical interior spaces, and how the facade can enact change within the interior space by manipulating external environmental conditions.

The main role of the envelope, which consists of vertical (facade) and horizontal (roof) components, is to lessen the impact of environmental fluctuations on occupants by providing a median for encapsulating a thermally viable interior environment. In order to provide universally acceptable, thermally comfortable spaces, comfort models are industry tools used to establish parameters for designing the internal thermal context of spaces so that the majority of occupants are satisfied with the internal environment[1]. The first standardized approach is the steady-state model developed by Povl Ole Fanger, an expert in the field of thermal comfort. This model was developed for application within air-conditioned spaces based on a heat balance model of the human body. Under Fangers model, thermal comfort within a given space is designed based on the prediction of mean thermal satisfaction of a group of people and their respective percentage of dissatisfaction. Known as the Predicted Mean Vote method, Fangers work became the basis of ASHRAE Standard 55, the most common standard for internal building comfort[2]. While this standard is widely applied, it assumes all human comfort lies within a defined zone of comfort averages that is acceptable for the general population. In this model, interior thermal comfort takes place irrespective of location and individual adaptation[3] (Fig.1). The second approach to designing comfort is known as the Adaptive Approach, which outlines that in occupant controlled, naturally conditioned spaces, the thermal response of the body's metabolism, and thus comfort, are affected by outdoor climate (Fig.2). The adaptive model was developed from field studies performed by Nicol, Humphreys, Auliciems, de Dear, Brager, and Cooper[4,5,6,7,8], on naturally ventilated buildings and was only first included in the ASHRAE Standard 55 in 2004 as an optional method for evaluating naturally ventilated buildings. Within the adaptive model, thermal comfort is recognized as a much more complex, dynamic spatial condition that is influenced by

[1] "Standard 55-2013: Thermal Environmental Conditions for Human Occupancy" ASHRAE. Atlanta USA, 2013.

[2] Rupp, Ricardo Forgiarini, Natalia Giraldo Vásquez, and Roberto Lamberts. "A review of human thermal comfort in the built environment." Energy and Buildings 105 (2015): 178-205.

[3] La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.

Additional information can be found at the following sources:

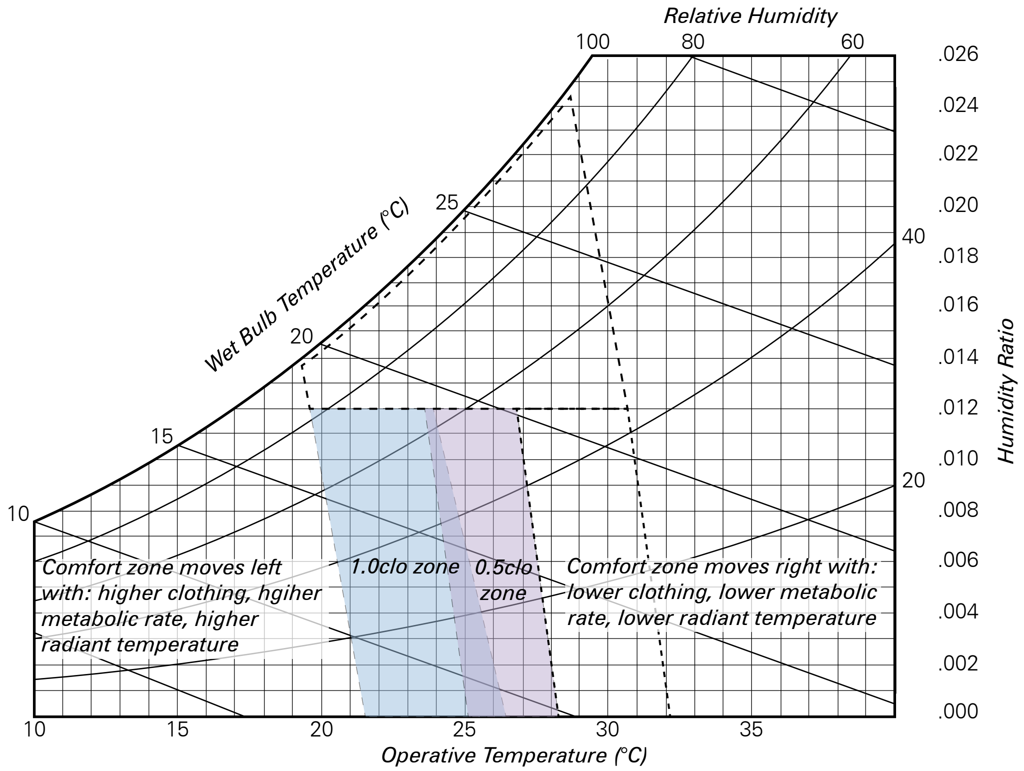
[4] Nicol, J. Fergus, and Michael A Humphreys. "Thermal comfort as part of a self-regulating system." (1973): 174-179

[5] Nicol, J. Fergus, and Michael A. Humphreys. "Adaptive thermal comfort and sustainable thermal standards for buildings." Energy and buildings 34, no. 6 (2002): 563-572.

[6] Humphreys, M. A., H. B. Rijal, and J. F. Nicol. "Updating the adaptive relation between climate and comfort indoors; new insights and an extended database." Building and Environment 63 (2013): 40-55.

[7] Auliciems, A. "Towards a psycho-physiological model of thermal perception." International Journal of Biometeorology 25, no. 2 (1981): 109-122.

[8] De Dear, Richard J., Gail Schiller Brager, James Reardon, and Fergus Nicol. "Developing an adaptive model of thermal comfort and preference/discussion." ASHRAE transactions 104 (1998): 145.



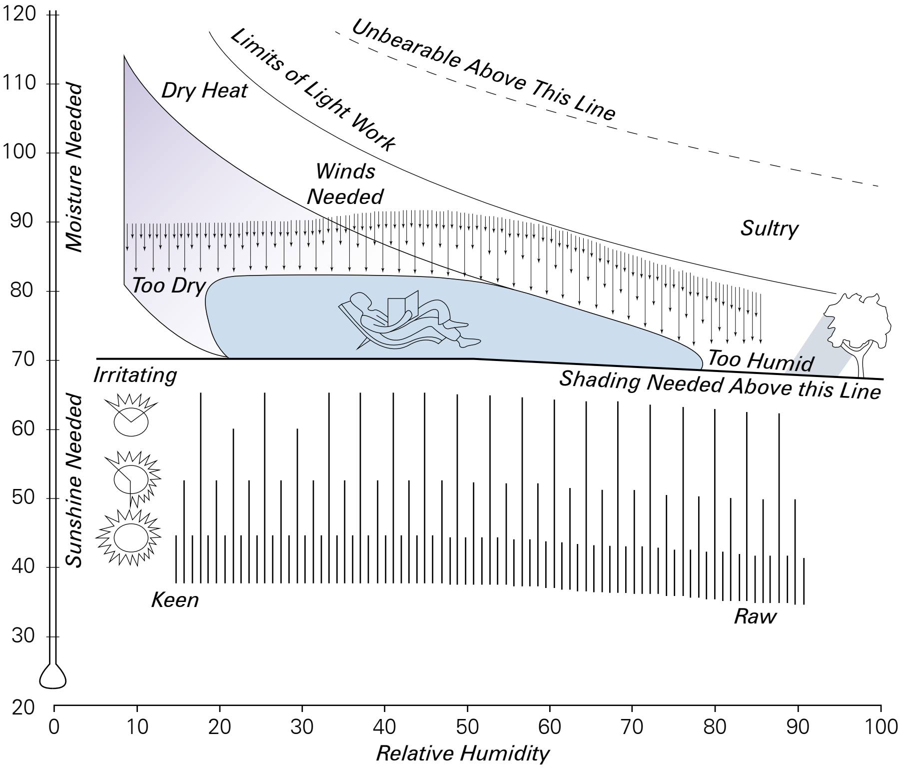


FIG. 1 (TOP) GRAPHIC COMFORT ZONE
Diagram Adapted from figure 5.3.1 of ASHRAE Standard 55 2013 for the acceptable range of operative temperature and humidity for spaces that have metabolic rates between 1.0 and 1.3 met, and clothing is between 0.5 clo and 1.0 clo, demonstrates how the average of comfort is placed into an optimal range with the aim of achieving 80% satisfaction.

FIG. 2 (BOTTOM) GRAPHIC COMFORT ZONE
Diagram adapted from Olgyay's building bioclimatic chart demonstrates how environmental factors play a fundamental role in the sensation of comfort and therefore the body is capable of achieving comfort within a much larger thermal range.
Diagram retrieved from: Olgyay, Victor. "Design with climate: bioclimatic approach to architectural regionalism". Princeton University Press, (1963).

numerous internal and external factors such as temperature, humidity, and air velocity. As such, it is understood that through physiological changes and behavioral adjustments, occupants who are occupying naturally ventilated spaces can withstand a significantly wider range of temperatures that are considered both acceptable and comfortable. This is because the individual perception of comfort is also altered by a variety of personal variables influenced by the natural environment. These include; recent thermal experience, changes to clothing, availability and use of control options, and shifts in expectation based on current outdoor climate. In addition to this, internal bodily adjustments resulting from individual metabolic rates, allow the body to achieve comfort in a much larger range of temperatures[9]. While the most common perception of the ideal thermal landscape is monotonous consistency, which goes unnoticed by occupants, changes in the perception of the thermal environment help to connect the human body with the daily rhythms of the natural world[10].

### *Passive Ventilation*

As an alternative strategy to mechanically controlled internal climates, passive ventilation offers a means of intentionally creating pressure differentials or using natural thermal buoyancy to circulate air into and out of internal spaces. The purpose of passive cooling strategies is to maintain thermal comfort either through the removal of hot air from interior environments or from increased air motion. The principles of natural ventilation are based on the buildings tendency to try and attain equilibrium with the external environment, which results in air movement from zones of high pressure to zones of low pressure[11]. This movement is affected by solar radiation as it impacts the temperature of the earth at different rates, and the generated motion, on both a local and global scale, is driven by imbalances of pressure resulting from regional land to water masses, temperature, buoyancy, and obstructions[12]. Due to these inconsistent patterns of flow, buildings which use passive ventilation strategies will not always experience constant flows of energy, and will more likely experience a daily rhythm resulting from a general pattern of dynamic, non-static external behavior of the local macroenvironment. Passively controlled thermal environments may also not experience an actual temperature drop during periods of increased air flow and because of this the thermal environment is managed through the increase or decrease of air movement; increasing comfort through the elevation of sweat evaporation from the surface of the skin[13].

The principles of passive ventilation generated by pressure differentials based on the common fluid dynamics fundamentals of Bernoulli's Principle and the Venturi Effect are focused on within this thesis for their capacity to be enacted through the facade. First published in 1738 in the book "Hydrodynamica", Bernoulli's principle is derived from the Law of Conservation of Energy, which states that the total energy of an isolated system for a given frame of reference will remain constant. Bernoulli's principle therefore concludes, that in a given field of flow, any increase in velocity is simultaneously accompanied by a reduction in pressure because the overall energy of the system is unable to increase or decrease, but can rather alternate conditions. The Italian physicist Giovanni Venturi applied this principle to the Venturi tube, which is, "a tube whose cross-section initially diminished in area until it reaches a minimum, then increases again"[14]. The Venturi tube is composed of three parts; the contraction section, the throat section and the diffusion section[15] and its effect on fluid dynamics is a result of fluids tendency to equalize pressure across two or more

[9] Lovel, Jenny. "Building envelopes: an integrated approach." Princeton Architectural Press, 2013.

[10] La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.

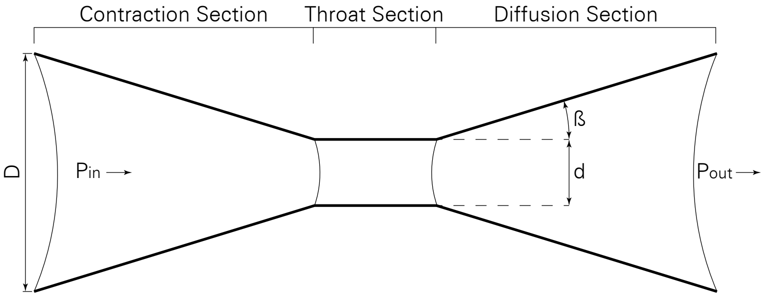
[11] Walker, Andy. "Natural ventilation." National Renewable Energy Laboratory (2010).

[12] La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.

[13] La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.

[14] Clancy, L. J. "Aerodynamics (Chapter 3)." Topics on pressure fields (1975): 22-59.

[15] Zhang, J. X. "Analysis on the effect of venturi tube structural parameters on fluid flow." AIP Advances 7, no. 6 (2017): 065315.



| | |
|---|---|
| ß | Diffusion Angle |
| D | Venturi Tube Inlet and Outlet Diameter |
| d | Throat Section Diameter |
| Δp | Inlet and Outlet Pressure Difference |
| | Contraction Ratio: Ratio between diameter of inlet versus diameter of outlet |

FIG. 3 (LEFT) VENTURI TUBE STRUCTURE
Diagram shows the three sections of the Venturi tube and significant variables affecting its performance.
Diagram adapted from information retrieved from: Zhang, J. X. "Analysis on the effect of venturi tube structural parameters on fluid flow." AIP Advances 7, no. 6 (2017): 065315.

zones. Therefore, as fluid flows through the throat section, the constricted area of the cross section causes the fluid to accelerate while also resulting in a decrease in pressure. The Venturi tube can be used to purposefully establish regions of high speed and/or low pressure for more efficient airflow (Fig. 3)[16].

Implementation of passive ventilation strategies utilizing these principles can be historically observed in regions with hot and arid climates. The fluid dynamics laws described by Bernoulli's principle are demonstrated by windcatchers; an architectural device used to achieve comfort through a reduction in humidity by the production of increased airflow (Fig. 4). Evidence of windcatchers in use has been found to date back to Pharaonic periods, where the house of Nebamun, depicted in illustrations from his tomb made in the 19th dynasty (1300 BC), shows a windcatcher with two openings; where one opening was situated windward to capture cool air and the other faced leeward to draw air within the space by suction through the structure (Fig. 5). This configuration is the functional basis of Bernoulli's principles and demonstrates the ability to generate airflow through the purposeful creation of pressure differentials. The two most common types of wind catchers include the unidirectional windcatcher, and the multi-directional windscoop (Fig. 6). The windcatcher is characterized by a shaft situated on the northern side of a space extended above the structure with an opening at its end facing the prevailing wind. The size of the opening at the top of the shaft is determined by the average air temperature of the surrounding environment; where a smaller opening is used in warmer temperature to induce a more substantial pressure drop, and larger inlets are used in cooler environments. The multi-directional windscoop also follows these same principles but incorporates four openings at the top of the shaft to catch breezes from all directions. Air circulation using the windscoop can be adjusted through closing one or more of the scoops[17]. The design of the windcatcher and windscoop have also been adapted and implemented in many modern day buildings. A project with successful application of such is the BedZED development completed in 2002 by architect Bill Dunster who specialized in environmental design at the Architectural Association architecture school of London. The BedZED development, located in London England, is an environmentally friendly mix-use housing development incorporating live/

FIG. 4 TRADITIONAL WINDCATCHER
Image shows the traditional design of a multi-directional windscoop located in Dubai.
Image retrieved from: Javaheri, Alireza . Digital image. 99% Invisible . Accessed December 26, 2017. https://99percentinvisible.org/article/windcatchers/.

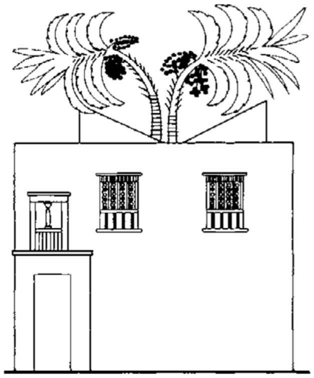


FIG. 5 WINDCATCHER OF NEBAMUN TOMB
Image shows a drawing of a house depicted within the tomb of Nebamun, illustrating the knowledge and use of windcatchers from 1300 BC.
Image retrieved from: El-Shorbagy, Abdel-moniem. "Design with nature: windcatcher as a paradigm of natural ventilation device in buildings." International Journal of Civil & Environmental Engineering IJCEE-IJENS 10, no. 03 (2010): 21-26.

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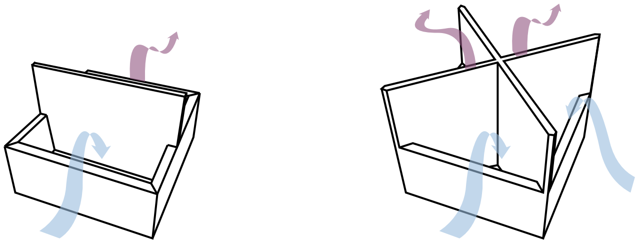
[16] Clancy, L. J. "Aerodynamics (Chapter 3)." Topics on pressure fields (1975): 22-59.

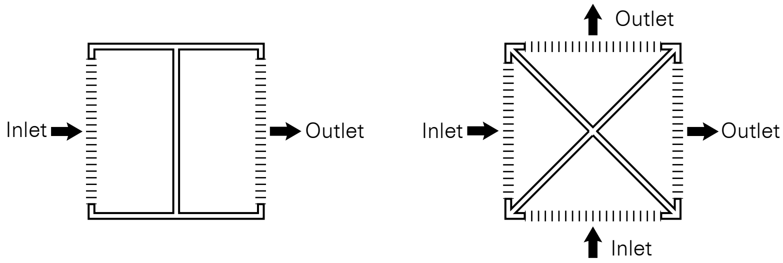
[17] El-Shorbagy, Abdel-moniem. "Design with nature: windcatcher as a paradigm of natural ventilation device in buildings." International Journal of Civil & Environmental Engineering IJCEE-IJENS 10, no. 03 (2010): 21-26.

FIG. 6 WINDCATCHER PRINCIPLES
Diagram demonstrates the functional principles of the unidirectional windcatcher and the multi-directional windscoop, demonstrating the relationship between the inlets and outlets in the production of airflow.



*Unidirectional Windcatcher Perspective Diagram*

*Multidirectional Windscoop Perspective Diagram*



*Unidirectional Windcatcher Plan Diagram*

*Multidirectional Windscoop Plan Diagram*

FIG. 7 BEDZED WINDCOWLS
Image shows the windcowls used within the BedZED development to passively cool interior spaces.
Image retrieved from: Andrews, Kate. Digital image. Inhabitat. January 17, 2008. Accessed December 26, 2017. https://inhabitat.com/bedzed-beddington-zero-energy-development-london/.

FIG. 8 KENSINGTON OVAL
Image shows the formal design of the Worrell, Weekes, and Walcott stand at the Kensington Oval allowing for passive ventilation across the tiered stands.
Image retrieved from: Richters, Christian. Digital image. ARUP Associates. 2007. Accessed December 26, 2017. http://www.arupassociates.com/en/projects/kensington-oval-barbados/.

work spaces, workspaces and retail units. The building is ventilated through the implementation of wind cows (Fig. 7), which were designed from first principles and further refined through the use of a wind tunnel. With a smaller funnel oriented towards the oncoming wind, the low-pressure zone within harnesses low velocity air, suctioning air into the building at a higher speed. At the same time, a larger outlet oriented in the opposite direction draws air out from the interior. The cowls generate sufficient pressure for the air to be ducted down into the building, delivering preheated air to each living room and bedroom while extracting air from the kitchen and bathrooms. The air is preheated on entry into the building through a heat recovery system that also prevents incoming and outgoing streams from mixing[18]. This passive application of Bernoulli's principles within a modern adaptation of the windcatcher is additionally demonstrated by the Worrell, Weekes, and Walcott Stand at the Kensington Oval designed by ARUP and completed in 2007. Located in Barbados, the formal conception of the design is driven by the occupant need for uninterrupted views, lighting, and comfort, which was achieved through passive ventilation and day lighting. The promotion of airflow through the stand is accomplished through the positioning of the stand in the direction of prevailing winds, while the form of the stand, as overlapping rings, ensures air flowing through the structure enters at an angle to provide optimum movement across the tiered stands. Air flow is drawn through the stand by the placement of vents and perforations at the rear section of the roof, ensuring the speed of the air increases by suction as it passes through the vents (Fig. 8)[19]. Adaptation of windcatcher principles has also taken place to produce active natural ventilation systems. The Zion National Park Visitors Centre in Utah, United States, created through collaboration by National Park Services and DOE's National Renewable Energy Lab in 2002, is an example of such. While the environmental conditions of the region are hot and dry during the summer and cold and icy in the winter, the building is cooled through cooltowers. Water vapour applied to the air at the top of a shaft cools the air, forcing it to fall by means of thermal buoyancy. As the air falls through the shaft, it increases in speed because of the condensed area available for flow

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[18] Twinn, Chris. "BedZED." Arup Journal 38, no. 1 (2003): 10-16.

[19] "The Worrell, Weekes and Walcott Stand, Kensington Oval, Bridgetown." All the information you need about steel construction, www.steelconstruction.org/design-awards/2008/commendation/the-worrell-weekes-and-walcott-stand-kensington-oval-bridgetown/.

within the tower and enters interior spaces by way of openings at the bottom of the tower. Other ventilation systems utilized within the building include natural ventilation through thermal buoyancy provided by situating clerestory windows to allow the escape of hot air while simultaneously drawing in cool air from windows placed lower in the rooms. Control of these passive systems, including the clerestory windows and the direction of distribution of air from the cooltowers, is automated through external mechanical monitor and control (Fig. 9)[20] . An additional modern utilization of Bernoulli's principle to passively cool spaces is seen within the Monodraught, who's technologies are akin to the windscoop with multiple inlets and controlled by automated systems measuring environmental factors to trigger change. These environmental factors are most commonly temperature or CO$_2$ levels, where change triggers either opening or closing of inlets respectively to allow airflow into interior spaces (Fig. 10). Air intake into the system can also be influenced by the end-user, who can override automation of the controls to adjust the systems performance to personal preference[21]. While individually, these precedents have little influence on the design of the hygroscopic mechanism, the fundamentals of air motion as described by Bernoulli's principle are demonstrated to be a means of successful passive cooling strategies that can be adapted into both passive and active systems.

In designing the exterior envelope studied within this thesis, understanding Bernoulli's principle and its successful manipulation of fluid flow through pressure variation within the Venturi tube is significant to the implementation of passive ventilation strategies within the facade. A comprehensive study completed by J. X. Jhang, analyzed the individual variables of the Venturi tube using Fluent software to understand which structural parameters influence most significantly the fluid flow and pressure variation through the Venturi tube. The variables studied included the contraction ratio, the diffusion angle, the ratio of the throat section length to diameter and the pressure differences between the inlet and outlet. Jhang outlined several assumptions at the start of experimentation in order to maintain consistency and accuracy. These include; the fluid used in experiments is incompressible, the physical properties of the fluid are constant, and the third, which states that the viscous dissipation, or the heat energy lost to transformation of the kinetic energy into internal energy, is negligible. The conclusion of this study found that within the Venturi tube, the minimum pressure, and therefore the greatest air velocity, takes place in the transitional area between the contraction section and the throat section. Additionally, the main structural parameters, which affect the performance of the Venturi tube, are the contraction ratio, which is the proportional ratio between the largest diameter of the contraction section and the diameter of the throat section, and the diffusion angle. Zhang found that when the diffusion angle was less than 35 degrees, or the contraction ratio was less that 0.2; the airflow through the Venturi tube was asymmetrical by the time it reached the diffusion section. Jhang found that this asymmetrical flow is a result of different inlet and outlet air pressures, so that the internal minimum pressure is negative. Due to this internal negative pressure, the airflow passing through the diffusion section experiences back-flow, and an upward motion of the air out of the Venturi tube[22].

These tested parameters of the Venturi tube outlined by Zhang are translated into design criteria for the hygroscopic mechanism (Fig. 15). The mechanism intends to allow for the contraction section of the Venturi tube to alter airflow and light entrance through the facade by opening or closing in accordance

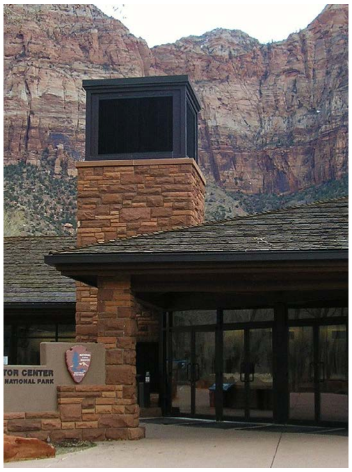

FIG. 9 ZION NATIONAL PARK VISITORS CENTRE
Image of the cooltowers used to passively ventilate the interior of the Zion National Park Visitors Centre.
Image retrieved from: Johnson, Bruce. "Zion National Park - Visitor Center." Digital image. Flickriver. March 20, 2006. Accessed December 26, 2017. http://www.flickriver.com/photos/alltheparks/2142498569/.

FIG. 10 MONODRAUGHT
Image retrieved from: Digital image. Monodraught. 2017. Accessed December 26, 2017. https://www.monodraught.com/resources/images?page=30&filter=natural-ventilation.

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[20] Mozaffarian, Romania. "Natural Ventilation in Buildings and the Tools for Analysis." PhD Diss., University of Florida, (2009)

[21] Su, Yuehong, Saffa B. Riffat, Yen-Liang Lin, and Naghman Khan. "Experimental and CFD study of ventilation flow rate of a Monodraught™ windcatcher." Energy and buildings 40, no. 6 (2008): 1110-1116.

[22] Zhang, J. X. "Analysis on the effect of venturi tube structural parameters on fluid flow." AIP Advances 7, no. 6 (2017): 065315.

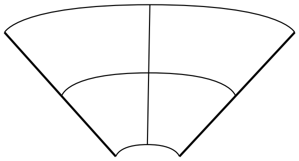


FIG. 11 VENTURI CROSS SECTION
Section through the contraction section of the Venturi tube showing the consistent tapering from the inlet to the outlet.

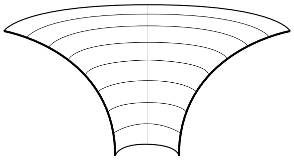


FIG. 12 HYGROSCOPIC CROSS SECTION
Section through the contraction section of the hygroscopic mechanism, showing the parabolic tapering from inlet to outlet.

with relative humidity levels of the external environment. There are however significant morphological differences between the Venturi tube and the design of the hygroscopic mechanism. Where the tapering of the Venturi tube takes place in a linear manner along the contraction section (Fig. 11), the hygroscopic mechanism does not open in a uniform tube, but rather tapers with a gradual increase in angle starting from the mouth of the contraction section and continuing to the throat section (Fig. 12). This alternative cross-sectional shape is tested and compared to the functionality of the original cross section of the Venturi tube through the use of computational fluid dynamics software run within the 3D modeling platform Rhinoceros. The test performed is a pressure drop test with the aim to predict internal flows of air within the mechanism. The intended outcome of this exercise is to demonstrate that despite the varying cross sections, the hygroscopic mechanism, when fully actuated, will be able to moderate air flow by purposefully generating an area of low pressure for increased air velocity. The comparison is completed by first modeling both the standard Venturi tube and the hygroscopic mechanism in their fully actuated positions respectively. The models are then arrayed to form barriers for the simulation of airflow across a facade deploying these mechanisms for passive ventilation (Fig. 13). The results of the simulation are mapped across a grid measuring both velocity and pressure as it flows from a prescribed inlet, through the barrier, to a prescribed outlet (Fig. 14).

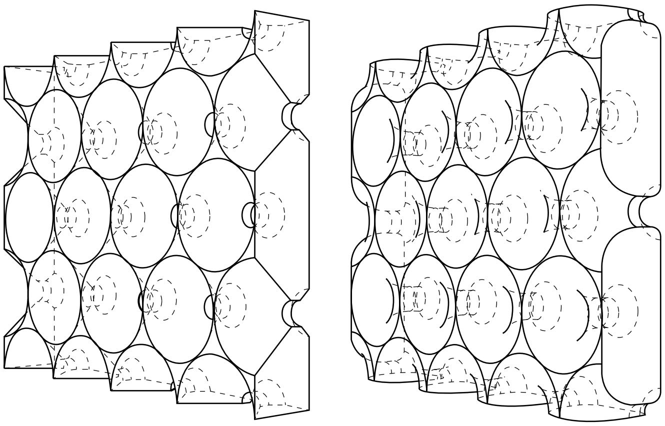


FIG. 13 (LEFT) STANDARD VENTURI AND HYGROSCOPIC CFD BARRIER
To test internal flows through the mechanism, both the standard Venturi tube (left) and the hygroscopic mechanism (right) are arrayed to form barriers.

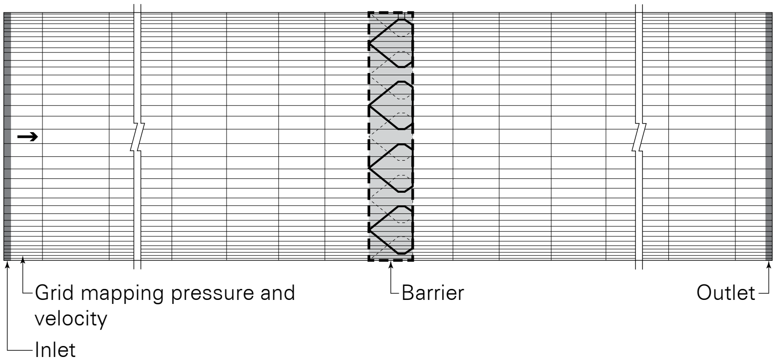
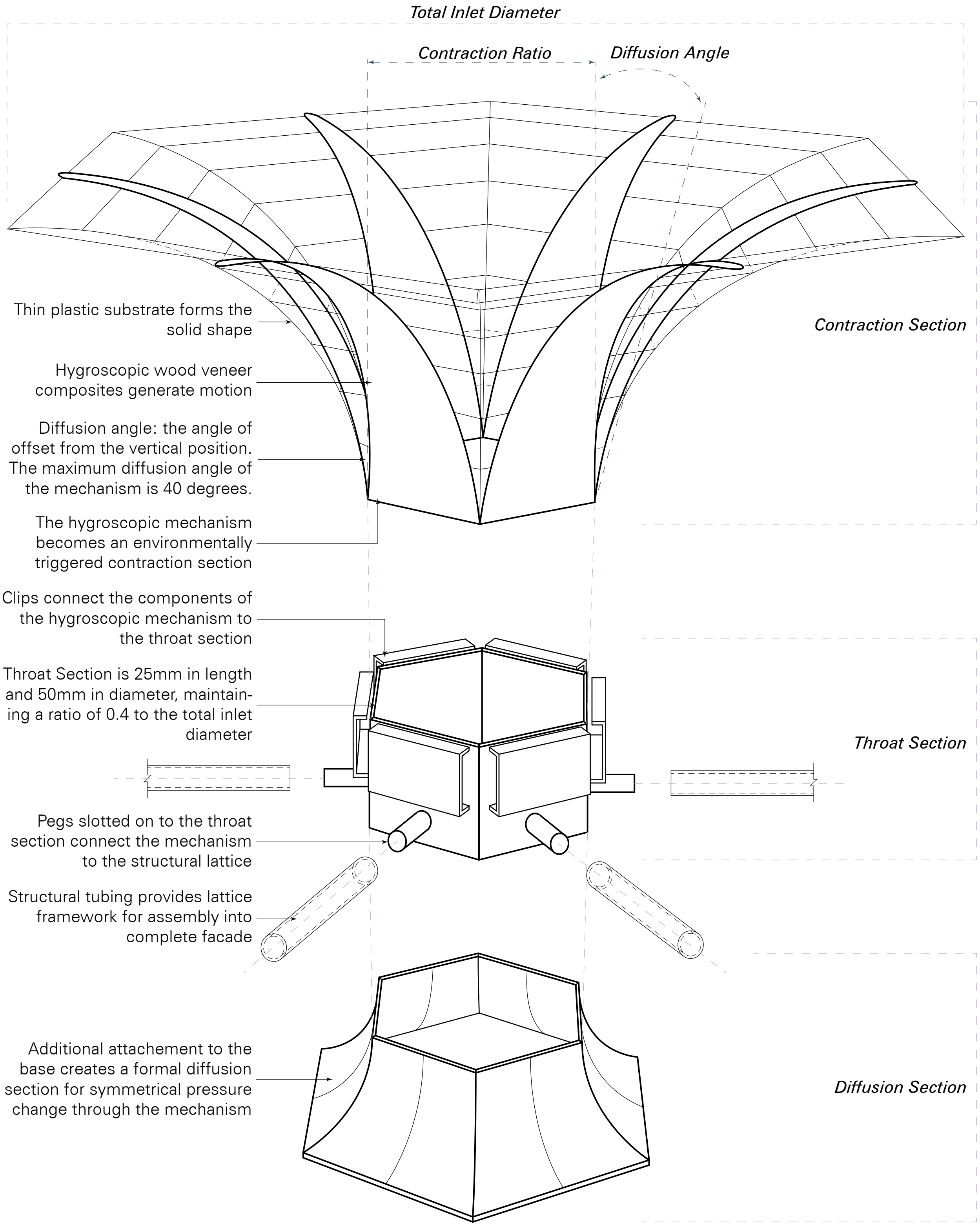


FIG. 14 (LEFT) SIMULATION PREPARATION
Fluid flow is calculated within a defined domain containing a prescribed inlet and outlet for air entering and exiting the simulation. The velocity and pressure resulting from the movement of air through the barrier is mapped across the grid. The software produces a map demonstrating the results along these points.



Thin plastic substrate forms the solid shape

Hygroscopic wood veneer composites generate motion

Diffusion angle: the angle of offset from the vertical position. The maximum diffusion angle of the mechanism is 40 degrees.

The hygroscopic mechanism becomes an environmentally triggered contraction section

Clips connect the components of the hygroscopic mechanism to the throat section

Throat Section is 25mm in length and 50mm in diameter, maintaining a ratio of 0.4 to the total inlet diameter

Pegs slotted on to the throat section connect the mechanism to the structural lattice

Structural tubing provides lattice framework for assembly into complete facade

Additional attachement to the base creates a formal diffusion section for symmetrical pressure change through the mechanism

FIG. 15 HYGROSCOPIC MECHANISM
Exploded axonometric diagram of proposed hygroscopic mechanism with attached base demonstrating the translated anatomy of the Venturi tube into the overall structure of the system.

The first simulation was performed on a barrier with a cross sectional distribution of the Venturi tube. The results of this simulation clearly demonstrate the conservation of energy laws outlined by Bernoulli's principle (Fig. 17 (a) and Fig. 18 (a)), which show a significant increase in velocity as it passes through the opening accompanied by a simultaneous drop in pressure. This simulation provides a reference for the results of the hygroscopic mechanism to be compared against.

The second simulation, which was performed on a barrier with a cross sectional distribution of the hygroscopic mechanism, is successful in producing the desired results (Fig. 17 (b) and Fig. 18 (b)). As air passes through the mechanism there is an increase in velocity at the same point as a decrease in pressure. However, the results also indicate that the distribution of air varies from the test completed using the standard Venturi tube. The areas of low pressure, and thus of increased velocity, is extended within this simulation likely as a result of the parabolic cross sectional tapering of the contraction section of the mechanism. As a result of this, the airflow leading away form the mechanism towards the outlet was found to experience a greater distribution of air flow at a higher velocity despite having a lower overall velocity then that of the standard Venturi simulation. Each simulation was completed using an average wind speed for the city of Toronto of roughly 4m/s or 16km/h[23].

To demonstrate the need for the form of a contracting tube, a third simulation was additionally performed. Completed using the same process and methods as the previous two, this simulation used a simple linear cross section for the arrayed openings to demonstrate what the performance of facade would be if it did not include a contracted portion midway through the perforated envelope (Fig. 16). The results of this simulation show that although there is airflow across the barrier, there is no additional drop of pressure as air passes through the barrier from inlet to outlet. This indicates that this cross section would only transmit air to the interior spaces as it is available in the macroenvironment. Without the contraction section, there is no suction or induced flow if the velocity of the air in the macroenvironment is low (Fig. 17 (c) and Fig. 18 (c)).

FIG. 16 (RIGHT) LINEAR CFD BARRIER
The diagram shows the barrier used for the control section of CFD testing. The structure of the barrier is an array of cylinders with a linear cross section.

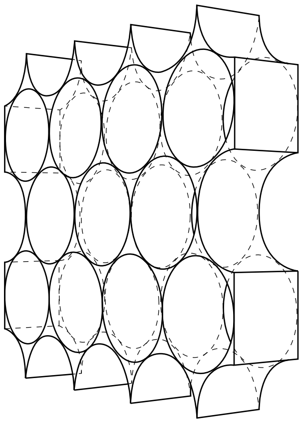


FIG. 17 (FACING PAGE) CFD VELOCITY
Diagrams show air stream patterns and corresponding velocities produced during the computational fluid dynamics simulations performed using the Rhinocerous 3D modeling platform. The scaler velocity scale associated with fig, 17 (c) has been adjusted for clarity of visual representation.

FIG. 18 (PAGE 48) CFD PRESSURE
Diagrams show air stream patterns and corresponding pressure gradient produced during the computational fluid dynamics simulations done through the Rhinocerous 3D modeling platform.

FIG. 19 (PAGE 49) HYGROSCOPIC MECHANISM
Diagrams show air stream patterns and corresponding velocities produced during the computational fluid dynamics simulations performed using the Rhinocerous 3D modeling platform. The diagrams show the hygroscopic mechanism as it performs to control air flow in a fully actuated, semi-actuated, and closed state.

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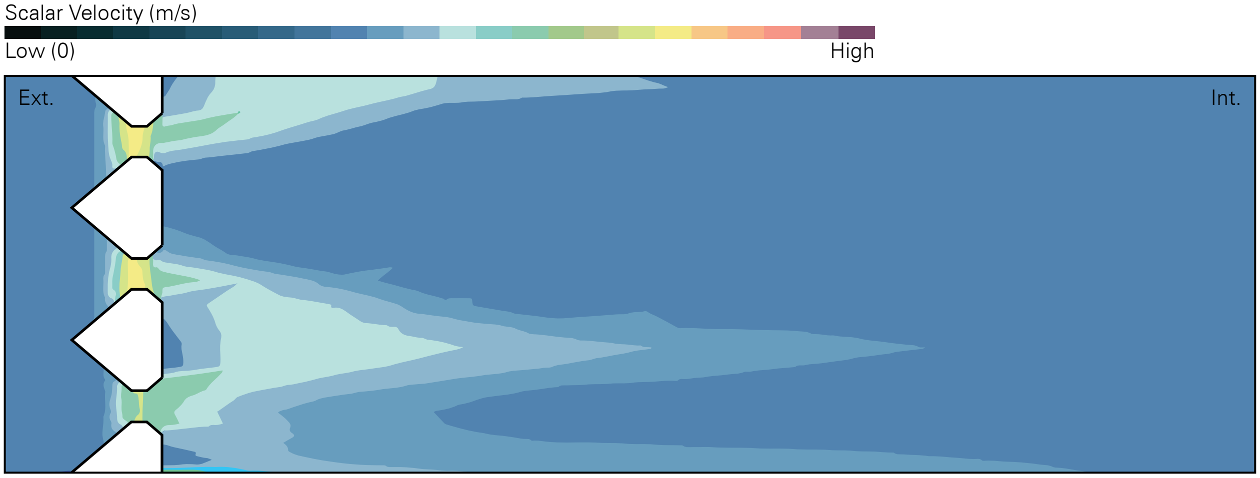
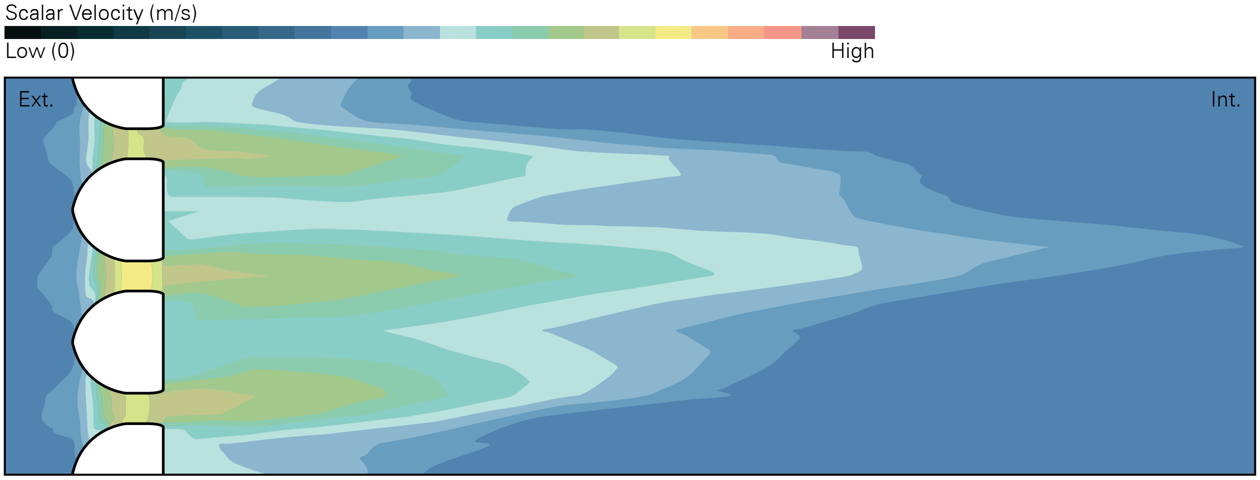
[23] Environment and Climate Change Canada. "Toronto Historical Wind Speed." Amateur Weather Statistics for Toronto, Ontario. https://toronto.weatherstats.ca/metrics/wind_speed.html.

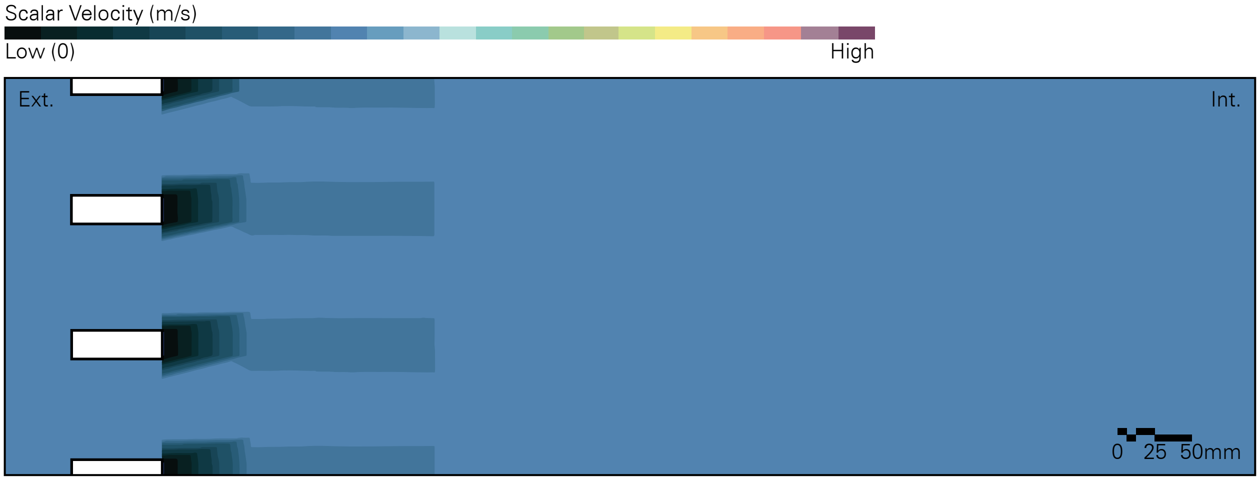
***(a) Standard Venturi Tube***
Overall Velocity: 4.3 m/s
Scale: 1:10



***(b) Hygroscopic Mechanism***
Overall Velocity: 2.9 m/s
Scale: 1:10

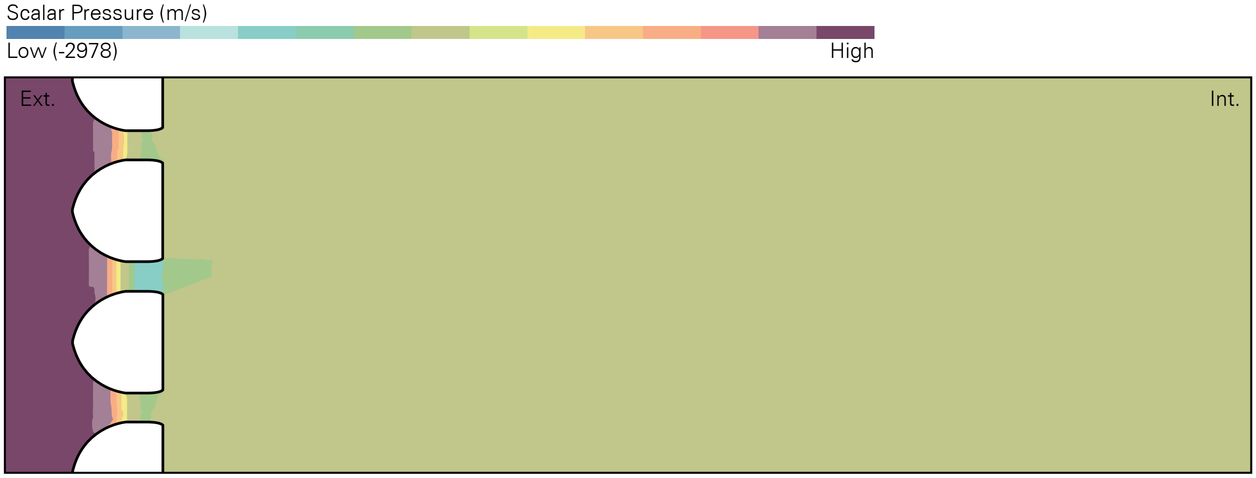


***(c) Control Section***
Overall Velocity: 4.0 m/s
Scale: 1:10

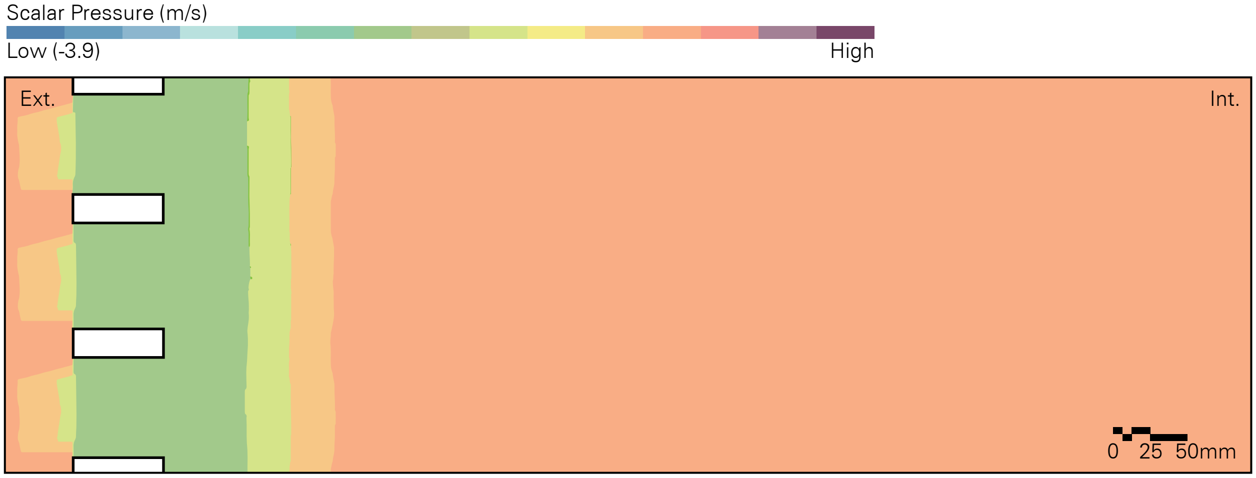


***(a) Standard Venturi Tube***
Overall Pressure: -50
Scale: 1:10

***(b) Hygroscopic Mechanism***
Overall Pressure: -42
Scale: 1:10



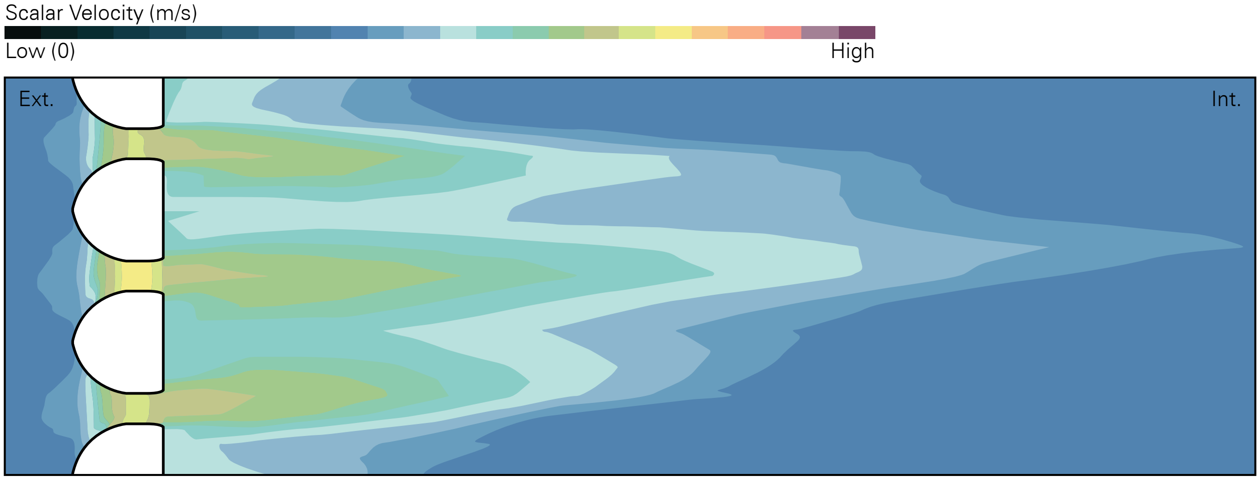
***(c) Control Section***
Overall Pressure: 0.001
Scale: 1:10



***(a) Hygroscopic Mechanism - Open***

Overall Velocity: 2.9 m/s

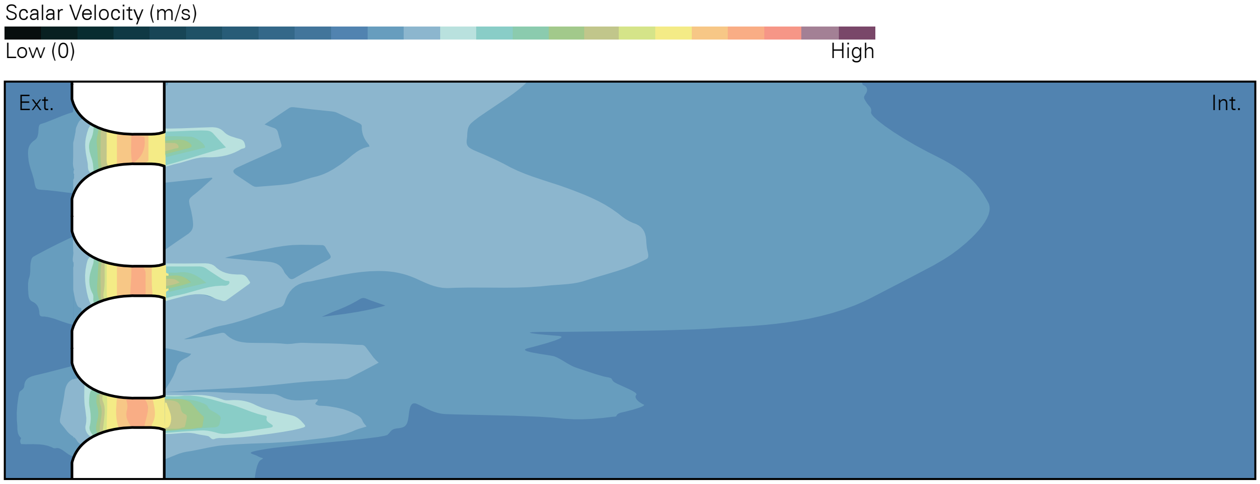
Scale: 1:10



***(b) Hygroscopic Mechanism - Partial Closure***

Overall Velocity: 2.9 m/s

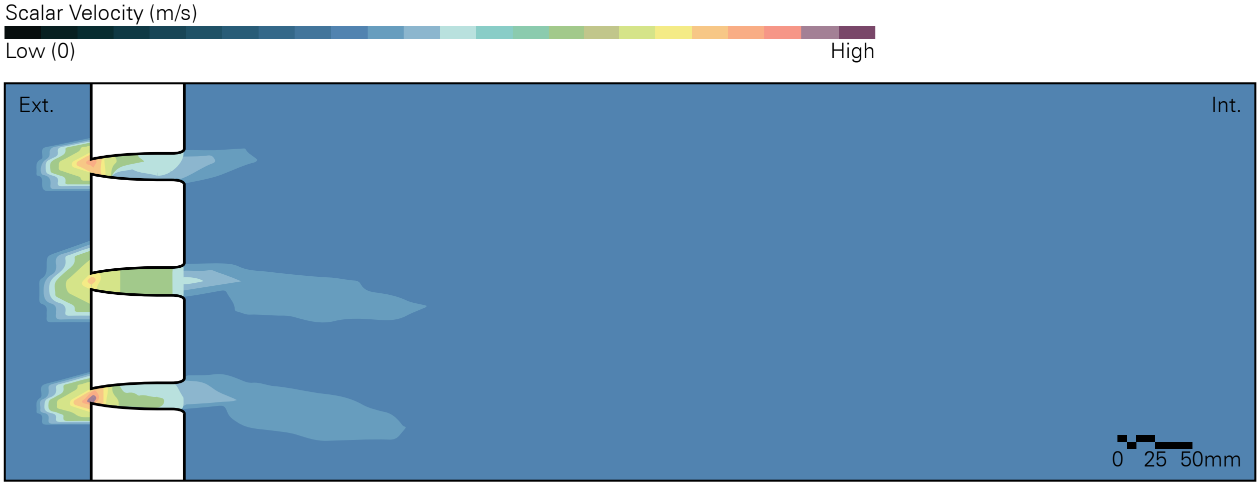
Scale: 1:10



***(c) Hygroscopic Mechanism - Closed***

Overall Velocity: 2.9 m/s

Scale: 1:10



To show how the mechanism is a semi-permeable barrier, capable of alteration and therefore periodic exclusion of airflow, additional simulations were performed at both a semi-actuated and closed state (Fig. 19 (a), (b), and (c)).

Overall, from these simulations, it was found that the hygroscopic mechanism would increase air flow across the facade through the purposeful creation of a low-pressure zone within the mechanism and seems to provide a greater distribution of increased air velocity within interior spaces as compared to the Venturi tube simulation. These simulations represent the study of internal flows using a pressure drop test performed in an ideal situation. For proof-of-concept they show that the form of the mechanism performs as intended through the creation of a low-pressure zone. However, for increased accuracy, further modeling of the mechanism within a specific site conditions would be required, because the air flow around the larger volume of the building itself would impact the flow through the individual mechanisms. Additionally, the simulations have been performed using a rigid grid for mapping the flow outcome. Due to the flexible nature of the models, mapping with a grid moving alongside the motion of the mechanism would improve the accuracy of the results.

### *Application of Passive Strategies*

Internal thermal environmental standards and parameters for achieving comfort in spaces with specific occupancy types are outlined in ASHRAE Standard 55. As an update to this model, new parameters are proposed as an Adaptive Comfort Standard (ACS), which allows for warmer indoor temperatures within naturally ventilated buildings. The ACS argues that thermal sensations, and thus satisfaction with the thermal environment, depend on the comparison between expectations of the indoor climate in a particular geographical context and what actually exists. According to the ACS, people who live or work in spaces that are naturally ventilated become accustomed to diversity in the thermal landscape as it reflects daily local patterns of climate variability[24]. For standards of adaptive comfort to apply, as outlined by ASHRAE 55, occupants of the space where passive ventilation will be used as the only method of cooling must be engaging in sedentary activities with a metabolic rate of 1 to 1.3 met, the program of the space must be as such that the occupants can adapt clothing between 0.5 to 1.0 clo and prevailing mean outdoor temperatures are greater than 10°C and less than 33.5°C[25].

For application of passive ventilation onto a specific site, this thesis will be focusing on the building located at 480/488 University Avenue, Toronto with an office occupancy. In accordance with the metabolic rates provided by ASHRAE Standard 55, an office occupancy has an average metabolic rate between 1.0 and 1.2 met, and a clo factor of 0.54 to 1.10 clo approximately (assuming typical attire ranging from long pants or knee length skirts with either short or long sleeved shirt and interchangeable sweaters or suit jackets). These values indicate that passive ventilation strategies can be incorporated with office occupancies. For application within the regional context; presently, Toronto's climate is classified as 'Dfa' under the Köppen Classification system, which is the most widely recognized climate classification method first published by Wladimir Köppen in 1884. Under the 'Dfa' classification, Toronto is recognized as a hot, humid continental climate[26]. While Toronto currently falls within the accepted

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[24] De Dear, Richard J., and Gail S. Brager. "Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55." Energy and buildings 34, no. 6 (2002): 549-561.

[25] "Standard 55-2013: Thermal Environmental Conditions for Human Occupancy" ASHRAE. Atlanta USA, (2013) Section 5.4

Met: the unit 'met' refers to the metabolic energy expenditure per unit of skin of the average body performing an activity as compared to the body at rest.

Clo: refers to the insulative value provided by clothing to maintain thermal equilibrium with an environment at 21°C with air movement of 0.1m/s. One 'clo' is roughly equivalent to an individual wearing trousers, a long sleeve shirt, and a jacket, or a skirt, long sleeve shirt, and a sweater

[26] La Roche, Pablo M. "Carbon-neutral architectural design." CRC Press, 2017.

temperature range for passively ventilated buildings during the months of May through September only, the predicted increase of average yearly temperatures asserts the need for passive cooling strategies over the majority of the year. In accordance with the study done by SENES Consultants Limited for the City of Toronto, the average annual temperature of the city is expected to increase by an average of 4.4°C, with an increase of 5.7°C during the winter and 3.8°C during the summer by 2049. The result of this overall temperature increase will be significant impacts to temperature degree days, which refer to how hot or cold the temperature during the day is and how long the days remain at this temperature. Degree days are used to determine the number of heating or cooling days of interior built spaces over the course of a year. For the city of Toronto, temperatures below 18°C are used to estimate heating requirements, while temperatures above 24°C are used to determine cooling requirements. The study found that the requirement for heating would be reduced by 31%, or one third and the cooling requirement would alternatively increase by 560%, or from 32 to 180 days of the year. This significant incline in temperature, and changes to local climate as a whole that have been predicted, emphasize the need for passive cooling strategies as a method of controlling thermal comfort and demonstrate is applicability to this changing northern climate[27]. By allowing the building facade to regain the responsibility of navigating across the transition from external to internal thermal landscapes, the built form can return to metabolizing in rhythm with the daily patterns, rather than exacerbating the problem through increased demand on energy intensive mechanical systems.

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27 Toronto Environment Office, SENES Consultants Ltd. "Toronto's Future Weather and Climate Driver Study: Outcomes Report." The City of Toronto (October 30, 2012)

# METHODS AND MATERIALS

## *Introduction and the Motion of Wood*

The development of an envelope system with passive performance is dependent on the selection of a material with naturally embedded mechanical characteristics that are actuated by environmental stimuli. In focusing on the thermal environment, wood veneer is used for its ability to perform dimensional changes corresponding to changes in atmospheric moisture content. Humidity is measured in two ways; the first is as relative humidity, which is the ratio between the amount of moisture in the air and the amount of moisture the air can hold at that temperature, while the second is absolute humidity, which is the actual measure of moisture in a given volume of air. The relationship and differences between relative and absolute humidity to temperature is important in understanding which conditions will produce movement in wood materials. Increasing the temperature of a given volume of air increases its capacity to hold moisture; therefore it requires more moisture in hot temperatures to achieve higher levels of relative humidity, whereas it requires less water in cold climates to achieve a high relative humidity because of the decreased capacity of the air to hold moisture. Therefore, the same amount of water in a given volume of air will produce a lower relative humidity at higher temperatures, and a high relative humidity at lower temperatures, while the absolute humidity will remain the same. As such, the movement of wood to the presence of moisture within the air is a physical response to changes in relative humidity only[1].

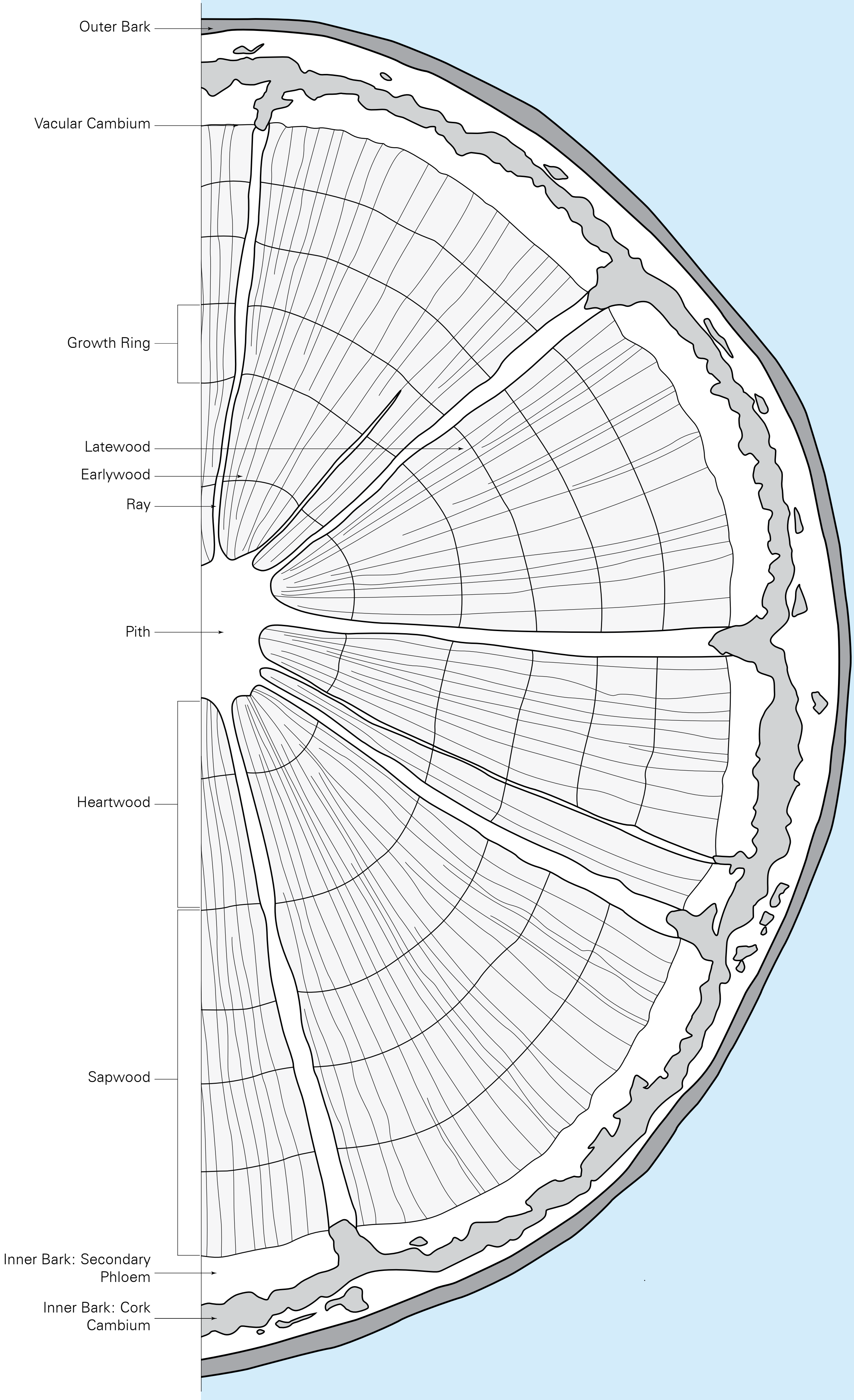
This motion is a dimensional change and is a result of moisture from the air being absorbed by the wood fibers. This absorption, or hygroscopic tendency of wood to absorb water from its environmental context, is due to its physical morphology and molecular assembly. This important structural makeup begins with the process of photosynthesis, which allows a tree to produce glucose. Through this production, long chains of glucose are formed to create cellulose, which then combines to form elementary fibers. These elementary fibers of cellulose then further group into bundles called microfibrils, which are the main structural component of the cell wall of wood and are responsible for the global expansion of wood to water[2].

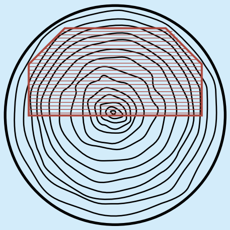
The dimensional changes seen in lumber and other wood products when in

FIG. 1 (FACING PAGE) CROSS SECTIONAL ANATOMY OF A TREE
The diagram shows a horizontal section through a tree trunk demonstrating the anatomy of the material and additionally, ways in which it can be cut in relation to the growth rings.

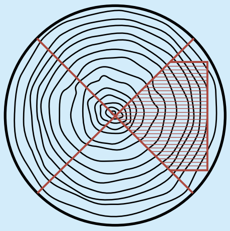
[1] Reeb, James Edmund. "Wood and moisture relationships." Corvallis, Or.: Extension Service, Oregon State University, 1995.

[2] Reeb, James Edmund. "Wood and moisture relationships." Corvallis, Or.: Extension Service, Oregon State University, 1995.

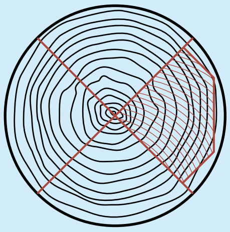




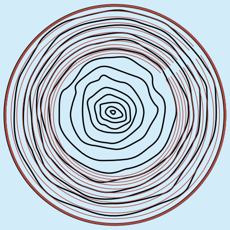
Flat/Plain Sliced



Quarter Sliced



Rift Sliced



Rotary Sliced

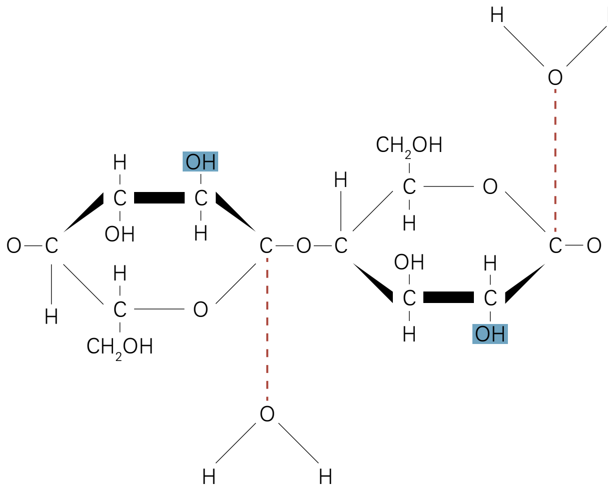


FIG. 2 HYDROGEN BONDING
The polarity of the cellulose molecule allows for the formation of microfibril chains because the (-)OH regions are attracted to OH regions of adjacent chains. Additionally, the polarity of the chains allows for a hydrogen bond to form between the polar water molecule and the cellulose molecule.
Diagram developed from information retrieved from: Thakur, Vijay Kumar, Manju Kumari Thakur, and Raju Kumar Gupta. "Raw natural fiber–based polymer composites." International Journal of Polymer Analysis and Characterization 19, no. 3 (2014): 256-271.

- - - Hydrogen bonding of the water molecule to the cellulose chain

— Bonding of cellulose molecules to adjacent chains

the presence of water is due to the relationship between the material and water in its live versus dead state. When a tree is live to when it is first felled, it is considered to be in the 'green' state and is retaining a large amount of moisture within it. This moisture is present within the tree in two forms. The first is as free water, which exists as either liquid or vapor in the cavities of the wood cells. The second form is as bound water, which is the water held into the wood by the microfibrils (the accumulation of cellulose fibers). The transfer of molecules into and out of the fibers of wood is a result of the polarity of waters molecular structure and the corresponding polarity of the cellulose chains. Bound water is therefore held within the microfibrils by hydrogen bonding between the cellulose and water molecules (Fig. 2)[3].

When wood is drying, moisture leaves the cavities of the cells first, and once all of the free water has evaporated from the wood, the wood has reached its fiber saturation point (FSP). When the wood reaches its FSP, water is no longer present within the cell, but the wood does not experience any physical changes in dimension because the cell walls remain fully saturated. Further drying of the wood results in bound water leaving the cell walls. This evaporation allows the microfibrils to contract and the moisture content to drop below the FSP. The simultaneous contraction of the microfibrils at the molecular level due to the evaporation of moisture results in global dimensional shrinkage of the wood. Wetting the wood causes this process to reverse. Bound water is accumulated within the microfibrils first, resulting in their expansion and a global lengthening of the wood, while any excess water is held within the cell cavity as free water. While free water does not contribute to the movement of the wood, it does however contribute to the overall weight of the wood. Different cuts of wood will experience varying dimensional changes depending on the direction of the growth rings relative to the angle of the cut. The greatest dimensional changes occur tangent to the growth rings because movement takes place along the growth ring. An intermediate amount will occur radial to the growth rings because the movement takes place as the grain extends outward from the center of the tree, and the smallest dimensional changes will occur longitudinal to the growth rings because the cells cannot substantially extend in length (Fig. 3)[4].

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[3] Reeb, James Edmund. "Wood and moisture relationships." Corvallis, Or.: Extension Service, Oregon State University, 1995.

[4] Reeb, James Edmund. "Wood and moisture relationships." Corvallis, Or.: Extension Service, Oregon State University, 1995.

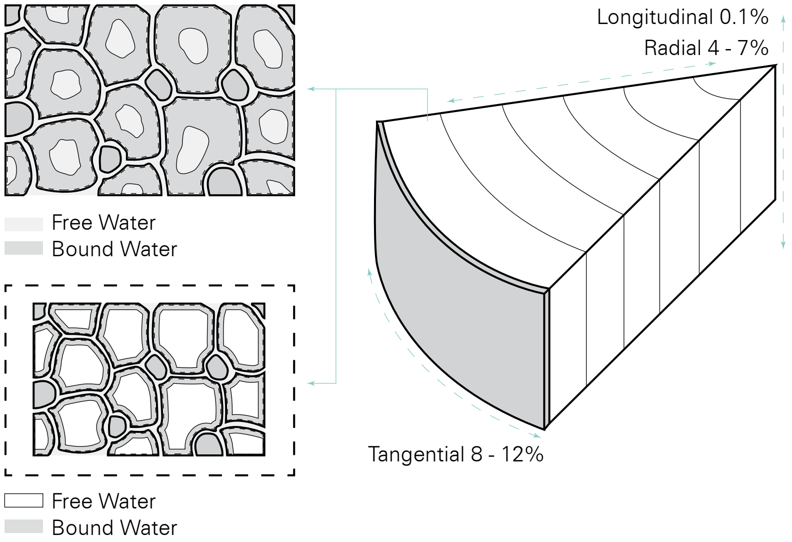

FIG. 3 HYGROEXPANSION
The diagram demonstrates the different directions of hygroexpansions and illustrates how bound water within the cell acts to produce this motion by cellular expansion. Diagram adapted form information retrieved from: Reeb, James Edmund. "Wood and moisture relationships." Corvallis, Or.: Extension Service, Oregon State University, 1995.

While there are other materials that experience physical changes to thermal factors, there are several advantages to using wood. Wood is a naturally produced, organic material with almost universal availability, a relatively low cost, a low environmental impact, and is lightweight while also exhibiting good structural performance[5]. Due to these factors, wood is a popular structural material both presently and historically, however its tendency to exhibit dimensional changes based on an increasing or decreasing moisture content has always been considered a deficiency. By reconsidering the application of wood as primarily a structural material, to considering it's natural movement as property to be enhanced rather than diminished, wood can be used to develop facade systems with passive environmental performance.

## Composite Mechanisms

### *Wood Veneer*

Biological precedents offer examples of ways to create responsive system using no-tech strategies[6]. The biological precedent of the conifer cone, whose structural composition of the bilayer enables it to have numerous cycles of repeatable motion, is a precedent for formal assemblies that produce no-tech movement. Through the exploration of the expansion of wood artificial moisture sensitive composites can be produced that have the same repeatable movements. These artificial bilayers consist of an active wood layer and a passive synthetic layer, expanding perpendicular to grain orientation (Fig. 4).

The overall behavior of the bilayer composition is dependent on a number of interacting factors as identified by Reichert et al. These include the choice of material for both the climate sensitive and climate independent layers, the thickness and orientation of these materials, the type of bond between the two materials, and the production conditions the bilayer was initially subject to[7,8]. For the active wood layer, wood veneer is used so that the actuation time is minimal and the overall dimensional changes are the most dramatic. Wood veneer refers to thin slices of wood, usually thinner than 3mm, obtained from

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[5] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[6] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[7] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[8] Reichert, Steffen, Achim Menges, and David Correa. "Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness." Computer-Aided Design 60 (2015): 50-69.

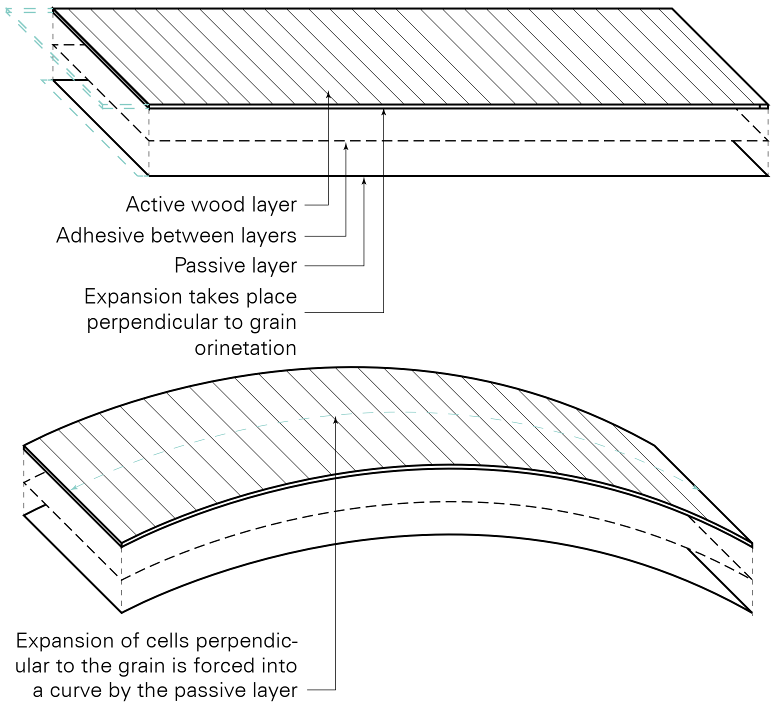

FIG. 4 WOOD BILAYER COMPOSITE
The diagram demonstrates the components of the wood veneer bilayer and how they interact with one another to produce repeatable transformations based on the specific configuration of materials with the grain orientation of the wood veneer.

a tree log. Veneer can be either peeled from logs or sliced from flitches (a slab of timber cut from the trunk to be made into smaller pieces) into sheets or leaves with a predetermined thickness and grain orientation. Wood veneers undergo several steps in their manufacturing process to ensure homogeneity in the final material, an important component for consistency in their architectural application. At the start of veneer processing, felled trees have their limbs removed and are transported to a sawmill where they are classified by species, and stacked in long piles known as log decks, and kept under high humidity conditions by either water spray or soaking to prevent degradation of material that occurs during drying. Following this, the logs are debarked either by a grinding wheel or jets of high-pressure water while the log rotates along its axis. The debarked logs are then moved to the mill where they are cut into sections and either quartered or halved depending on the intended end product. These prepared logs are known as peeler blocks, and are soaked and heated in order to soften the wood, which is necessary for uniform slicing. This process involves placement of the peeler blocks into steamers where they are submerged at temperatures ranging from $80^{o}$C to $100^{o}$C for 18 to 72 hours, depending on the type of wood and the size of the block. Once the peeler blocks have completed soaking, they are transported to the peeler lathe where they are cut. The cut of the veneer is important to its performance as a hygromorphic bilayer because of the relationship of cellular expansion to grain orientation. There are several different ways veneer can be cut, which include: flat slicing, quarter slicing, rift slicing, and rotary slicing (Fig. 1)[9].

Plain sliced veneer is created when a halved log is sliced parallel to the center of the growth rings. This produces a radial grain orientation, which dries faster on one side of the leaf over the other, resulting in the “cupping” of the veneer in the opposite direction of the growth rings. Alternatively, quarter sliced veneer is the result of a quartered log being placed to cut so that the growth rings

FIG. 5 (FACING PAGE) VENEER CUT COMPARISON
The diagram, adapted from the experiments performed by Holstov et al., demonstrates the extent of curvature achieved from different cuts of wood. Though the diagram shows that both rotary cut veneer as well as plain sliced veneer demonstrate greater hygroscopic motion, rotary cut veneer is largely unavailable, while plain sliced veneer experiences a ‘cupping’ motion of double curvature produced as a result of different drying speeds between the twos faces of the board. This cupping is more prevalent within thicker wood selections.

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[9] “Plywood.” How Products Are Made. 2017. http://www.madehow.com/Volume-4/Plywood.html.

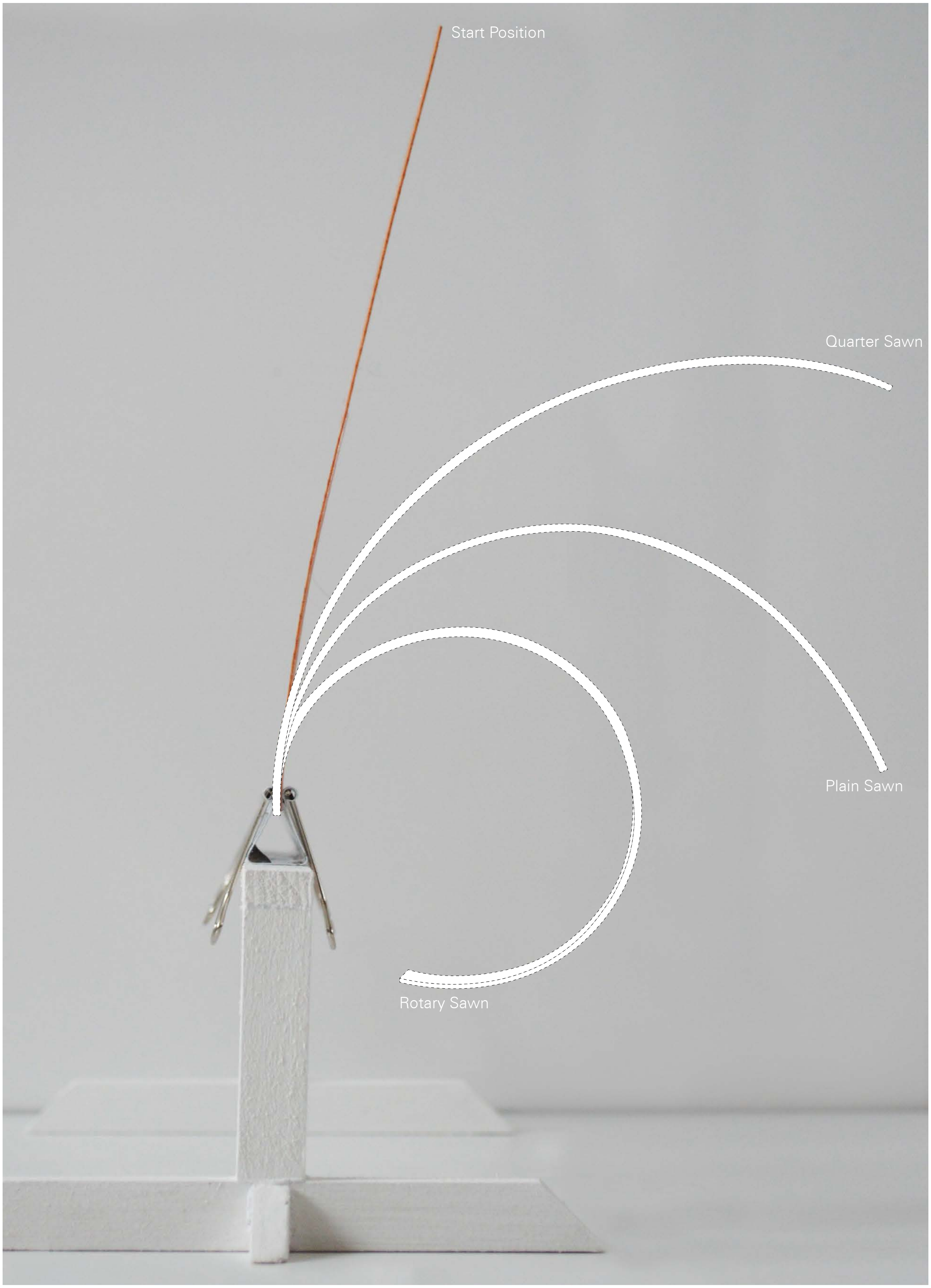
Start Position
Quarter Sawn
Plain Sawn
Rotary Sawn

FIG. 6 BLACK CHERRY BILAYER
Active Layer: 0.6mm black cherry veneer
Passive Layer: 0.13mm PET plastic
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: standard epoxy adhesive
Objective: single bend

FIG. 7 BLACK CHERRY BILAYER
Active Layer: 0.6mm black cherry veneer
Passive Layer: 0.13mm PET plastic
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: standard epoxy adhesive
Objective: sinusoidal bend

58

59

FIG. 8 HARD MAPLE BILAYER
Active Layer: 0.6mm black cherry veneer
Passive Layer: 0.13mm PET plastic
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: standard epoxy adhesive
Objective: single bend

FIG. 9 HARD MAPLE BILAYER
Active Layer: 0.6mm black cherry veneer
Passive Layer: 0.13mm PET plastic
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: standard epoxy adhesive
Objective: sinusoidal bend

60

61

FIG. 10 BLACK WALNUT BILAYER
Active Layer: 0.6mm black walnut veneer
Passive Layer: 0.13mm PET plastic
Grain Orientation: horizontal
Relative Humidity: 35%
Temperature: 23°C
Joinery: standard epoxy adhesive
Objective: single bend

FIG. 11 BLACK WALNUT BILAYER
Active Layer: 0.6mm black walnut veneer
Passive Layer: 0.13mm PET plastic
Grain Orientation: horizontal
Relative Humidity: 35%
Temperature: 23°C
Joinery: standard epoxy adhesive
Objective: single bend

62

63

FIG. 12 EUROPEAN BEECH BILAYER
Active Layer: 0.6mm black cherry veneer
Passive Layer: 0.13mm PET plastic
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: standard epoxy adhesive
Objective: single bend

FIG. 13 EUROPEAN BEECH BILAYER
Active Layer: 0.6mm black cherry veneer
Passive Layer: 0.13mm PET plastic
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: standard epoxy adhesive
Objective: sinusoidal bend

64

65

are perpendicular to the cutting blade. Quartered veneer dries evenly on both board faces, thus producing uniform and highly predictable motion. Lastly rotary sliced veneer is produced by centrally mounting a log, which is then turned along a blade, 'unwrapping' the veneer tangent to the growth rings. Though rotary cut veneer produces the largest dimensional responses to the uptake of moisture, because it is cut along the growth ring of the tree, it is not always commercially available for all potentially applicable wood species[10]. The wood veneer used throughout this thesis is quartersawn because it has a highly predictable and stable movement while being commercially available in all applicable species of wood.

Species of wood used is also important to its performance as a successful adaptive bilayer. The first functional characteristic that focuses the selection of wood is selecting between a hardwood or softwood species. During the lifetime of a hardwood tree species, it uses vertical conduits called vessels for the transportation of water from the roots to the leaves. After the tree is felled, these vessels can be seen when the trunk is cut on its end grain. Appearing as pores, the vessels are located within the growth rings of the wood. Hardwood species are divided into three categories based on the arrangement of these pores; ring-porous, semi-ring-porous, and diffuse-porous. Ring-porous species have pores varying in size, with larger pores located in the earlywood (wood formed at the start of the growing season) and small pores located in the latewood (wood formed in the latter portion of the growing season), forming distinct rings of descending size moving from early to latewood. Similarly to this, semi-porous hardwood species maintain the gradient in pore diameter, with larger pores located in the earlywood and smaller pores in the latewood, however semi-porous wood does not develop clear rings. In contrast to the other two categories, diffuse-porous species have no early to latewood pore arrangement and no significant differences in pore size[11]. These differences are important to the performance of the wood. Variation within the pores results in differences of both structural and hygroscopic performance between earlywood and latewood. As a result, when these species are incorporated into this bilayer configuration, the inconsistencies are amplified and performance is decreased. This is also true for softwood species, though they lack pores, they too exhibit different hygroscopic behavior between earlywood and latewood[12].

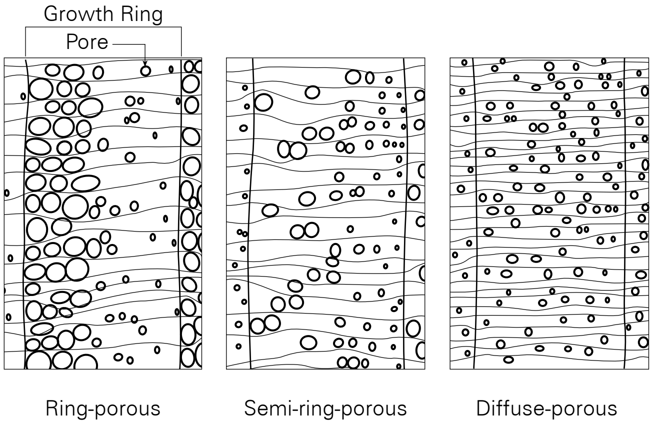

FIG. 14 (RIGHT) HARDWOOD VESSEL DISTRIBUTION
The diagram, adapted from information retreived from Holstov et al. demonstrates the distribution of vessels within the three categories of ring-porous, semi-ring-porous, and diffuse-porous, which generate variability in the hygroscopic performance of hardwood species.

[10] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[11] Meier, Eric . "Hardwood Anatomy." The Wood Database. http://www.wood-database.com/wood-articles/hardwood-anatomy/.

[12] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

FIG. 15 (RIGHT) WOOD SPECIES
From left to right and top to bottom: Black Cherry, Hard Maple, Black Walnut, and European Beech

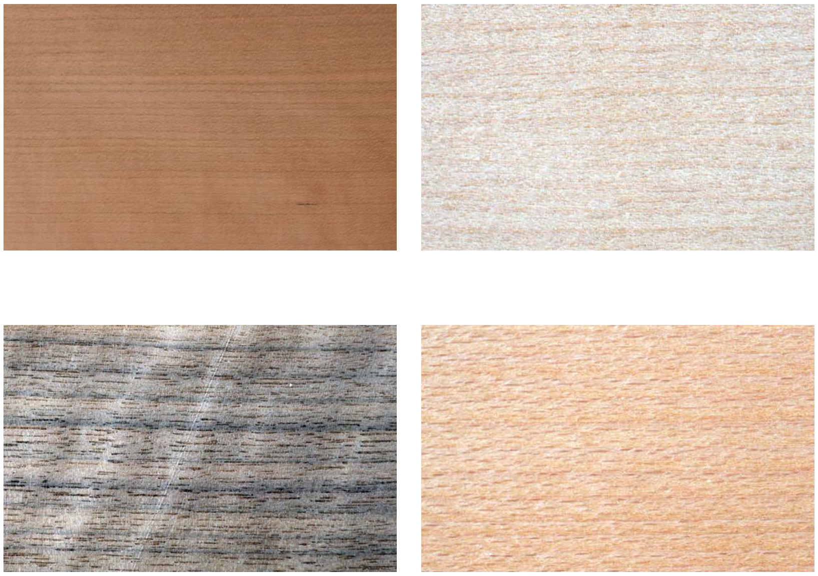

FIG. 16 (BELOW) EUROPEAN BEECH BILAYER: GRAIN ORIENTATION

Active Layer: 0.7mm European beech veneer
Passive Layer: 0.13mm PET plastic
Grain Orientation: varies
Relative Humidity: 38%
Temperature: 25°C
Joinery: standard epoxy adhesive
Objective: angled curvature

The wood grain was tested at 30 degrees, 45 degrees, and 60 degrees off horizontal (left to right). This test demonstrates the relationship between grain orientation and direction of expansion, always expanding perpendicular to the grain direction, in the presence of constriction applied by the passive layer, the composite coils.

The wood species tested include black cherry, hard maple, black walnut and European beech. The physical properties affecting the hygroscopic performance of these hardwood species are as follows:

**Black Cherry** (Prunus serotinal): exhibits a straight grain with a fairly even texture, and is a semi-porous to diffuse-porous hardwood. This species experiences 3.7% radial shrinkage, and 7.1% tangential shrinkage.

**Hard Maple** (Acer saccharum): exhibits a generally straight grain with an even texture, and is a diffuse-porous hardwood. This species experiences 4.8% radial shrinkage, and 9.9% tangential shrinkage.

**Black Walnut** (Juglans nigra): predominantly shows a straight grain with occasional irregularities, and has a medium texture. This species is considered a semi-ring-porous hardwood. This species experiences 5.5% radial shrinkage, and 7.8% tangential shrinkage.

**European Beech** (Fagus sylvatica): maintains a straight grain with fine to medium uniform texture, and is a diffuse-porous hardwood. This species experiences 5.7% radial shrinkage, and 11.6% tangential shrinkage[13].

The results of testing these species of hardwood demonstrated that European beech veneer produced the largest deformation and is therefore used for all further hygroscopic mechanism development. This choice of wood species is, however, not without drawbacks. European beech is more susceptible to insects, and is less durable than other hardwoods. In exterior applications this becomes problematic, as many methods of preservation, such as coatings, aiming to protect wood against weathering, will result in the loss of the woods hygroscopicity[14].

Reichert et al. observed another parameter of the wood active layer when it was found that the orientation of grain is important to the shape of the deformation. Within the studies completed by Reichert et al., the maximum curvature was seen to occur perpendicular to the grain orientation. Not only this, but changing the grain orientation so that it is on an angle results in a curling motion rather than a flat curve[15] (Fig. 68).

### *Passive Layer*

Amplifying the motion produced by the absorption of water from the air is crucial to the performance of the hygroscopic bilayer. Though the veneer would experience dimensional changes without a passive layer counterpart, the use of a passive layer increases the dimensional output by providing constraint to its planar hygroexpansion, thus forcing it to bend. Various materials can be used for the passive layer, such as a secondary layer of wood veneer to produce a cross-grained veneer laminate, fiberglass or carbon fiber reinforced polymers (FRP's), or synthetic polymers such as Polyethylene Terephthalate (PET) and Polycarbonate (PC). However, it was found that the best performance is produced when the passive layer is non-hygroscopic, flexible, and durable so as to undergo repeated transformations without breaking down[16].

The stiffness and thickness of the passive layer in relationship to the active layer is also important for improved motion. Holstov et al. found that if the

[13] Meier, Eric . "Hardwood Anatomy." The Wood Database. http://www.wood-database.com/wood-articles/hardwood-anatomy/.

[14] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[15] Reichert, Steffen, Achim Menges, and David Correa. "Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness." Computer-Aided Design 60 (2015): 50-69.

[16] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

passive layer was the same stiffness as the active layer then the two should be the same thickness. Alternatively, if the passive layer selected is thicker then the active layer, then it should be less stiff, and if it is thinner then the inverse is true. The material used as the passive layer for the purposes of this thesis is Mylar, which is a flexible plastic sheet product made from PET resin. This material was chosen because it is thinner and of relatively the same thickness as the wood veneer used for the active layer. PET products can also be recycled during the end-of-life processing of the bilayers, if decoupled from the wood veneer[17]. The thickness of the active layer is also important to the timescale of the responsive facade. Holstov et al. found that thicker active wood layers could be used to respond to environmental conditions taking place on a daily, or monthly time scale because of slower molecular diffusion and evaporation of water through the wood fibers, while thinner wood veneers could be used to respond to hourly changes in relative humidity[18]. A thin wood veneer with a thickness of 0.6mm and a passive PET layer with a thickness of 0.13mm were chosen for this study because of the specific office occupancy of the site and the need for quicker response times. High levels of occupancy and large changes in the external thermal environment taking place during the day require the responsive behavior of the facade to happen on a smaller time scale.

Depending on the desired results, the hygroscopic behavior of the mechanisms can also be manipulated by controlling the environment of their production. While the expansion of wood fibers is a constant parameter of the hygroscopic mechanism, assembling the wood into a bilayer in humid conditions versus dry conditions results in inverse behavior when under constraint from the passive layer. Bilayers assembled in dry conditions undergo deformation into a curve because of the constraint caused by the passive layer in wet conditions. Alternatively, bilayers assembled in wet conditions, when the wood is has already reached its FSP, will experience this deformation when introduced to dry conditions. The passive layer in this instance is providing constraint to the dimensional shrinkage, rather than expansion[19]. It is through this process that the composites can be programmed to open or close in the dry or wet state (Fig. 17).

FIG. 17 (FACING PAGE) PROGRAMMING BILAYER COMPOSITES
The veneer bilayers demonstrate the ability to program the deformation of the hygromorphs. The veneer composites shown in the image demonstrate the varying responses of composites produced in a dry versus wet state. From left to right, the first and second composites have been assembled in an environment with 84% relative humidity, and while they have different grain orientations, their actuation is visible as they have been placed within a dry environment. Alternatively, the third composite has been assembled in a dry environment and therefore exhibits no change.

Improving the environmental sensitivity of the passive layer can be further explored through the use of FRP's reinforced with natural fibers such as hemp, jute, or flax[20]. Additionally the use of bioplastics can allow for increased environmental consciousness of the veneer composite by replacing petroleum based plastics, which contribute to GHG emissions, with plastics derived from biopolymers originating from living organisms of either plant or animal base. However the term bioplastic involves three classes of biopolymers with varying degrees of bio-derivative content and most often refers to any biodegradable plastic even if they are entirely petroleum based. The first class of polymers includes those extracted directly from biomasses that may or may not need modification after extraction. Starch, or cellulose polymer based bioplastics belong to this class. The second class of polymers includes those produced directly in microorganisms or in genetically modified crops, and the third class of polymers includes those produced through a synthetic method of polymerization where a bio-based monomer is combined with bio-based polyol. Polylactic acid (PLA) bioplastics are an example of this third class[21]. For the purpose of this thesis, a brief exploration into starch-based plastics was undergone using two different recipes. The first recipe tested used 4 tbsp. of water, 1 tbsp. of cornstarch, 1 tsp. of glycerin, and 1 tsp. of vinegar to produce a translucent flexible plastic material. The second recipe tested incorporated 1/2

[17] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[18] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[19] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[20] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[21] Queiroz, Antonio UB, and Fernanda P. Collares-Queiroz. "Innovation and industrial trends in bioplastics." Journal of Macromolecular Science®, Part C: Polymer Reviews 49, no. 2 (2009): 65-78.

tsp. of gelatin to improve strength and elasticity. The result of the second test was a malleable, translucent plastic sheet observed to be much stronger than the original test[22]. Though bioplastics and natural fiber FRP's offer a hopeful alternative to petroleum-based plastics, they still pose challenges for application within a veneer composite. This is as a result of higher water absorption by the natural fiber FRP's and water solubility of the bioplastics derived from only organic material[23].

FIG. 18 STARCH BASED BIOPLASTIC TEST A
The image shows the results of the first test of producing starch based bioplastics. This test used a combination of water, corn starch, glycerin and vinegar to produce a translucent flexible plastic.

FIG. 19 STARCH BASED BIOPLASTIC TEST B
The image shows the results of the second test of producing starch based bioplastics. This test incorporated gelatin to the original mix to strengthen and improve elasticity.

### *Adhesives*

The repeatability of the deformations is vital to the performance of the bilayer as a functioning facade. As such, the bond between the active layer and the passive layer is vitally important. The bonding material must be strong enough to transfer shear stresses from the active layer, while maintaining flexibility that allows it to undergo repeated transformations without breaking down, must not restrict the movement of the bilayer and must be easily dissolved or non-toxic for this strategy of design to remain environmentally concious[24]. Standard wood glues, however, and other polyvinyl acetate (PVA) water-based glues are not suitable for maintaining the hygroscopicity of the wood. This is because the glue itself is absorbed into the cells of the wood, preventing the uptake of moisture for reversible cell expansion. Additionally, bioadhesives remain largely under development, and are not commercially available for use. As such, this study explores a variety of petroleum derived adhesives for their application within hygroscopic bilayers.

The first glue tested was a standard two-part epoxy, which dries as a flexible solid and has a strong bond to both the wood veneer active layer and the plastic passive layer. The curing process of epoxy is through the reaction of either Bisphenol A (BPA), a product of combining one acetone unit with two phenol groups, and/or Novolac, a substance representing the intermediate stage of polymerization that can be usefully manipulated before polymerization is complete, with Epichlorohydrin. A reaction between these two chemicals with the curing agent results in a cumulative interlocking network of cross linkages. The polarity of this molecular bond is responsible for the superior adhesion of epoxy to the materials it joins. In use the epoxy does not noticeable impede on the motion of the bilayer and remains both flexible while maintaining a strong bond to both of the passive and active layer even after repeated deformations[25] (Fig. 20). The second glue tested is a flexible plastic adhesive and of the same class of compounds as epoxy. The glue has a polyurethane base, which is also polar due to the molecular reaction used to create it and is hydrophobic[26]. On application the glue cannot withstand repeated uses and the bilayer is easily delaminated after multiple tests. In addition to this, the glue adheres the two material layers immediately on contact making adjustments to their positioning impossible. Polyurethane based glues are challenging to handle because their intermediary stage before curing is toxic and carcinogenic while the cured product will yellowing over time with prolonged UV exposure. The use of this adhesive within the bilayer resulted in a reduced transformation as compared to the bilayer with a standard epoxy adhesive[27] (Fig. 21). The third glue tested is an outdoor adhesive with a synthetic rubber base containing the chemicals of toluene, which is an aromatic hydrocarbon, and hexane, which is a linear saturated hydrocarbon that is used as a cheap, relatively safe, and largely nonreactive non-polar solvent. This adhesive is composed of synthetic elastomers that have been tackified by the addition of resins. This synthetic

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[22] "The basics of making corn starch bioplastic." Green Plastics. December 31, 2016. Accessed November 2017. http://green-plastics.net/posts/76/qaa-help-with-cornstarch-pla-plastic-project/.

[23] Mohammed, Layth, MOHAMED NM Ansari, Grace Pua, Mohammad Jawaid, and M. Saiful Islam. "A review on natural fiber reinforced polymer composite and its applications." International Journal of Polymer Science 2015 (2015).

[24] Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

[25] "Chemistry of Epoxies." Progressive Epoxy Polymers Inc. . Accessed May 21, 2017. http://www.epoxyproducts.com/chemistry.html.

[26] Król, Piotr, and Boena Król. "Surface free energy of polyurethane coatings with improved hydrophobicity." Colloid and polymer science 290, no. 10 (2012): 879-893.

[27] "Polyurethane Adhesives." Polyurethane Adhesives Characteristics and Uses. Accessed May 21, 2017. http://www.christinedemerchant.com/adhesive-glue-polyurethane.html.

FIG. 20 EUROPEAN BEECH VENEER
Active Layer: 0.6mm
Passive Layer: 0.13mm
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: standard epoxy resin
Objective: single bend

FIG. 21 EUROPEAN BEECH VENEER
Active Layer: 0.6mm
Passive Layer: 0.13mm
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: flexible plastic adhesive
Objective: single bend

FIG. 22 EUROPEAN BEECH VENEER
Active Layer: 0.6mm
Passive Layer: 0.13mm
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: synthetic rubber adhesive
Objective: single bend

FIG. 23 EUROPEAN BEECH VENEER
Active Layer: 0.6mm
Passive Layer: 0.13mm
Grain Orientation: horizontal
Relative Humidity: 26%
Temperature: 25°C
Joinery: silicone adhesive
Objective: single bend

rubber adhesive dries to a semi-flexible bond and has good shear properties, which allows for similar curvature in the bilayer to that experienced with the epoxy resin[28]. During the course of deformation, it was found that the use of this adhesive slowed the movement of the bilayer and restricted its return back to a flat state. The workability of the product was also more difficult than the other adhesives and resulted in poor consistency of the glue within the bilayer (Fig. 22). The final glue tested was a waterproof silicone adhesive with a base of acetoxy silicone. Though the product cures to a flexible silicone elastomer, which is a polymer containing silicone together with carbon, hydrogen and oxygen, it produces acetic acid as a byproduct, which can be corrosive to some metals. In general, this adhesive is stable, resistant to extreme environments, and maintains elongation, flexing, strength, and compression performance even during extreme temperature changes[29]. On use of this product, the bilayer was slow to actuate and did not achieve the same curvature as seen with any of the other adhesives. This is speculated to be a result of added thickness from the silicone increasing the overall dimension of the passive layer, thus providing more resistance against the wood veneer. The material is, however, easily applied in even coats with a flexible bond that remains in tact even after repeated motion, and could be used in applications where the active wood veneer is thicker than the combined thickness of the silicone with the passive plastic layer (Fig. 23).

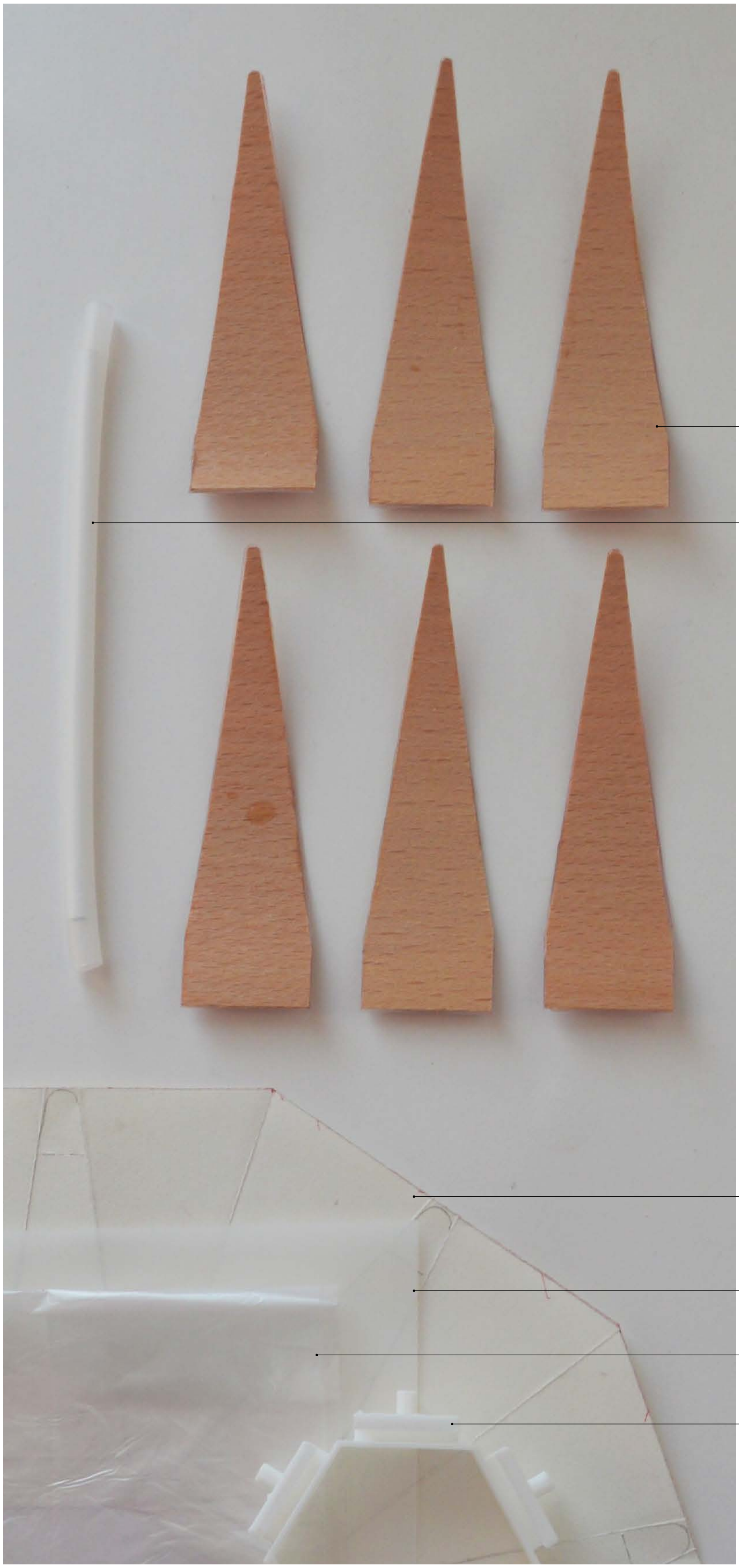
From this study of appropriate adhesives, including the use of epoxy based adhesives, polyurethane and plastic based glues, synthetic rubber based glues, and silicone adhesives, it has been found that standard epoxy provides the best choice as an adhesive for this application. This is because it results in the greatest deformation while also being the least harmful petroleum derived substance for both physical handling and for environmental consideration. More testing and research of bioderived adhesives will further reduce the environmental impacts of hygromorphs as a strategy for responsive envelope systems.

### *Prototype Development*

The final prototype culminates the functional principles and formal examples of the Venturi tube, the Ipomoea flower, and the conifer cone, to produce a mechanism for passive cooling. Developed to moderate interior comfort through adaptation within the facade, the mechanism passively cools by mediating both light and air. The motion principles of the single wood veneer bilayer are extrapolated on through coupling multiple wood composites with a thin plastic exterior to produce a singular mechanism. The final formal assembly produces a hexagonal cone with a parabolic cross section on actuation. Moderating the environmental conditions of light and air is achieved through increasing the opacity of the facade through actuation of the mechanism in humid conditions. To ensure this adaptive shape change will produce a cooling effect, the veneer bilayers have all been assembled in dry conditions to make certain that actuation of the material, and thus the allowance of airflow through the mechanism, will be triggered by the increase in the contextual environments relative humidity. The prototype has been produced using a combination of six wood veneer bilayers and their corresponding PET passive plastic layers joined through standard epoxy resin, thin plastic for connecting the individual composite segments, and a 3D printed base where the bottom of each composite is held into place (Fig. 24).

[28] "Chemistries." Adhesives Research. 2017. Accessed May 21, 2017. http://www.adhesivesresearch.com/technologies/chemistries/.

[29] "XIAMETER® Brand Acetoxy Sealants." Silicones Simplified - Xiameter: from Dow Corning. 2017. Accessed May 21, 2017. https://www.xiameter.com/en/ExploreSilicones/ProductTypes/Sealants/Pages/Acetoxy-Sealants.aspx.



European beech veneer composites

Plastic tubing forming the latticework between the mechanisms

Stencil used to produce the continuous thin plastic ‘lamina’ connecting the composites to one another

PET plastic material used for the passive layer of the veneer composites

Thin plastic connecting material

3D printed base with stabilizing clips for attachment to the composite segments

FIG. 24 PARTS OF THE PROTOTYPE
The image shows the individual parts of the prototype before they are assembled into the final prototype.

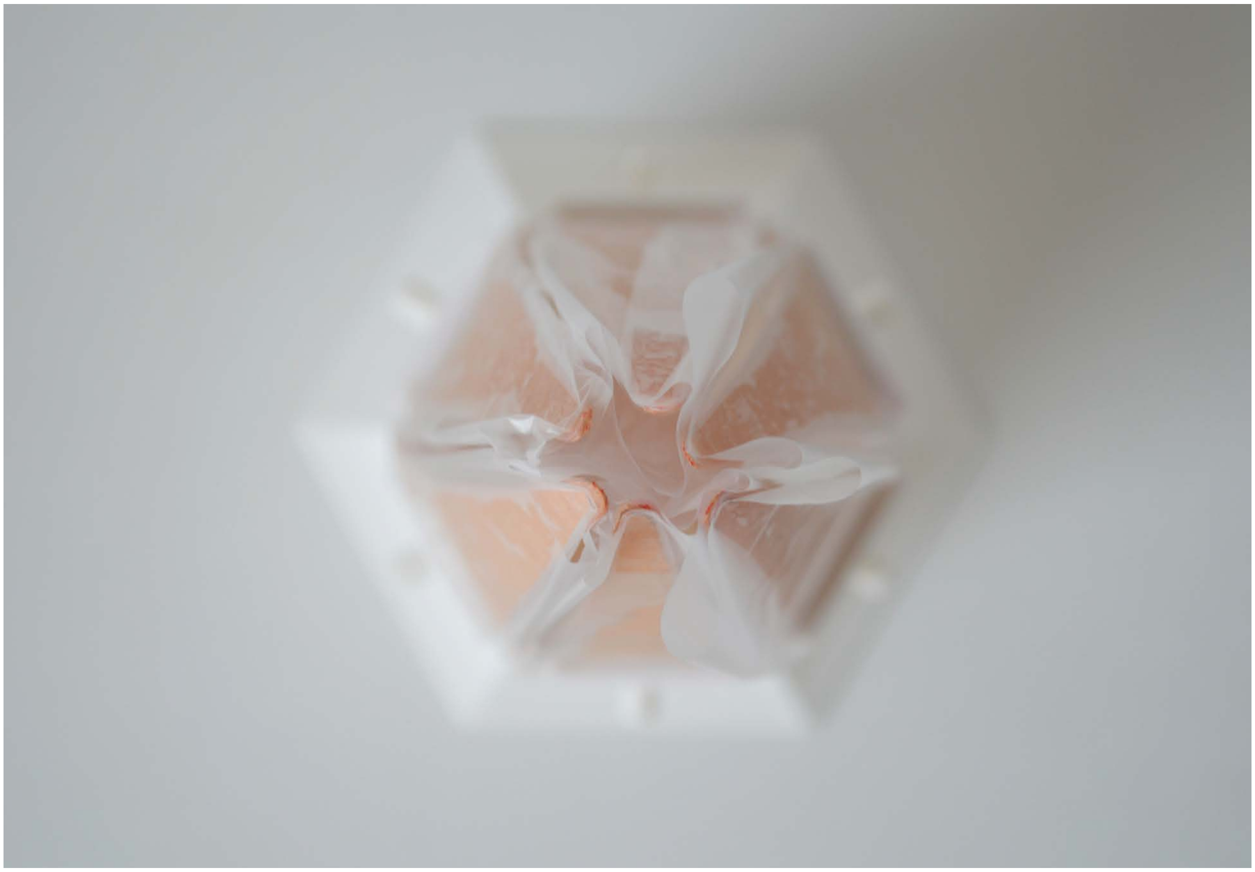


FIG. 25 (ABOVE) FINAL PROTOTYPE
The image shows the final assembly of the hygroscopic prototype from above, demonstrating the clustering of the mechanisms composites to a point.

FIG. 26 (FACING PAGE) FINAL PROTOTYPE
The image shows the final assembly of the hygroscopic prototype in elevation, demonstrating the relationship between the hygroscopic segments to the attached base and the behavior of the bilayers as they come to a singular point at their ends.

The final assembly of the hygroscopic mechanism (Fig. 25 and Fig. 26) before actuation forms a single hexagonal cone. The throat and diffusion sections, which have been produced through 3D printing, also include protrusions for attachment to a latticework of tubing for connection of mechanisms to one another (Fig. 27 and 28). Additionally, the hygroscopic bilayers began as rectangular segments, which over time and through testing, developed to include a tapered point to ensure unobstructed individual movement of each piece. The thin plastic exterior, which is connected to the PET passive layer of each segment, folds within the bilayer grouping.

FIG. 27 FINAL PROTOTYPE
The image shows the final assembly of the hygroscopic mechanism placed within the latticework for representation of how the mechanism can be coupled to form a responsive facade.

FIG. 28 FINAL PROTOTYPE
The image shows the final assembly of the hygroscopic mechanism placed within the latticework for representation of how the mechanism can be coupled to form a responsive facade.

The environment, through an increase in relative humidity, triggers the motion of the hygroscopic mechanism. The motion visualized within Fig. 28 through Fig. 36 is produced through direct wetting onto an assembly produced in an environment with relative humidity of 15% and 25°C. The uptake of moisture into the fibrils of the veneer results in its expansion to produce the global movement of the mechanism.

FIG. 29 (FACING PAGE) FINAL PROTOTYPE MOTION
The image shows the final assembly of the hygroscopic mechanism in a still visualization of the completed motion from closed to entirely open.

FIG. 30 FINAL PROTOTYPE MOTION
The image shows the final assembly of the hygroscopic mechanism in its closed state.

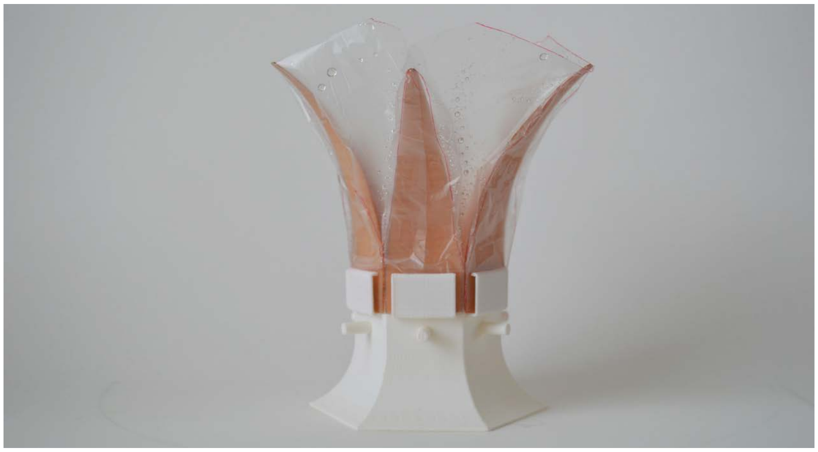


FIG. 31 FINAL PROTOTYPE MOTION
The image shows the final assembly of the hygroscopic mechanism in its partially open state.

FIG. 32 FINAL PROTOTYPE MOTION
The image shows the final assembly of the hygroscopic mechanism in its open state.

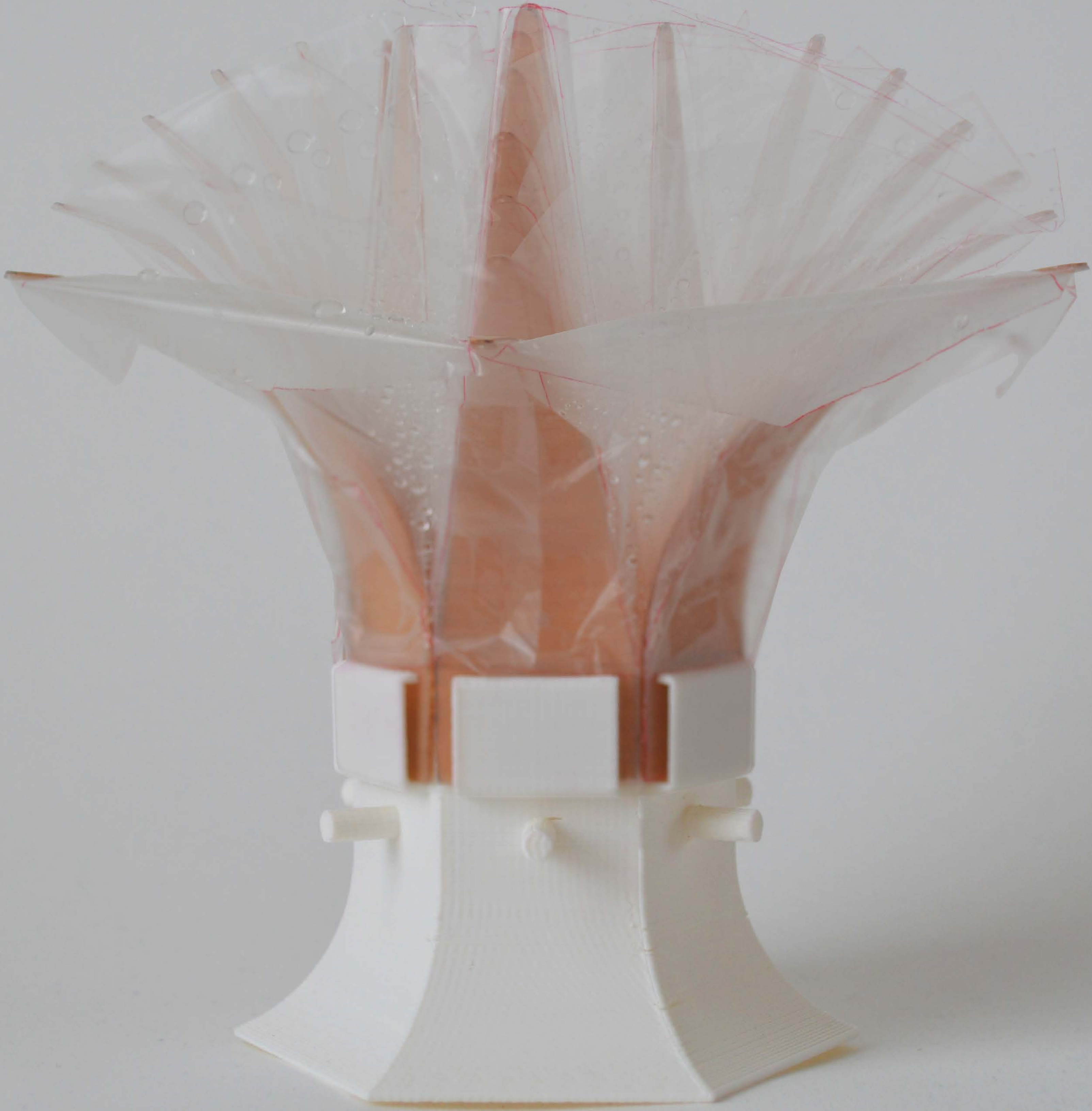


FIG. 33 (FACING PAGE) FINAL PROTOTYPE MOTION
The image shows the final assembly of the hygroscopic mechanism in a still visualization of the completed motion from closed to entirely open.

FIG. 34 FINAL PROTOTYPE MOTION
The image shows the final assembly of the hygroscopic mechanism in its closed state.

FIG. 35 FINAL PROTOTYPE MOTION
The image shows the final assembly of the hygroscopic mechanism in its partially open state.

FIG. 36 FINAL PROTOTYPE MOTION
The image shows the final assembly of the hygroscopic mechanism in its open state.

# SITE APPLICATION

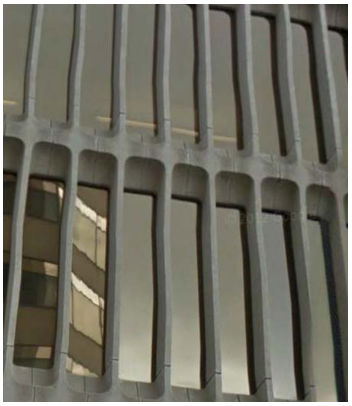


FIG. 1 ORIGINAL FACADE OF THE GLOBAL HOUSE
Image of the concrete grille facade designed by WZMH Architects for the original Global House. Image retrieved from: White, Craig . "Global House to be Globally Made Over into The Icon." Urban Toronto. December 7, 2012. Accessed December 14, 2017. http://urbantoronto.ca/news/2012/12/global-house-be-globally-made-over-icon.

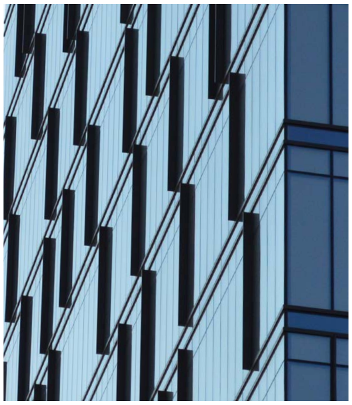


FIG. 2 FACADE AFTER RESKINNING
Image of the facade replaced with the glass curtain/window wall systems showing the randomized fins and narrow mullion spacing, mimicking the grille.

FIG. 3 (FACING PAGE) 480/488 UNIVERSITY AVENUE VIEW FROM SOUTH EAST CORNER
The image shows the original office tower currently under development in Toronto.

## *Site Conditions*

The site chosen for implementation of the design proposal is located at 480/488 University Avenue, which occupies the corner of University Avenue and Dundas Street West in downtown Toronto. The original building to the site, known as the Global House, was designed by WZMH Architects and was completed in 1968. The original facade, as an example of international style architecture, was a precast concrete grille that has gradually deteriorated over the lifespan of the building (Fig. 1). Due to heavy crumbling as a result of weathering, inefficiencies in thermal control from single pane windows, poor lighting quality from deep-set windows, and unhappy occupants as a result of restricted views, the building is to be reskinned. Alongside this development, the current 18-storey commercial office tower is to receive an additional 37 storey residential tower above for a total of 55 storeys that will also include amenity spaces for social and recreational activities[1]. The current progress of this development can be seen in fig. 3.

While the design for the tower renewal is the work of Core Architects, the addition of 37 storeys to the existing tower is made possible through the use of complex steel braces designed by Sigmund Soudack and Associates. The new facade, to enclose the entirety of the building, is a combination of both curtain wall and window wall systems (Fig. 2). The design of the curtain wall is said to pay homage to its predecessor through randomized fins and narrow mullion spacing that references the composition of the concrete grille. The new cladding is meant to improve both building performance and improve occupant satisfaction through the allowance of more natural light, improved insulation through the replacement of single pane windows, and improved views to the exterior. Since occupant comfort was a concern of the residents within the existing office tower, the building will also receive an updated HVAC system to ensure comfort in accompaniment of the new, entirely glazed, exterior[2].

The design research and analysis undergone within this thesis uses the opportunity provided by this unique development to explore the ways in which a facade system assembled with hygroscopic meteorosensitivity can be implemented within an urban environment to enable passive responsive

[1] Landau, Jack . "Re-Skinning of 488 University Continues at Dundas & University." Urban Toronto. May 20, 2016. Accessed December 14, 2017. http://urbantoronto.ca/news/2016/05/re-skinning-488-university-continues-dundas-university.

[2] Landau, Jack . "Re-Skinning of 488 University Continues at Dundas & University." Urban Toronto. May 20, 2016. Accessed December 14, 2017. http://urbantoronto.ca/news/2016/05/re-skinning-488-university-continues-dundas-university.

behavior of the envelope to its immediate atmospheric context. While the facade is specifically engaging with the office occupancy located on the third and fourth floors, the assembly has been imagined into a number of different scenarios.

### *Humidity Emitters*

Actuation of the facade takes place through the uptake of moisture into the fibrils of the wood veneer, which can result from activities or changes in environmental moisture content originating from either side of the facade. From the interior space enclosed within the envelope, the human body is the emitter of humidity. This emission of moisture is a result of metabolic process controlling internal bodily temperature through a continuous heat exchange with the surrounding environment. This heat exchange can either increase or decrease depending on the perceived thermal state of the body, which monitors its internal thermal conditions by measuring the temperature of the blood as it passes through the skin, spine, and several abdominal organs[3]. The majority of heat released from the body occurs through the skin, while a small percentage takes place as a result of respiration. Heat release through the skin takes place through dry heat losses of convection, conduction and radiation, as well as wet losses through evaporation of sweat from the surface of the skin[4]. The temperature of the epidermis itself also plays a secondary role in the production of sweat, where a warmer skin temperature in comparison to the internal temperature of the body can rapidly increase the sweat rate of the body for evaporative cooling. Vapor accumulation within the environment directly outside the body is the result of a latent heat transfer between the surface of the body and the environment, accounting for 25% of the body's total heat loss (though this transfer most commonly takes place between the skin and clothing prior to an additional latent transfer from the clothing to the environment). Without the production of sweat, the body still maintains a constant diffusion of moisture to the environment through the loss of water vapor through the skin, where the heat loss resulting from this process is referred to as "insensible evaporation". The loss of moisture through insensible evaporation amounts to approximately 100 to 150ml per day per $m^2$ of skin surface, where the skin surface of the average male is $1.8m^2$ and the average female is $1.6m^2$, equating to 6% of the body's total daily heat loss. Evaporative heat loss and an additional latent transfer takes place through the breathing cycle, which involves the transfer of vapor from the body to the environment through the exhalation of air[5].

Actuation of the facade through fluctuations in relative humidity within the exterior environment will also take place. The presence of water vapor within a given volume of air is highly correlated to the temperature of that volume[6]. Therefore, in urban environments, the distribution of humidity is largely based on local contexts along with the dewfall, evapotranspiration, and urban heat island effect taking place at the time. Both local and global distributions of humidity within volumes of air are not zonally uniform, but rather have points of various intensities and decrease with altitude. Global maximums occur at the equator, while global minimums take place at the subtropical regions around 30 degrees north and south[7]. For the specific site studied within this thesis, high humidity levels are a result of two global factors; the first is the movement of air masses from the Gulf of Mexico and the second is a result of the Bermuda high, a semi-permanent and subtropical region of high atmospheric pressure which

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[3] Arens, Edward A., and H. Zhang. "The skin's role in human thermoregulation and comfort." Center for the Built Environment (2006).

[4] Voelker, Conrad, Sabine Hoffmann, Oliver Kornadt, Edward Arens, Hui Zhang, and Charlie Huizenga. "Heat and moisture transfer through clothing." In eleventh international IBPSA conference. 2009.

[5] Arens, Edward A., and H. Zhang. "The skin's role in human thermoregulation and comfort." Center for the Built Environment (2006).

[6] Pierrehumbert, Raymond T., Hélène Brogniez, and Rémy Roca. "On the relative humidity of the Earth's atmosphere." The General Circulation (2007).

[7] Peixoto, JoséP, and Abraham H. Oort. "The climatology of relative humidity in the atmosphere." Journal of Climate 9, no. 12 (1996): 3443-3463.

[8] Mortillaro, Nicole. "Why it's so hot." Global News. June 24, 2013. Accessed January 01, 2018. https://globalnews.ca/news/667352/why-its-so-hot/.

pushes humidity into the region on southwesterly winds[8]. Extremely localized differences in relative humidity will be a result of changes in temperature, and therefore the capacity of the air to hold moisture, due to shading, reflectivity of local materials, and heat capacity of materials. Proximity to Lake Ontario also has an effect on the local climate through the production of cooler summer and warmer winter temperatures than what would occur if the lake were removed. Additionally, moisture evaporation from the lake contributes to the humidity of the region[9].

### *Design Applications*

Within the office occupancy located on the third and fourth floors of 480/488 University Avenue, the floor plate is organized so the desk spaces are located around the perimeter of the building. While this ensures that occupants have natural lighting and views to the exterior, thus addressing concerns vocalized during the design process of the new facade, most of the occupants observed had began to leave the shading devices down permanently due to discomfort (Fig. 4 through 6).

FIG. 4 INTERIOR OF OFFICE A
Image shows a view of the typical floor plan of this office occupancy, demonstrating the use of shading devices for improved comfort.

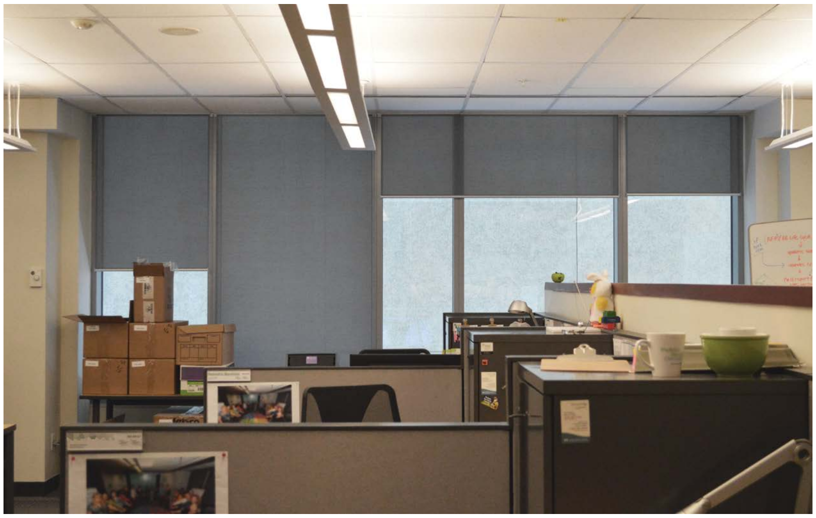

FIG. 5 INTERIOR OF OFFICE B
Image shows a view of the typical floor plan of this office occupancy, demonstrating the use of shading devices for improved comfort.

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[9] "The Climate and Weather of Toronto, Ontario." Living in Canada. Accessed January 01, 2018. https://www.livingin-canada.com/climate-toronto.html.

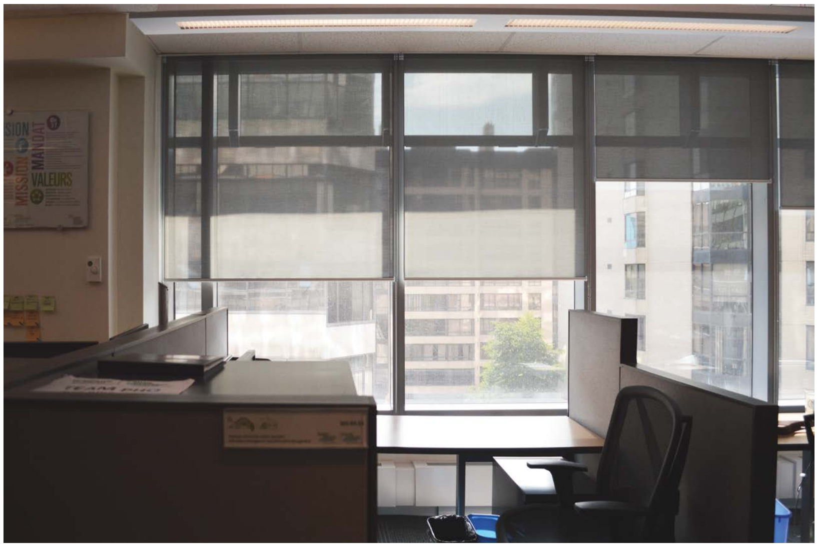
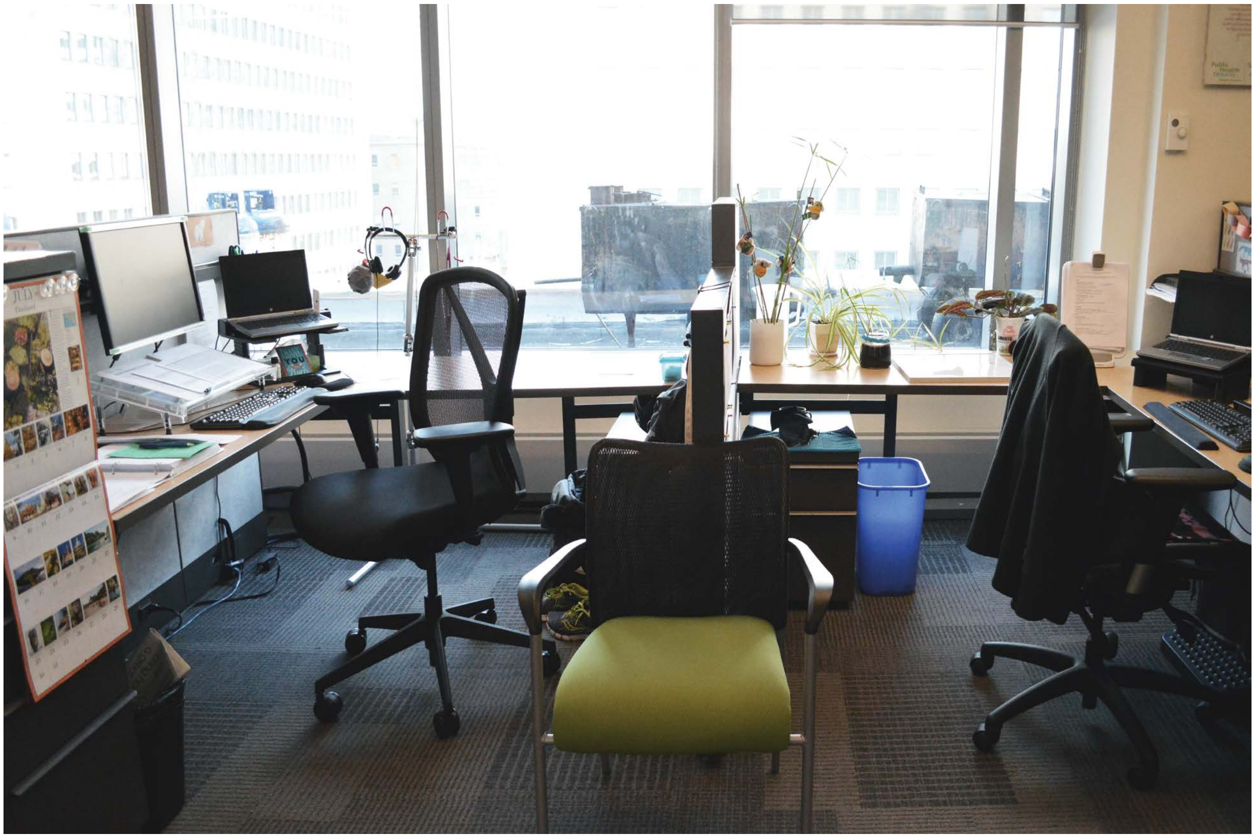


FIG. 6 INTERIOR OF OFFICE C
Image shows a view of the typical floor plan of this office occupancy, demonstrating the use of shading devices for improved comfort.

FIG. 7 UTILIZATION OF SINGULAR OFFICE SPACE
Image shows a the use of a single workspace unit within the perimeter of the office space.

A typical workspace shown in fig. 7 is used to explore the new spatial qualities with which the implementation of the responsive facade would provide if it were to be used within this reskinning development. The following scenarios compare the spatial qualities provided by the hygroscopic envelope within both cloudy and sunny environments, during various humidity variations. The first; showing the facade in a humid atmospheric context, the second; in a slightly humid context and the third; a non-humid context (Fig. 8.a through 10.b).



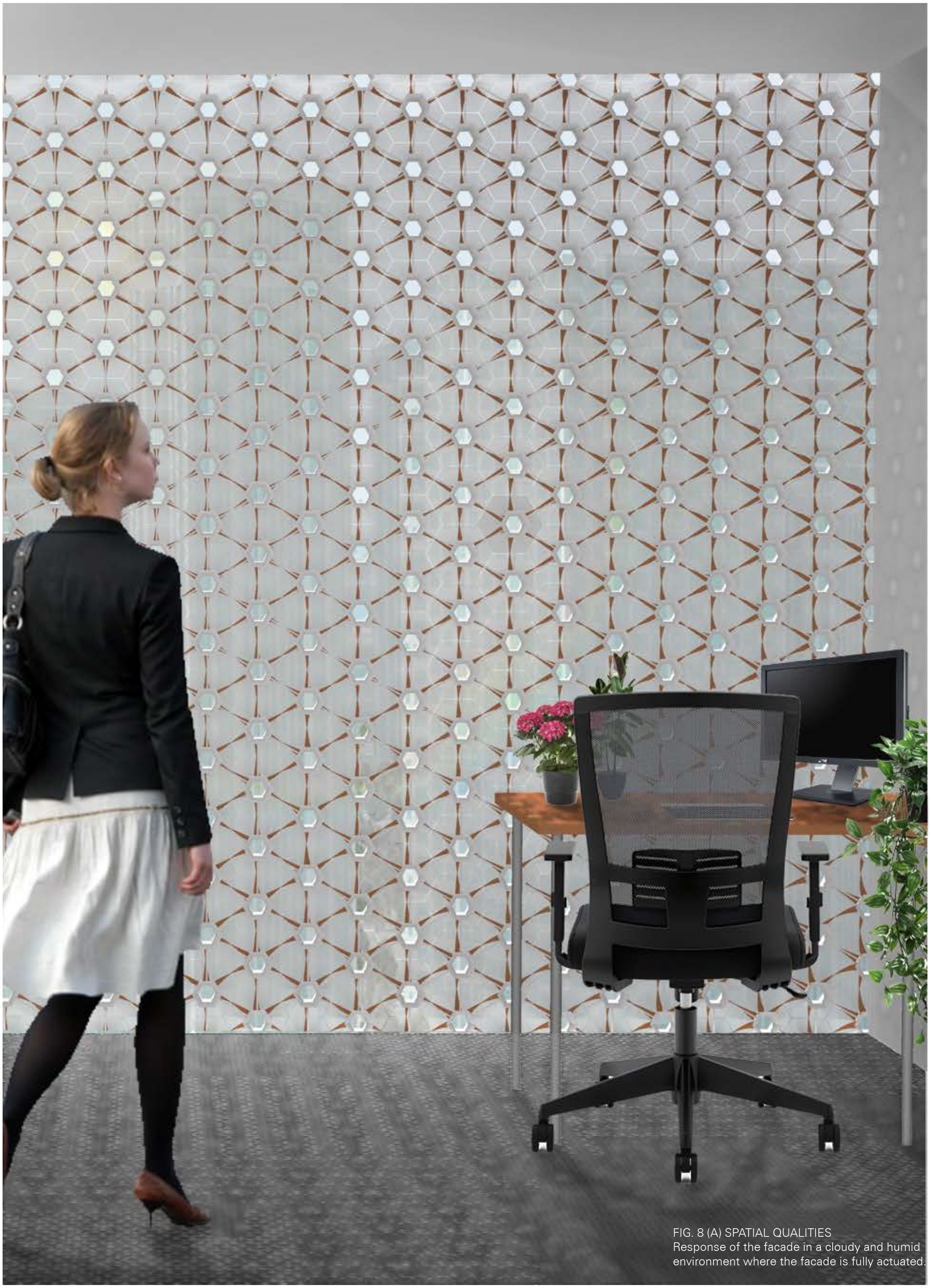


FIG. 8 (A) SPATIAL QUALITIES
Response of the facade in a cloudy and humid environment where the facade is fully actuated.

FIG. 8 (B) SPATIAL QUALITIES
Response of the facade in a sunny and humid environment where the facade is fully actuated.

FIG. 9 (A) SPATIAL QUALITIES
Response of the facade in a cloudy and semi-humid environment where the facade is partially actuated.

FIG. 9 (B) SPATIAL QUALITIES
Response of the facade in a sunny and semi-humid environment where the facade is partially actuated.

FIG. 10 (A) SPATIAL QUALITIES
Response of the facade in a cloudy and non-humid environment where the facade is inactive.

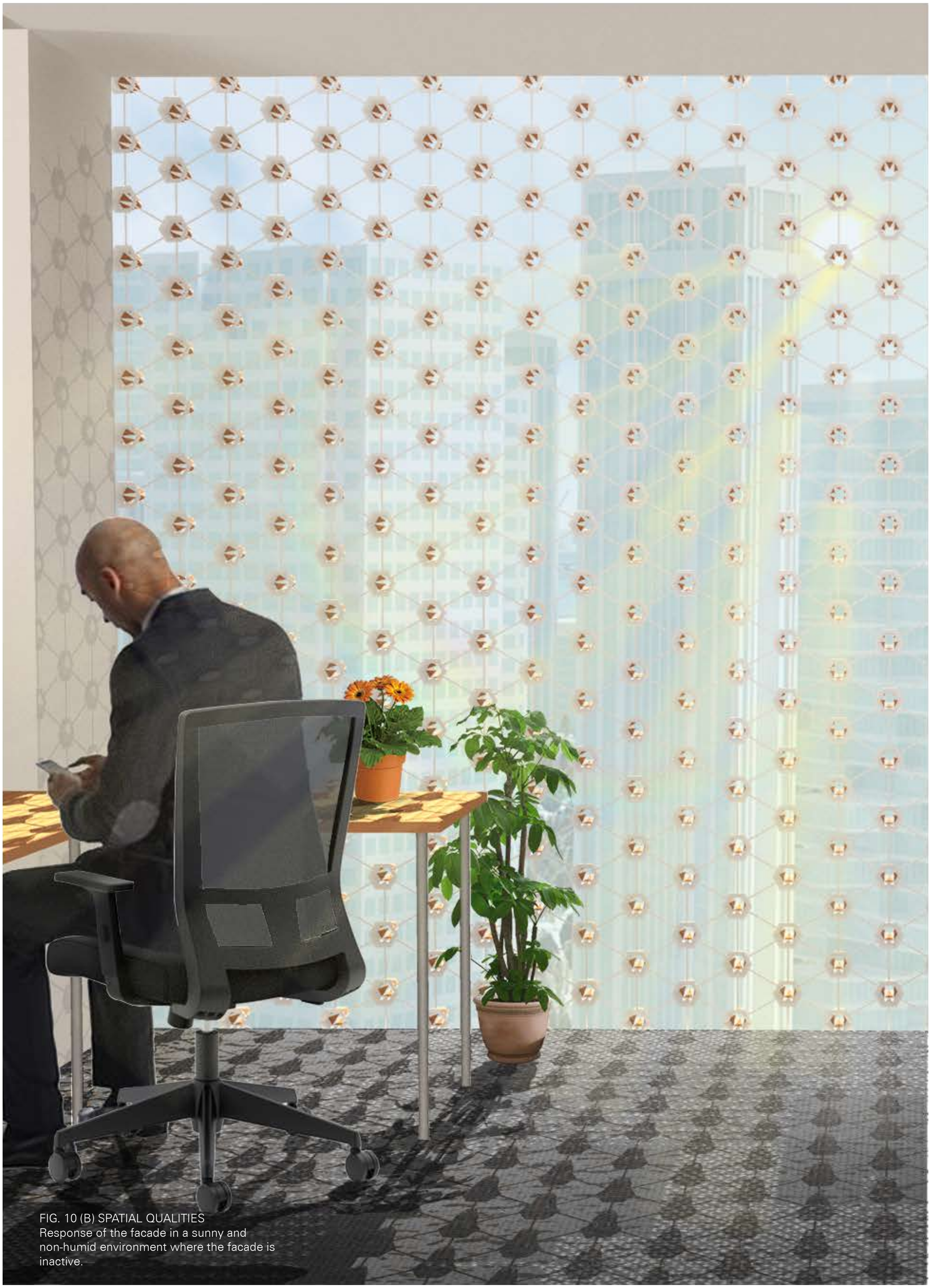
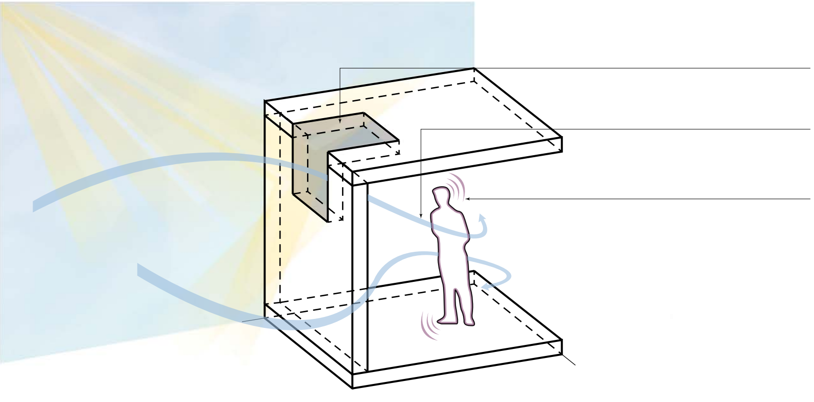


FIG. 10 (B) SPATIAL QUALITIES
Response of the facade in a sunny and non-humid environment where the facade is inactive.



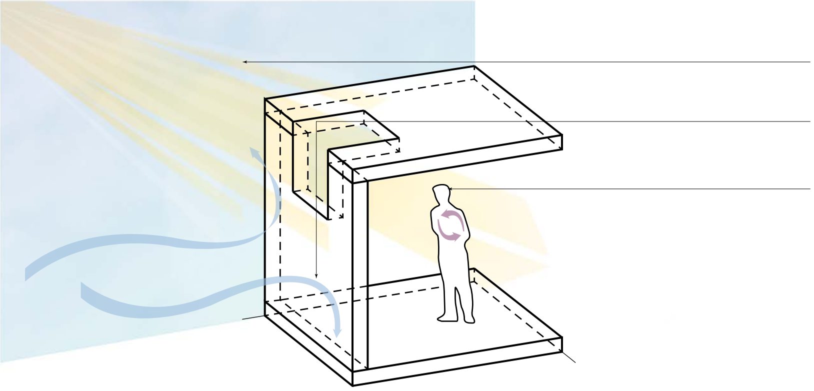
Exclusion of light to prevent heat gain

Allowance of air for increased movement and ventilation

Body tries to prevent temperature increase through dissipating heat

Increasing comfort with the addition of humidity requires increased air movement as the capacity of the body to reduce internal heat through evaporation is diminished by the reduced capacity of the air to absorb moisture.

*Comfort in Hot Environments*



Inclusion of light to increase heat gain

Preventionof air transmission for decreased movement and ventilation

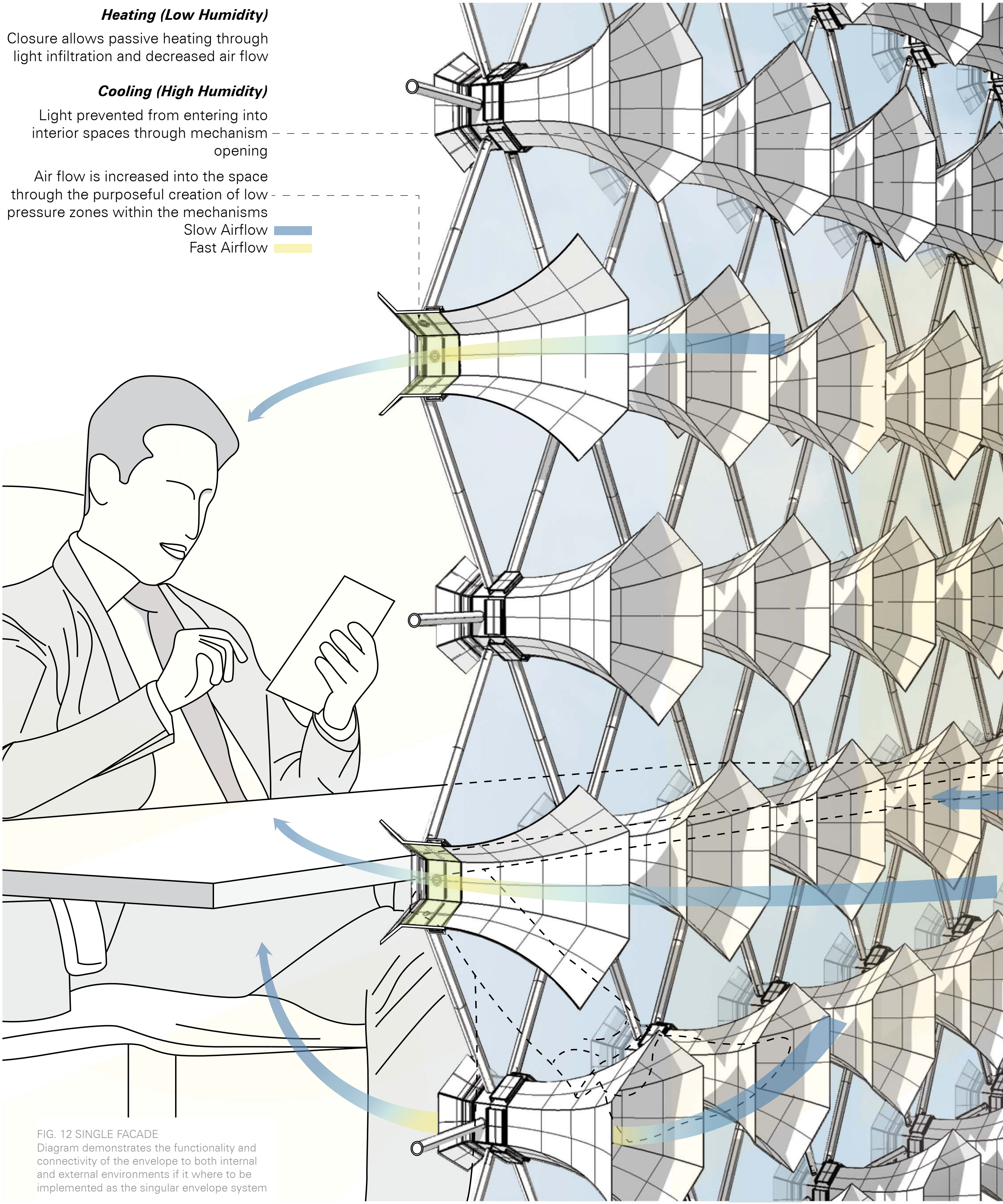
Body tries to increase internal temperature through heat retention

Increasing comfort within the presence of humidity results in a reduction of ventilation needs as the additional environmental humidity will deminish the insulation value of the clothing worn by the occupant through an increase in the rate of heat transfer.

*Comfort in Cold Environments*

FIG. 11 COMFORT AND ENVIRONMENT
The way the body achieves comfort is manipulated by the environmental conditions it interacts with. The presence of humidity amplifies these conditions by making it difficult for the body to either dissipate heat in warm temperatures or retain heat in cooler temperatures.

To improve spatial qualities, the performance of the mechanism is calibrated to correspond to the comfort needs of the occupant in relationship to the environment. In hot temperatures, the occupant needs to dissipate heat in order to maintain comfort. This corresponds to an envelope that allows for increased ventilation while simultaneously excluding excessive natural lighting to prevent solar heat gain. This is accomplished through the assembly of the mechanism whereby the opacity of the facade is increased as the mechanism opens to simultaneously admit airflow. The importance of this airflow is increased as the humidity of a given environment rises since the capacity of the air to absorb moisture from the skin is diminished with increased moisture content. This process is inverse for environments of lower temperatures. As the body of the occupant moves from heat dissipation to heat retention, the envelope should alternatively allow for natural solar gain and exclude the infiltration of air from the external environment. While the mechanism would allow for passive solar gain during low humidity periods of global closure, the limitations of the calibrated material would still result in the opening of the mechanism to the presence of humidity regardless of cooler temperatures. This relationship is explored through potential applications of the facade into different envelope systems. The first application of the design, seen in fig. 12, is as the sole mediator between the interior and exterior conditions. While this implementation of the design would most likely be insufficient for year-round use within the Toronto context of the site, it would be suitable for more temperate climates. A more suitable application for the site-specific environment would be the visualization of application seen in fig. 13, where the responsive system has been deployed



***Heating (Low Humidity)***

Closure allows passive heating through light infiltration and decreased air flow

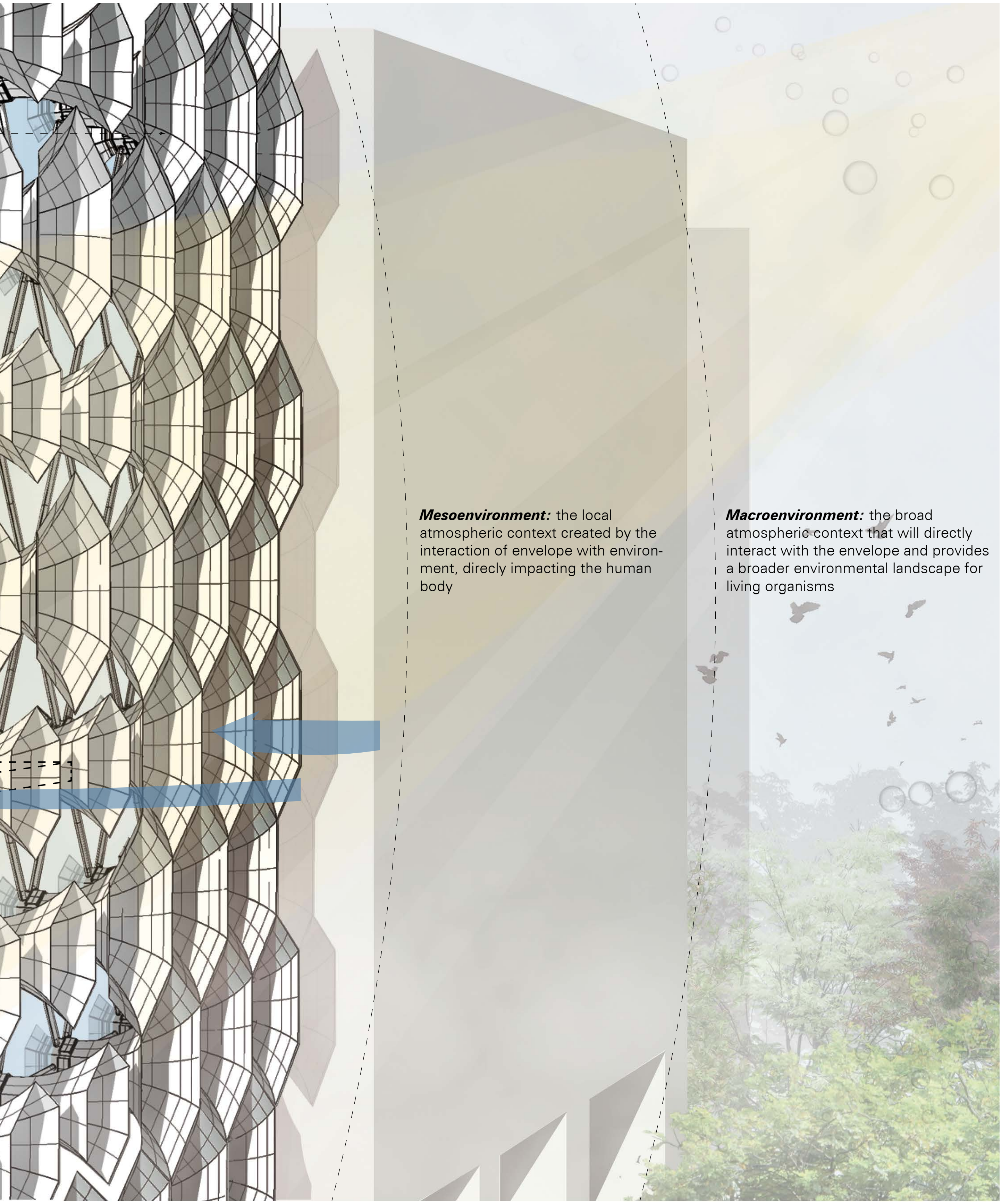
***Cooling (High Humidity)***

Light prevented from entering into interior spaces through mechanism opening

Air flow is increased into the space through the purposeful creation of low pressure zones within the mechanisms

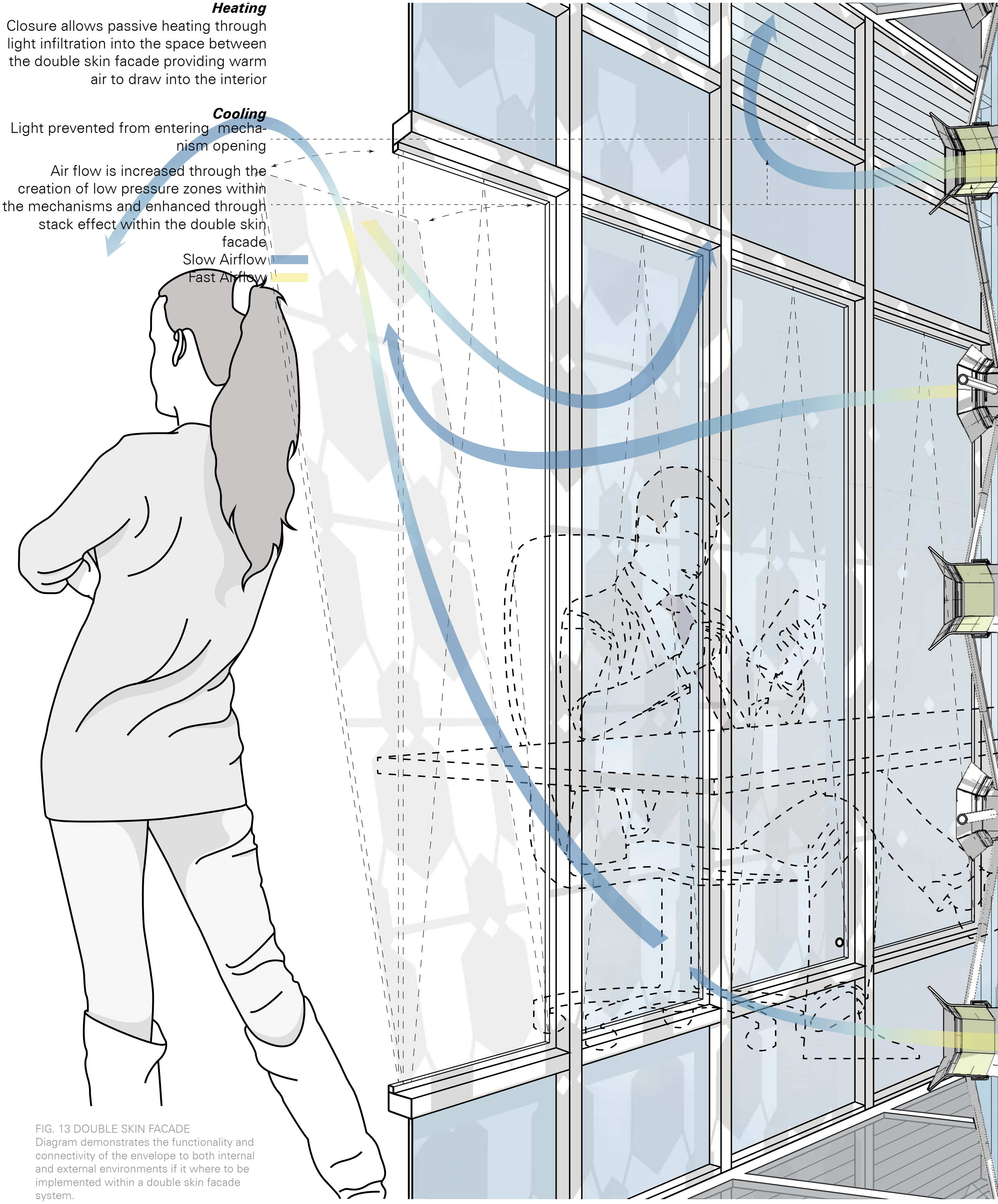
Slow Airflow 🟦
Fast Airflow 🟨

FIG. 12 SINGLE FACADE
Diagram demonstrates the functionality and connectivity of the envelope to both internal and external environments if it where to be implemented as the singular envelope system



***Mesoenvironment:*** the local atmospheric context created by the interaction of envelope with environment, direcly impacting the human body

***Macroenvironment:*** the broad atmospheric context that will directly interact with the envelope and provides a broader environmental landscape for living organisms



***Heating***

Closure allows passive heating through light infiltration into the space between the double skin facade providing warm air to draw into the interior

***Cooling***

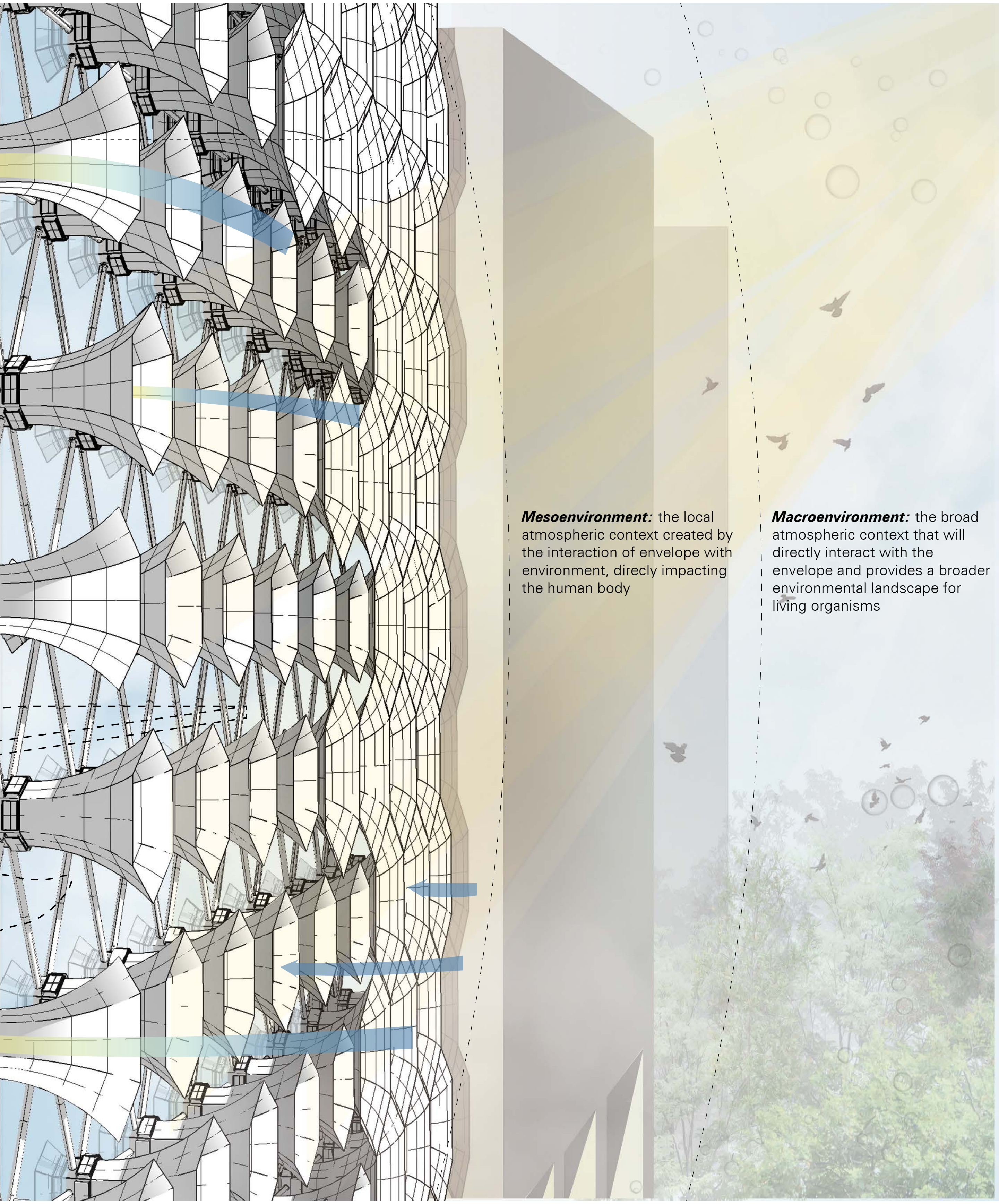
Light prevented from entering mechanism opening

Air flow is increased through the creation of low pressure zones within the mechanisms and enhanced through stack effect within the double skin facade

Slow Airflow 🟦

Fast Airflow 🟨

FIG. 13 DOUBLE SKIN FACADE
Diagram demonstrates the functionality and connectivity of the envelope to both internal and external environments if it where to be implemented within a double skin facade system.



**Mesoenvironment:** the local atmospheric context created by the interaction of envelope with environment, direcly impacting the human body

**Macroenvironment:** the broad atmospheric context that will directly interact with the envelope and provides a broader environmental landscape for living organisms

**Heating**

Closure of the mechanisms allows passive heating through light infiltration into the interior and decreased air flow

**Cooling**

Light prevented from entering into interior spaces through mechanism opening

Air flow is increased into the space through the purposeful creation of low pressure zones within the mechanisms

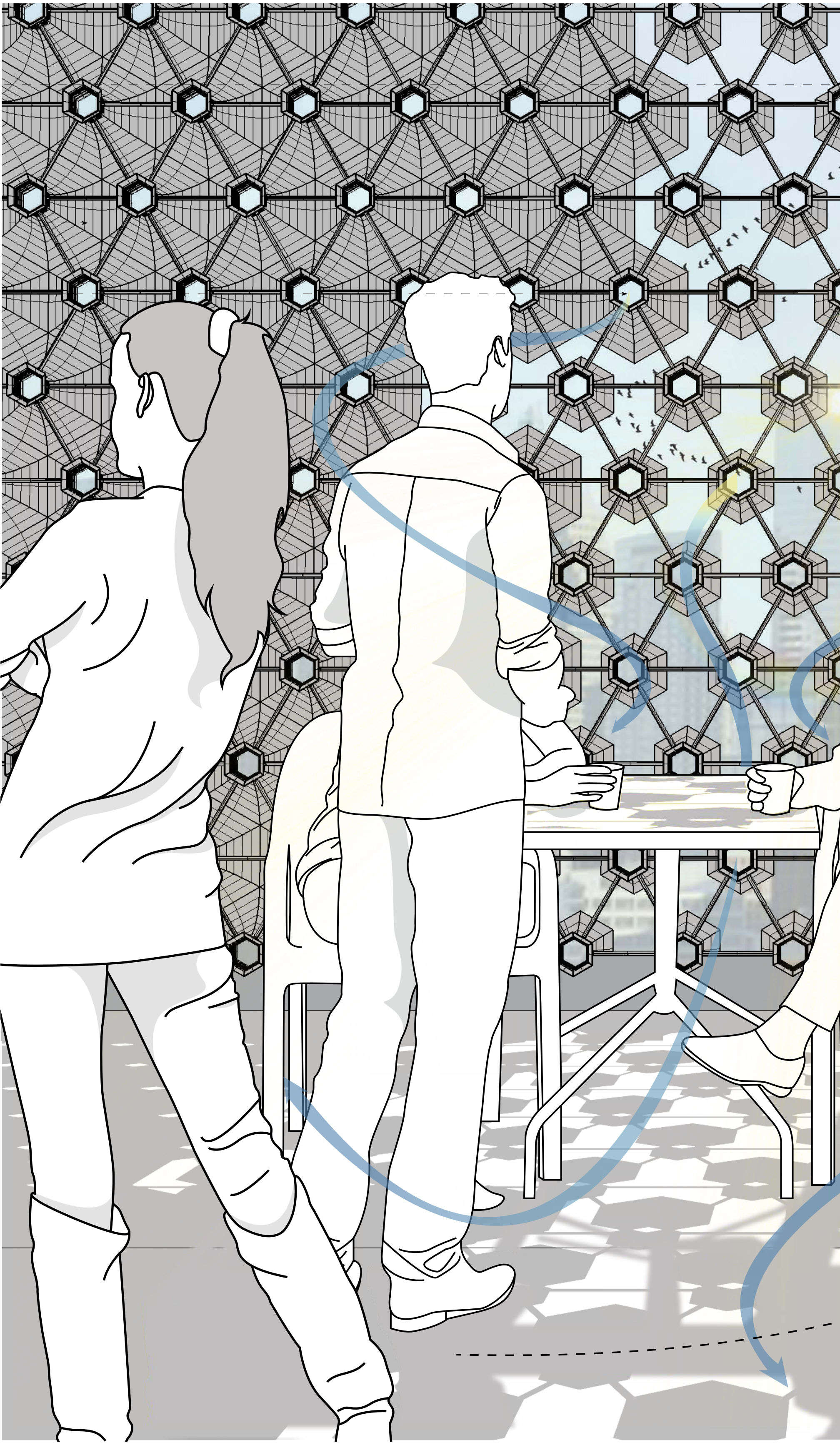
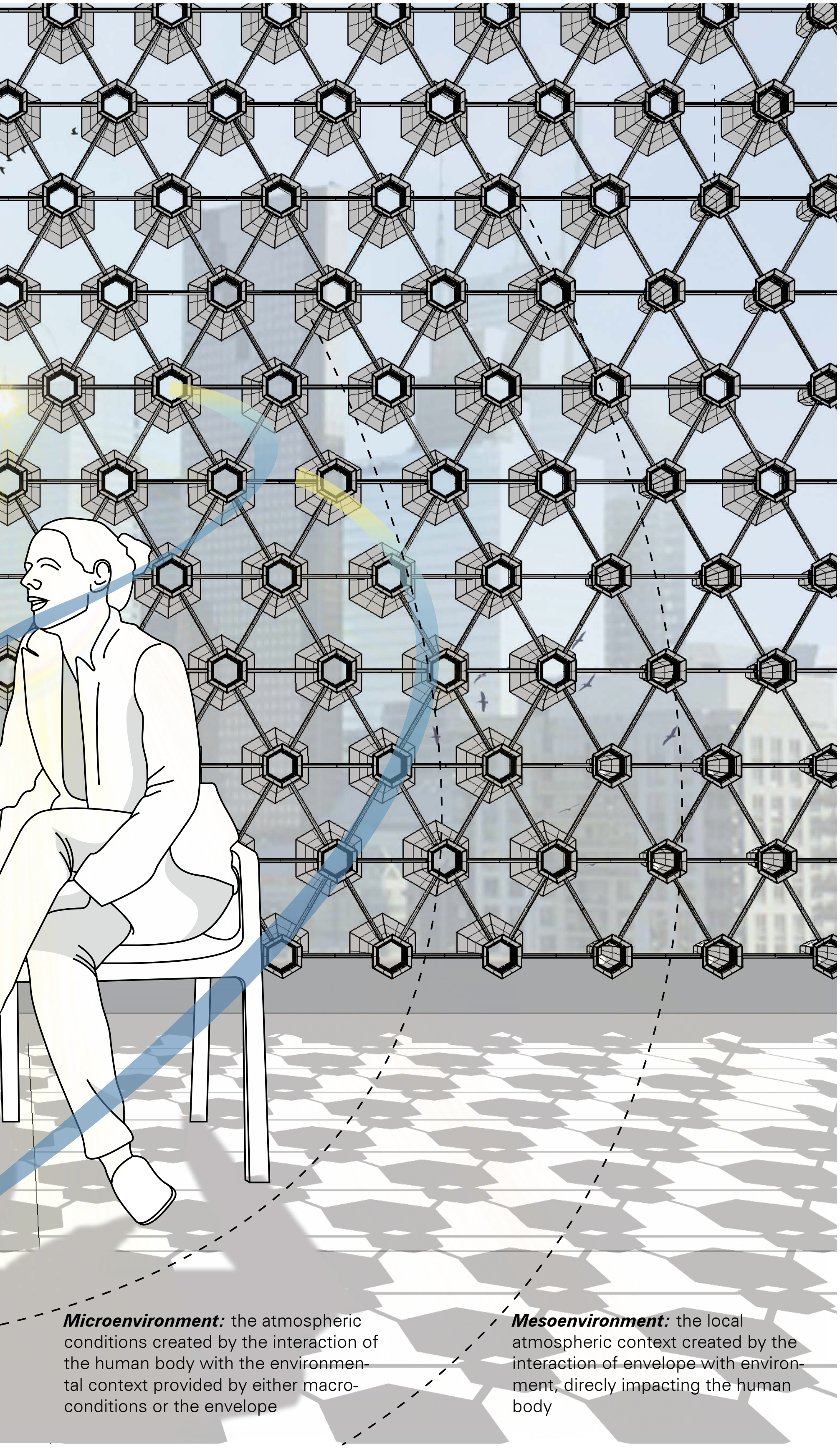


FIG. 14 BRISE SOLEIL
Diagram demonstrates the functionality and connectivity of the envelope to both internal and external environments if it where to be implemented as the envelope surrounding an informal atmospheric space such as those of outdoor amenities and patios.



**_Microenvironment:_** the atmospheric conditions created by the interaction of the human body with the environmental context provided by either macro-conditions or the envelope

**_Mesoenvironment:_** the local atmospheric context created by the interaction of envelope with environment, direcly impacting the human body within a double skin facade. Within this situation, the air movement generated by the low-pressure zone would be coupled with stack effect created within the interstitial space between envelopes. The occupants would have the benefit of both a passive responsive system with increased personal adaptive control through operable segments within the interior envelope. This strategy of implementation would allow for the facade to continue performing within climates experiencing greater variability and colder temperatures. A third potential application for this facade design, that could also take place within the chosen site conditions, is as a responsive facade for an interstitial space such as an amenity patio, or other flexible environment that is expected to require additional thermal mediation by the individual occupant (Fig. 14). Within each visualization of potential application, the operation of the facade is demonstrated as it would be affected by the emitters within the environment. Through these explorations the responsive envelope proposed within this thesis is presented within a variety of functional situations, and while they may not all be directly applicable to the Toronto climate chosen for specific application within this thesis, they explore the ways in which adaptability within the facade can both be implemented into existing typical conditions and improve on the spatial qualities and comfort of the interior.

# CONCLUSION

*"The urban dweller and the city are in a state of constant flux - changing and evolving in reaction to emerging contexts and conditions. The [urban building] of the future fosters this innate quality, essentially functioning as a living organism in its own right - reacting to the local environment and engaging the users within." - Josef Hargrave & Ralf Wilson*[1]

This thesis has presented research into the creation of hygroscopic, autonomously responsive, envelope systems through the research and development of a wood veneer composite mechanism. The ambition of this mechanism was to demonstrate the ways in which amplification of natural material properties, specifically those that demonstrate movement triggered through environmental change, can be incorporated into architectural envelope systems to achieve passive performance alongside environmental adaptation. Created as a passive cooling strategy, the mechanism extrapolates on the functional performance of the Venturi tube, the Ipomoea flower, and the conifer cone, to produce a design capable of controlling the passage of airflow and transmission of light into interior spaces. This system is proposed as a low cost and low-tech alternative to energy intensive technological strategies that are deployed within contemporary envelopes to generate responsive behavior through networks of sensors, actuators, and control mechanisms. The use of hygroscopic bilayer composites allows for sensing and actuating of the mechanism to take place within the same system as a result of environmentally triggered material properties. This allows the envelope to regain the role as environmental mediator as the physical structure of the facade is involved in the atmospheric changes arising from both the enclosed interior and the terrestrial exterior.

While this thesis presents an exploration into the ways in which morphological characteristics can be used to generate passive adaptation within facade systems, further development is needed to ensure the success of the system. The first area in need of further development were the design to be taken further is the computational fluid dynamics modeling done to demonstrate proof-of-concept flow. Though the use of this software was successful in demonstrating internal flows within the mechanism, both the grid used to map the data points as well as the barrier used to alter airflow are rigid. To develop the mechanism further and increase its accuracy, the grid would have to move in sequence with the

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[1] Hargrave, Josef, and Ralf Wilson. "Imagining the tall building of the future." CTBUH Journal 3 (2013).

motion of the mechanism as it opens. Additionally, large scale performance testing would also be required, as global air movement flowing around a building volume would alter the flow of air through the mechanism.

Further large-scale development would also need to take place for a user analysis. Testing such as this would allow for confirmation of performance, ensuring that the envelope is controlling comfort, and ensure that occupants are satisfied with passive adaptation of the thermal environment. Additional analysis would also need to be completed on the performance of the envelope as the local climate changes, ensuring the mediation of airflow and light infiltration remains even if the local context of the built application changes.

Continued development and exploration into materials with passive adaptive performance would allow for greater functionality and response to a wider variety of environmental factors. Currently, with the materials proposed within the mechanism, it is only capable of responding to fluctuations in relative humidity, and while this does allow for environmental mediation, additional material coupling and further exploration would allow for growth of the system. Alongside this, the materials used for the passive layer within the composite as well as the adhesive between the two materials are petroleum based. Further development and use of true bioplastics as well as bio-adhesives would improve the environmental sustainability of the mechanism and improve end-of-life recycling. Additionally, in responsive systems such as this, there is no possibility for manual intervention after the final assembly. However a possible solution to this could be to incorporate meteorosensitive systems as hybrids, as demonstrated for example by the double skin facade where manual intervention can take place within a secondary system.

## *Further Development*

As social systems move further into a new geological era, cultural adaption is inevitable and necessary to survival. Through the use of adaptive systems, which utilize material properties to achieve passive performance, the production of GHG emissions by buildings as a direct result of interaction between the envelope with the given environment, can be significantly reduced. Dense urban centers of future populations will not only have to navigate through steadily increasing general and ambient temperatures, but will also experience significant contextual change over their lifetime. Systems such as the hygroscopic one presented within this thesis aim to discuss ways in which building envelopes can react and reintegrate themselves within this uncertainty so as to effectively navigate between the needs of both occupant and environment. While the presented design suggests a scale of the envelope to be a slender reveal from building surfaces, consistent with present day contemporary envelope design, continued extrapolation of biomimetic principles could both increase the scale and functionality of the mechanism. Alternatively, different cuts of wood such as rotary sliced veneer in the place of quartersawn veneer, or composite materials with maintained hygroscopic properties, can largely increase the potential scale of the structures. This would additionally increase the possibilities for application within the facade, having the potential to engage the facade more explicitly with the occupancy of its spaces or with other surrounding buildings. Implications of this type of research into the design realm of architectural practice could be a reevaluation of both the facades material assembly and functionality, as performance is no longer limited to technological equipment.

Further steps needing to take place in order to achieve this larger application are within material studies of both the active and passive layers. Increasing the hygroscopic capacity of wood veneer and the biosafety of the adhesives and passive layers used within the coupled mechanism. Despite draw-backs, systems such as the hygroscopic one focused upon within this thesis, offer an exciting opportunity for improving building performance and ensuring occupant comfort in continuously fluctuating environmental conditions by reinstating an open dialogue between the human and terrestrial environment, reconnecting occupants with daily rhythms and patterns of the natural world.

# BIBLIOGRAPHY

Arens, Edward A., and H. Zhang. "The skin's role in human thermoregulation and comfort." Center for the Built Environment (2006).

Armstrong, rachel. "How Do the Origins of Life Sciences Influence 21st Century Design thinking?" PDf. Proceedings of the European Conference on Artificial life, (2015): 2-11 Doi: http://dx.doi.org/10.7551/978-0-262-33027-5-ch002

Benyus, Janine M. "Biomimicry: innovation inspired by nature." (2002).

Baseta, Efilena . "Hygro." Accessed November 2017. http://cargocollective.com/efilenabaseta/ Hygro.

Cannon, Walter Bradford. "The wisdom of the body." 1939.

"Chemistries." Adhesives Research. 2017. Accessed May 21, 2017. http://www.adhesivesresearch.com/technologies/ chemistries/.

"Chemistry of Epoxies." Progressive Epoxy Polymers Inc.. Accessed May 21, 2017. http:// www.epoxyproducts.com/chemistry.html.

Clancy, l. J. "Aerodynamics (Chapter 3)." Topics on Pressure Fields (1975): 22-59.

Dawson, Colin, Julian FV Vincent, and Anne-Marie Rocca. "How pine cones open." Nature 390, no. 6661 (1997): 668-668.

De Dear, Richard J., and Gail S. Brager. "Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55." Energy and buildings 34, no. 6 (2002): 549-561.

El-Shorbagy, Abdel-moniem. "Design with nature: windcatcher as a paradigm of natural ventilation device in buildings." International Journal of Civil & Environmental Engineering IJCEE-IJENS 10, no. 03 (2010): 21-26.

"Energy." UN-Habitat. 2012. https://unhabitat.org/urban-themes/energy/.

Environment and Climate Change Canada. "Toronto Historical Wind Speed." Amateur Weather Statistics for Toronto, Ontario. https:// toronto.weatherstats.ca/metrics/wind_speed. html.

Fiorito, Francesco, and Mattheos Santamouris. "High Performance Technologies and the future of architectural design." TECHNE-Journal of Technology for Architecture and Environment 13 (2017): 72-76.

Fitch, James Marston. "American Building: 2, the Environmental Forces that Shape it." Vol. 2. Houghton mifflin, (1972) 239 - 241

Fitch, James Marston, and Daniel P. Branch. "Primitive architecture and climate." Scientific American 203, no. 6 (1960): 134-144.

Furuto, Alison. "Bloom/Do|SU Studio Architecture". ArchDaily (2012). <https://www. archdaily.com/215280/bloom-dosu-studio- architecture/> iSSN 0719-8884

Gruber, P. "Biomimetics in architecture: architecture of life and buildings." Wien: Springer. (2010)

Guo, Qiaohang, Eric Dai, Xiaomin Han, Stephen Xie, Eric Chao, and Zi Chen. "Fast nastic motion of plants and bioinspired structures." Journal of the Royal Society Interface 12, no. 110 (2015): 20150598.

Haraway, Donna. "A Cyborg manifesto: Science, technology, and socialist-feminism in the late 20th century." In the international handbook of virtual learning environments. Springer Netherlands. (2006) 117-158.

Hargrave, Josef, and Ralf Wilson. "Imagining the tall building of the future." CTBUH Journal 3 (2013).

Hensel, Michael. "Performance-oriented architecture: rethinking architectural design and the built environment." John Wiley & Sons, 2013.

Hoberman, Chuck. "Transformation in architecture and design." Transportable Environments 3 (2006): 70-73.

Holstov, Artem, Ben Bridgens, and Graham Farmer. "Hygromorphic materials for sustainable responsive architecture." Construction and Building Materials 98 (2015): 570-582.

"Ipomoea." Fine gardening. Accessed December 26, 2017. http://www.finegardening.com/morning-glory-ipomoea.

Kolarevic, Branko, and Vera Parlac. "Adaptive Building Skins." The Routledge Companion for Architecture Design and Practice: Established and Emerging trends (2015).

Koning, Ross E. "The role of ethylene in corolla unfolding in ipomoea nil (Convolvulaceae)." American journal of botany (1986): 152-155.

Knaack, Ulrich, Tillmann Klein, Marcel Bilow, and Thomas Auer. “Façades: principles of construction.” Birkhäuser, 2014.

Król, Piotr, and Boena Król. “Surface free energy of polyurethane coatings with improved hydrophobicity.” Colloid and polymer science 290, no. 10 (2012): 879-893.

Kwok, Alison G., and Walter T. Grondzik. “The green studio handbook: environmental strategies for schematic design.” Enquiry: A Journal for Architectural Research 4, no. 2 (2007).

La Roche, Pablo M. “Carbon-neutral architectural design.” CRC Press, 2017.

Lally, Sean. “Air from other Planets: A Brief History of Architecture to Come.” Lars muller Publishers, 2013.

Landau, Jack. “Re-Skinning of 488 University Continues at Dundas & University.” Urban Toronto. May 20, 2016. Accessed December 14, 2017. http://urbantoronto.ca/news/2016/05/ re-skinning-488-university-continues-dundas- university.

Lovel, Jenny. “Building envelopes: an integrated approach.” Princeton Architectural Press, 2013.

Ma, Ying, and Junqi Sun. “Humido-and thermo- responsive free-standing films mimicking the petals of the morning glory flower.” Chemistry of Materials 21, no. 5 (2009): 898-902.

Mathews, F. “Towards a Deeper Philosophy of Biomimicry.” Organization & Environment 24, no. 4 (2011): 364-87. doi:10.1177/1086026611425689.

Meier, Eric . “Hardwood Anatomy.” The Wood Database. http://www.wood-database.com/ wood-articles/hardwood-anatomy/.

Menges, Achim, and Steffen Reichert. “Performative Wood: Physically Programming the Responsive Architecture of the HygroScope and HygroSkin Projects.” Architectural Design 85, no. 5 (2015): 66-73.

Mohammed, Layth, Mohamed NM Ansari, Grace Pua, Mohammad Jawaid, and m. Saiful Islam. “A review on natural fiber reinforced polymer composite and its applications.” International Journal of Polymer Science 2015 (2015).

Mortillaro, Nicole. “Why it’s so hot.” Global News. June 24, 2013. Accessed January 01, 2018. https://globalnews.ca/news/667352/why- its-so-hot/.

Mozaffarian, Romania. “Natural Ventilation in Buildings and the tools for Analysis.” PhD Diss., University of Florida, (2009)

Pachauri, Rajendra K., Myles R. Allen, Vicente R. Barros, John Broome, Wolfgang Cramer, Renate Christ, John A. Church et al. “Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change.” IPCC, 2014.

Pawlyn, Michael. “Biomimicry in architecture.” Vol. 15. Riba Publishing, (2011).

Peixoto, JoséP, and Abraham H. Oort. “The climatology of relative humidity in the atmosphere.” Journal of Climate 9, no. 12 (1996): 3443-3463.

Pierrehumbert, Raymond T., Hélène Brogniez, and Rémy Roca. “On the relative humidity of the Earth’s atmosphere.” The General Circulation (2007).

“Plywood.” How Products Are made. 2017. http://www.madehow.com/ Volume-4/Plywood. html.

“Polyurethane Adhesives.” Polyurethane Adhesives Characteristics and Uses. Accessed May 21, 2017. http://www.christinedemerchant. com/adhesive-glue-polyurethane.html.

Portoghesi, Paolo. “Nature and architecture.” (2000).

Queiroz, Antonio UB, and Fernanda P. Collares- Queiroz. “Innovation and industrial trends in bioplastics.” Journal of Macromolecular Science®, Part C: Polymer Reviews 49, no. 2 (2009): 65-78.

Ramirez-Figueroa, C., l. Hernan, A. Gnyet, and M. Dade-robertson. “Bacterial Hygromorphs: Experiments into the integration of soft technologies into building skins.” Proceedings of ACADiA 2016 - Posthuman Frittiert: Data, Designers and Cognitive Machines, Michigan, Ann Arbor. Association for Computer Aided Design in Architecture, (2016). 244-253.

Reeb, James Edmund. “Wood and moisture relationships.” Corvallis, or.: Extension Service, Oregon State University, 1995.

Reichert, Steffen, Achim Menges, and David Correa. “Meteorosensitive Architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness.” Computer-Aided Design 60 (2015): 50-69.

Rupp, Ricardo Forgiarini, Natalia Giraldo Vásquez, and Roberto Lamberts. “A review of human thermal comfort in the built environment.” Energy and Buildings 105 (2015): 178-205.

Song, Kahye, Eunseop Yeom, Seung-Jun Seo, Kiwoong Kim, Hyejeong Kim, Jae-Hong Lim, and Sang Joon Lee. “Journey of water in pine cones.” Scientific reports 5 (2015): 9963.

Sonnewald, Uwe. “Physiology of Movement.” In Strasburger’s Plant Sciences, pp. 531-568. Springer Berlin Heidelberg, 2013.

“Stack Ventilation and Bernoulli’s Principle.” Stack Ventilation and Bernoulli’s Principle | Sustainability Workshop. 2017. https://sustainabilityworkshop. autodesk.com/buildings/stack-ventilation-and-bernoullis-principle.

“Standard 55-2013: Thermal Environmental Conditions for Human Occupancy” ASHRAE. Atlanta USA, 2013.

Steffen, Will, Paul J. Crutzen, and John R. McNeill. “The Anthropocene: are humans now overwhelming the great forces of nature." AMBIO: A Journal of the Human Environment 36, no. 8 (2007): 614-621.

Straube, John . "BSD-042: Historical Development of the Building Enclosure." Building Science Corporation. November 15, (2010)

Su, Yuehong, Saffa B. Riffat, Yen-Liang Lin, and Naghman Khan. "Experimental and CFD study of ventilation flow rate of a Monodraught windcatcher." Energy and buildings 40, no. 6 (2008): 1110-1116.

Sung, Doris Kim. "Skin Deep: Breathing life into the layer between man and Nature." AIA report of University research 3 (2007).

"The basics of making corn starch bioplastic." Green Plastics. December 31, 2016. Accessed November 2017. http://green-plastics.net/ posts/76/qaa-help-with-cornstarch-pla-plastic- project/.

"The Climate and Weather of Toronto, Ontario." Living in Canada. Accessed January 01, 2018. https://www.livingin-canada.com/climate- toronto.html.

"The History of Beehive-Shaped Homes." Earthbag Building, www.earthbagbuilding.com/ articles/beehive.htm.

"The Worrell, Weekes and Walcott Stand, Kensington Oval, Bridgetown." All the information you need about steel construction, www.steelconstruction.org/design-awards/2008/commendation/the-worrell-weekes-and-walcott-stand-kensington-oval- bridgetown/.

Toronto Environment Office, SENES Consultants Ltd. "Toronto's Future Weather and Climate Driver Study: outcomes report." The City of Toronto (October 30, 2012)

Twinn, Chris. "BedZED." Arup Journal 38, no. 1 (2003): 10-16.

Walker, Andy. "Natural ventilation." National Renewable Energy Laboratory (2010).

"World's population increasingly urban with more than half living in urban areas | UN DESA Department of Economic and Social Affairs." United Nations. July 10, 2014. http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html.

van Doorn, Wouter G., and Uulke van Meeteren. "Flower opening and closure: a review." Journal of Experimental Botany 54, no. 389 (2003): 1801-1812.

Voelker, Conrad, Sabine Hoffmann, Oliver Kornadt, Edward Arens, Hui Zhang, and Charlie Huizenga. "Heat and moisture transfer through clothing." In eleventh international IBPSA conference. 2009.

"XIAMETER® Brand Acetoxy Sealants." Silicones Simplified - Xiameter: from Dow Corning. 2017. Accessed May 21, 2017. https:// www.xiameter.com/en/ExploreSilicones/ Producttypes/Sealants/Pages/Acetoxy-Sealants. aspx.

Zhang, J. X. "Analysis on the effect of venturi tube structural parameters on fluid flow." AIP Advances 7, no. 6 (2017): 065315.

### *References*

Auliciems, A. "Towards a psycho-physiological model of thermal perception." International Journal of Biometeorology 25, no. 2 (1981): 109-122.

De Dear, Richard J., Gail Schiller Brager, James Reardon, and Fergus Nicol. "Developing an adaptive model of thermal comfort and preference/ discussion." ASHRAE transactions 104 (1998): 145.

Humphreys, m. A., H. B. Rijal, and J. f. Nicol. "Updating the adaptive relation between climate and comfort indoors; new insights and an extended database." Building and Environment 63 (2013): 40-55.

Nicol, J. Fergus, and Michael A. Humphreys. "Adaptive thermal comfort and sustainable thermal standards for buildings." Energy and Buildings 34, no. 6 (2002): 563-572.

Nicol, J. Fergus, and Michael A Humphreys. "Thermal comfort as part of a self-regulating system." (1973): 174-179

# APPENDIX A

## *Motion Visualization*

This appendix is a video file of the completed cycle of movement done by the hygroscopic mechanism. The file name of this video file is, “Hygroscopic Mechanism Motion.mp4”. If you accessed this thesis from a source other than the University of Waterloo, you may not have access to this file. You may access it by searching for this thesis on https://uwspace.uwaterloo.ca/UWSpace.

# APPENDIX B

## *RhinoCFD*

An important tool used in this thesis was the computational fluid dynamics (CFD) plugin for the 3D modeling platform Rhinoceros. This plugin allowed for the visualization of internal flows through the model and to demonstrate how the design produced would interact with atmospheric phenomena. For this thesis, the models were tested using air, however other fluids can be applied, along with additional parameters to more closely simulate specific situations.

The process of testing models with this CFD plugin is fairly simple and begins with the creation of a solid object or closed surface/polysurface. Objects which are not solid/closed objects/surface are not recognized by the software as an

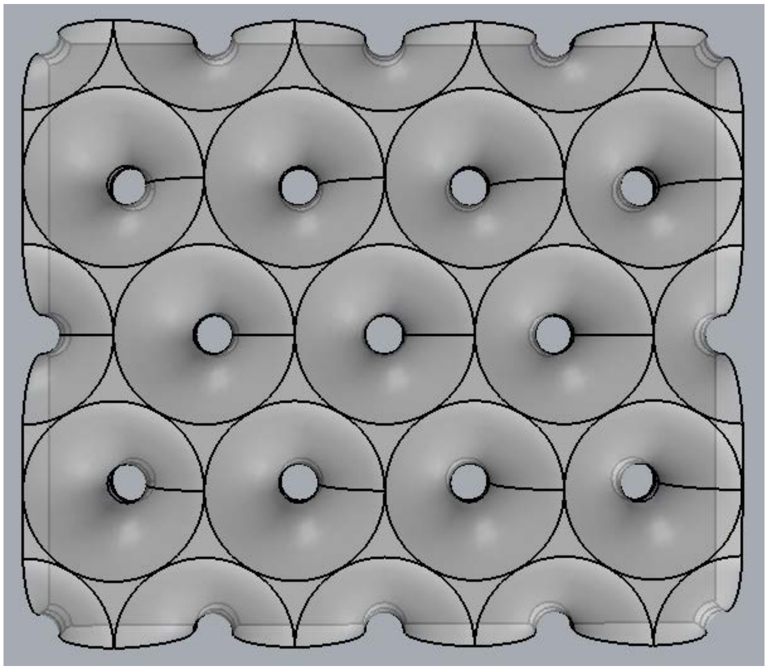

FIG. 101 (RIGHT) SOLID SURFACE
The image shows the closed object used for CFD testing within this thesis.

object and will not produce results even if a domain is successfully made. In order to model the fluid flow through or around the model, an area within the Rhino platform must be designated for mapping and the production of results. This is referred to as creating a domain, which can be selected and will be placed by the software around the closed object created for testing and can be adjusted after it is placed. The domain should be adjusted so that there is room around the object for the air to flow into and out of the domain smoothly, and for the resulting air flow patterns to be mapped without obstruction from the domain. Adjusting the dimensions of the domain is done with the 'gumball' and moving the points along the axis to the desired size. Following this is the creation of an inlet and an outlet by assigning domain faces. The inlet represents the side of the domain where the air enters into the calculated area, and will flow from the inlet to the outlet, where it leaves the simulation. It is during this time when conditions such as speed of the fluid and its parameters for flow are set

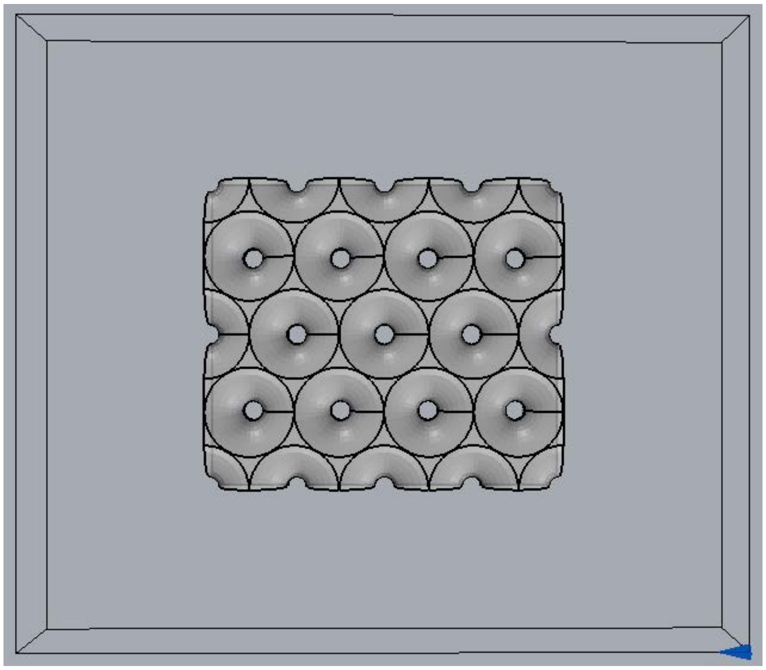

FIG. 102 (RIGHT) CREATING A DOMAIN
This image shows the domain as it is automatically placed by the RhinoCFD plugin around the solid object

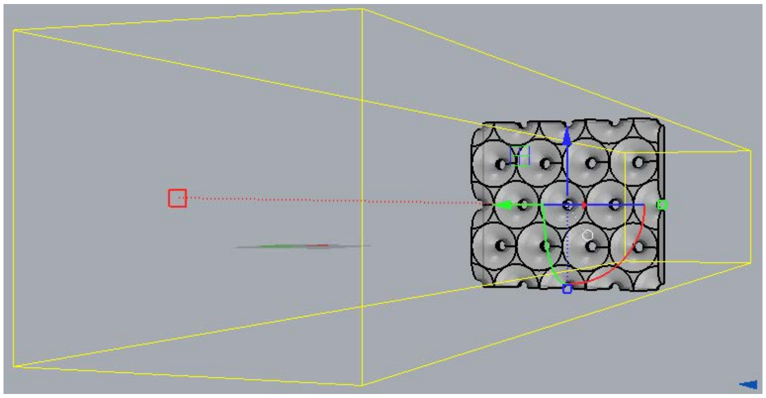

FIG. 103 (RIGHT) ADJUSTING THE DOMAIN
Adjusting the domain is done using the 'gumball' and extruding the sides along the axis until they are at a reasonable distance away from the object for even air flow and unobstructed results.

and applied to the inlet. Using the tool bar, parameters such as temperature, gravitational pull, velocity, and makeup of the fluid can be changed for precise simulations. The results will be indicated by an arrow pointing in the direction of intended flow. For the simulations produced for this thesis, air with a velocity of 4 m/s was used for all simulations and both the domain inlet and outlet were set along the 'x' axis, with the inlet being the face closet to the point

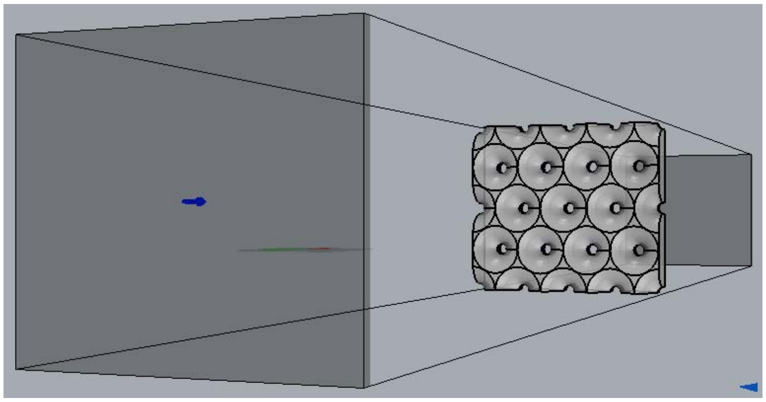

FIG. 104 (RIGHT) INLETS AND OUTLETS
The creation of air flow within the domain is done by applying domain faces. This produces a designates inlet for air to flow from and an outlet, for air to flow out of the simulation. The inlet and outlet are indicated on this image by the darker gray zones at either end of the defined domain box.

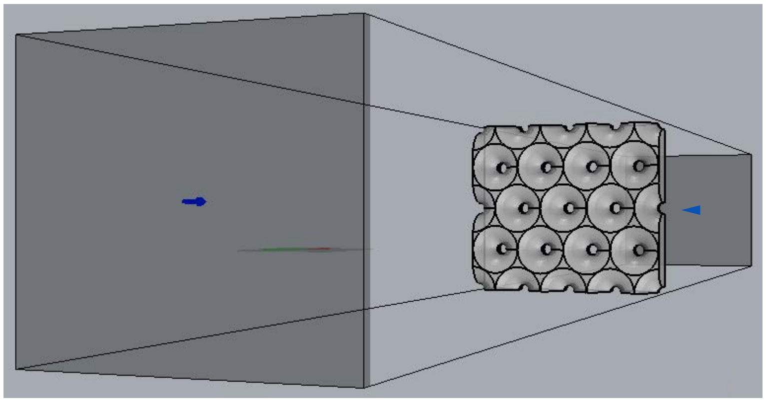

FIG. 105 (RIGHT) PROBE
Placement of the probe within the domain allows for greater accuracy of the simulation. The probe should be placed in between the object/barrier and the outlet at the center of the domain.

'0,0,0' within Rhino. For more precise calculations, the probe (blue triangle) can be moved downstream from the object, roughly in the middle between the object and the outlet and in the center of the domain along the 'z' axis. Moving the probe additionally helps to place the grid, used for calculating the results of the fluid flow, within the domain. The grid can also be adjusted for increased or decreased accuracy. With a smaller grid structure, the CFD software must do more spot calculations, resulting in a longer simulation time. The grid was increased for the simulations done within this thesis for more precise simulation results.

Once the grid is placed, the model is ready to run the solver. Produced from this process is a series of graphs indicating the results of the spot calculations as both a graph and a set of data points. The simulations done for this thesis took approximately five minutes to complete, but the run time could be increased or decreased depending on the parameters set up at the start an the grid structure set into place for the simulation. The graphs indicate both the calculations of the air flow through or around the object along with the percent error of the simulation in progress (generally, a low percentage of error is more desirable). On completion of the simulation, it will close automatically and return to the Rhino platform to load results. The results will display along the grid plane that was placed earlier in the setup process, but can be adjusted to cut through different areas of the model with the use of the 'gumball'. Additionally, more than one plane can be applied to the model at once. This allows for the results of more than one section to appear within the model together. The results of the simulation can be adjusted to show different variables such as velocity or pressure using the control panel, and additional probes can be added to show the results of the testing in alternative ways, such as a streamline effect versus a cut plane. The scale used to generate the results can also be shown within the Rhino platform, so that there is numerical reference associated with the colored visualization of the CFD calculations.

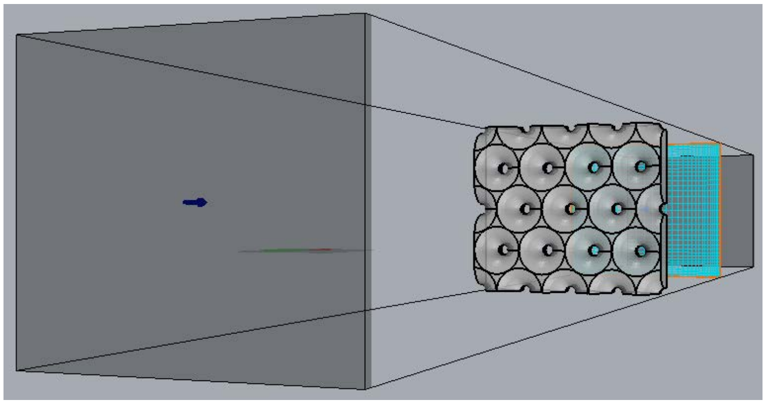

FIG. 106 (LEFT) GRID
Adjustment and placement of the grid within the domain defines both the plane for the simulation and the number of calculation points for the simulation to run.

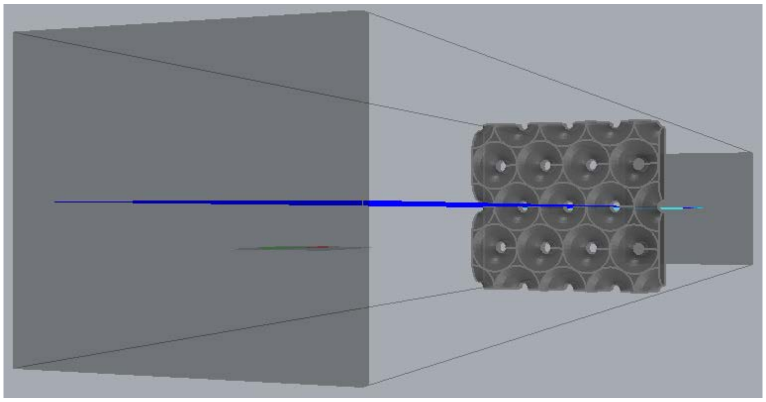

FIG. 107 (LEFT) RESULTS
Loading the results into the Rhino platform produced a planar visualization along the plane of the grid previously placed.

The final results of the RhinoCFD software show a comprehensive analysis of the effects of a given design on the flow of atmospheric fluid, and is an easily understood tool for visualizing the environmental impact of design decisions. Though this thesis only engaged the software for the two variables of velocity and pressure, it can be used to also show other variable such as turbulence, to specifically analyze the consequences of form on fluid flow.

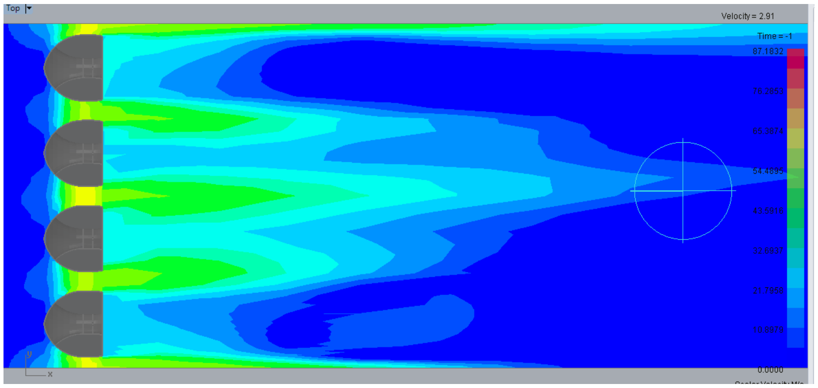

FIG. 108 (RIGHT) CUT PLANE
Image shows the produced CFD results as a cut plane section in plan.

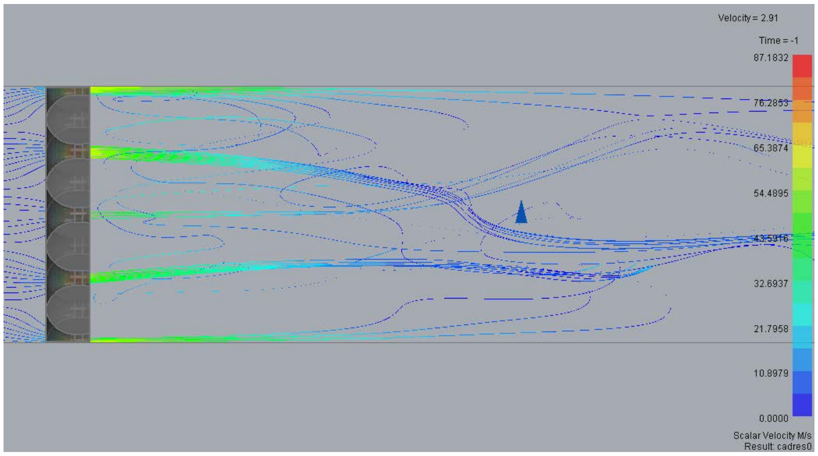

FIG. 109 (RIGHT) STREAM LINE
Image shows the produced CFD results as a stream line section in plan.

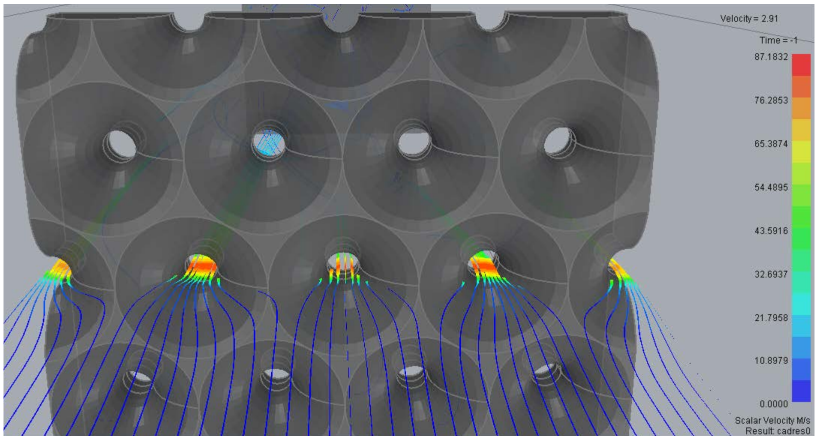

FIG. 110 (RIGHT) STREAM LINE PERSPECTIVE
Image shows the produced CFD results as a stream line modeled in the 3D platform.

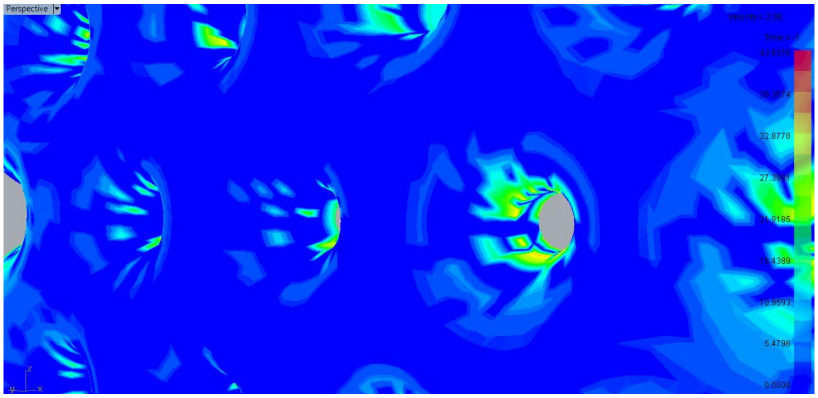

FIG. 111 (RIGHT) SURFACE CONTOUR
Image shows the produced CFD results as a surface contour on the barrier/object itself. This is helpful for visualizing precise points on the model where change takes place relative to the form of the model.