An Ectothermic Approach to Heating and Cooling in Buildings

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The built environment is responsible for nearly 40% of global energy use, significantly contributing to carbon emissions. Targeting a carbon negative future would require a rethinking of the way we heat and cool buildings, distancing ourselves from the predominant model for the building envelope as a boundary that excludes the weather and instead adopting alternatives that transform the building envelope to a mediator that actively regulates heat exchange. In this paper, we explore the potential for a building boundary that actively heats and cools a building by forming dynamic relationships with surroundings. Most decarbonizing efforts today focus on realizing net-zero operational carbon either via the production and distribution of renewable energy or via passive house strategies that target the reduction of the active energy demand. We propose a third alternative. Instead of an endothermic model for heating and cooling in which energy is brought in the interior, transformed by a mechanical system and then distributed, we propose an ectothermic envelope system that dynamically forms a relationship with its environment, by choosing to absorb or release heat directly from or to the environment.

From a design perspective, we will show a modular building energy system, comprised of a double hydronic heating and cooling layer. In essence, we are developing for a building, the equivalent to a vascular system that can move liquids at different locations to thermo-regulate. We will show how this vascular system can use ambient heat as heating and cooling sources for a building.

From a more technical perspective, since all simulation tools available today assume an endothermic approach, we will show an alternative using Modelica and co-simulation for simulating an ectothermic approach. We are developing a weather chamber, which can generate an artificial version of the weather from data to test how our system would dynamically respond.

INTRODUCTION

In the 1930s, Le Corbusier proposed the Neutralizing Wall, a radically unique building envelope, in which air-based radiant pipes were embedded between two glass panels, as a mediator between the interior and exterior climate (Ramírez-Balas 2013). As a system, it was designed to carry pre-heated or cooled air through pipes embedded in the wall section to dynamically optimize heat exchanges between distinct environments by reducing temperature differences. What Le Corbusier proposed is a dynamic "thermal mass" behavior that would allow a more efficient heat transfer between inside and outside. Although this idea was not realized, unlike any precedent at the time which understood the building envelope as an isolator, Le Corbusier's Neutralizing Wall showed great potential in a different type of model for a building envelope one that can actively exchange heat between the interior and exterior climates.

ECTOTHERMIC HEATING AND COOLING APPROACH

Today, it is a well-known fact that the building sector is responsible for consuming close to 40% of total U.S. primary energy use and is therefore a significant contributor to carbon emissions (EIA 2018). Both residential and commercial building energy use is primarily responsible for space heating and cooling; 38% of residential energy use and 29% of commercial energy use was dedicated to heating and cooling in the U.S (EIA 2018). It has been well established that a building envelope —exterior walls, roof, and foundation— is a substantial contributor to heating and cooling energy use, which accounts for 10% of total U.S. primary energy use (Langevin 2019). Therefore, building envelope design and associated technologies can play a significant role in reducing the carbon footprint of the built environment as a whole.

To mitigate undesirable heat exchange between the exterior and interior environment through a building envelope, an ideal envelope is considered to be one that blocks all heat transfer (Bleil de Souza 2007). Based on this ideal, the predominant practice for building thermoregulation requires technology that on one hand maximizes a building's insulation, while on the other all heating and cooling occurs internally through thermo-fluidic-and-electrical systems (Moe 2012). In nature, a similar thermoregulating approach of this predominant building model can be found in warm-blooded animals (Figure 1).

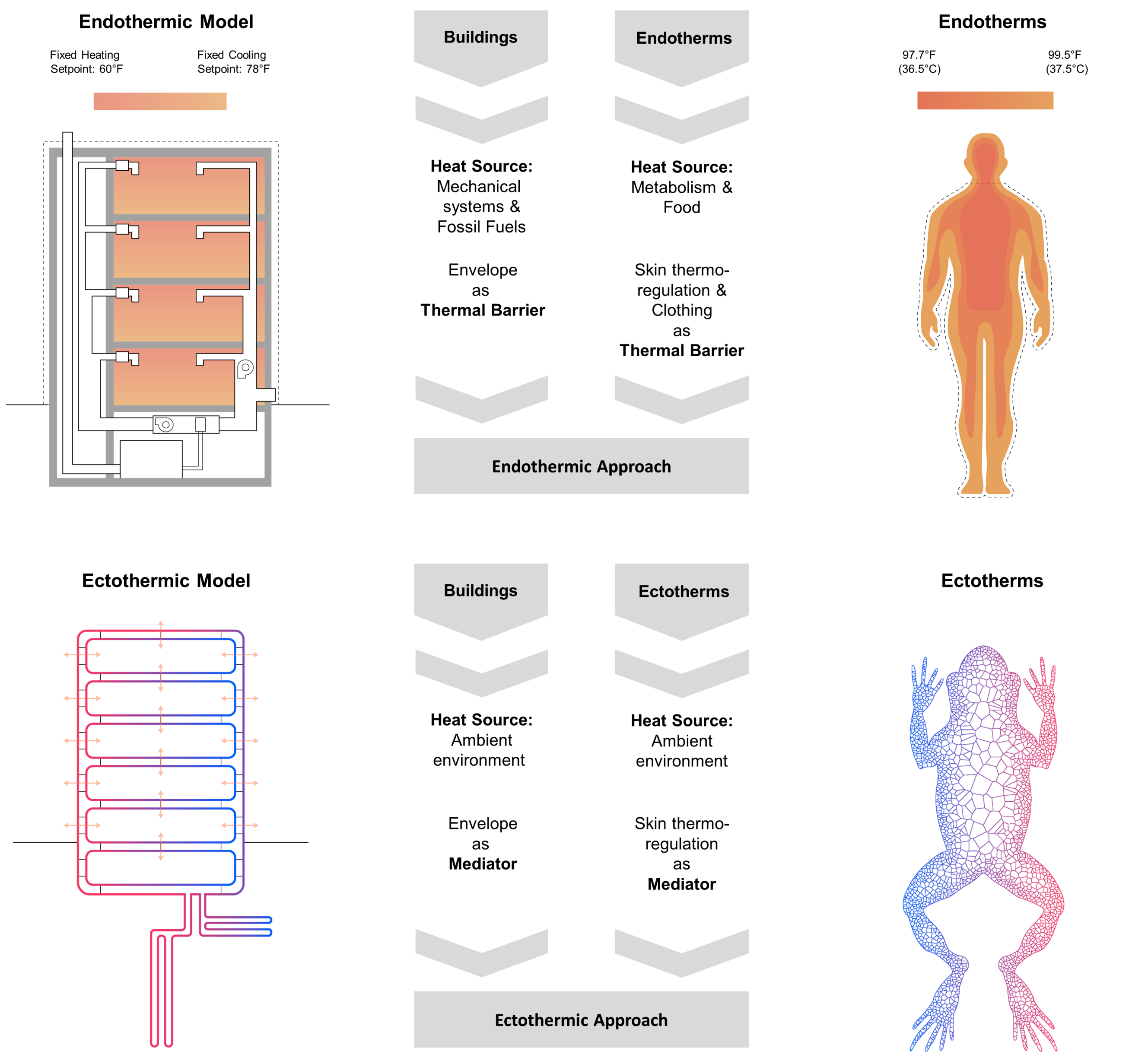

Figure 1. The concept of an endothermic and ectothermic model.

Known as endotherms in biology, these animals generate heat internally through metabolizing food. The energy produced is then distributed throughout the body, through the vascular system, to maintain a target body temperature. In this process, the skin of an endotherm is either minimizing heat loss or optimizing heat exchange between the skin and the external environment. Due to this similarity in thermoregulation, many "bio-inspired" adaptive building envelope technologies have been proposed based on the endothermic approach (Badarnah 2010). Today, following this predominant model, most decarbonizing efforts focus on realizing net-zero operational carbon either via the production and distribution of renewable energy or via passive house strategies that target the reduction of the active energy demand.

A carbon-negative future would require us to rethink how we thermoregulate buildings and distance ourselves from the predominant building model that treats the building envelope as a barrier against the weather. Recently, a radically different building model has emerged that considers that the building envelope forms a dynamic relationship between the interior and exterior environment by choosing to absorb or release heat directly from or to the environment. Similar to le Corbusier's original proposition, the building envelope does not act as an insulator, but instead, it becomes a heating and cooling system that actively thermoregulates a building. Available ambient energy resources become the primary energy source for heating and cooling. A biological analogue to this thermoregulating approach can be found in cold-blooded animals, known as ectotherms (Figure. 1). Rather than relying on internal metabolism for heat production, ectotherms mainly directly use external energy resources to regulate their body temperature. The skin of an ectotherm works as a mediator between their body and the external environment. A few examples are currently under development that theoretically demonstrate architectural design concepts and associated technologies of thermally adaptive building envelopes based on the ectothermic model.

In this paper, we classify various building envelope models based on the endothermic and ectothermic thermoregulating approach with a historical analysis to explore the connection between different models and articulate the potential for a building envelope model that actively heats and cools a building by forming dynamic relationships with its environment. Further, we introduce a unique climate-adaptive building component, that can move heat at different locations where and when needed in order to thermoregulate. We also outline a research methodology that demonstrates the feasibility of the proposed system.

HISTORICAL ANALYSIS OF BUILDING BOUNDARY MODELS

Before we go into the way we understand the endothermic and ectothermic approach in building design, we explore design paradigms of a building envelope with emphasis on the relation of the weather, heating and cooling technologies, and building design. To be specific, we examine how a heating and cooling energy system is correlated to an aspect of the design of buildings with references to built and theoretical works that exemplify each design paradigm. As the diagram (Figure. 2) shows, we classify building envelope models based on two distinctions. One is the distinction between an "exclusive" and an "inclusive" boundary, and the other the distinction between a "passive" and an "active" one.

The exclusive boundary refers to one acting as an isolator to any weather conditions. This weather-rejecting approach aims to minimize heat transfer between the interior and exterior, while active thermoregulation of a building would be purely controlled by thermo-fluidic-and-electrical systems. **The inclusive boundary** is the one acting as a weather-adapted model that is designed to allow heat exchange between the interior and exterior to reduce or even completely eliminate the dependency to mechanical systems.

The passive and the active boundary are classified based on the controllability of heat transfer processes of a building envelope. **The passive boundary** refers to a non-controllable building envelope whose thermal behavior is predetermined by its fixed form and fixed thermal characteristics of its materials. On the other hand, **the active boundary** has the ability to control heat transfer between an indoor and outdoor environment on demand. In general, this model requires a dynamic feedback control system in most cases with sensors and actuators that change an envelope's thermal behavior by either changing its form or changing the thermal characteristics of its materials.

Based on those terms we have classified building envelopes into four categories: the passive exclusive, the active exclusive, the passive inclusive, and the active inclusive envelope.

The passive exclusive envelope, the most dominant in the building industry today minimizes undesirable thermal impacts to the interior environment of a building through a compact and sealed building form and the use of high thermal resistance materials. Since air conditioning was introduced in the early 20th century, buildings have primarily been designed to be controlled exclusively by mechanical systems. By isolating the interior from the fluctuating weather, reduced heat exchange between the interior and exterior is considered to produce lower heating and cooling energy demands. Modern building standards for construction and comfort are fundamentally developed for the passive exclusive boundary. ASHRAE 90.1, the U.S. building construction standard, provides the guideline of desirable R-value of an envelope depending on climate conditions (ASHRAE 2013). The predictive mean vote method, the occupant thermal comfort metrics, excludes all factors related to the exterior environment and considers solely the relation of occupant metabolic activities and environmental factors generated artificially (ISO 2005). However, there are instances of passive exclusive envelopes that are creatively used for building thermoregulation. Phillippe Rahm, who created the novel spatial concept of *"Form and Function Follow Climate,"* showed a new potential of an isolated interior space (Rahm 2006). In his early works, he designed a building envelope that guided air movement in the interior taking advantage of temperature differences occurring by thermodynamics, which make the warm air rise and the cold air fall. In his projects, thermo-electric devices, such as a heated metal surface, were developed to accelerate thermodynamic phenomena. Here, Rahm intentionally designed the envelope to be fully isolated, removing any external impacts on the thermally gradient interior space.

The active exclusive envelope dynamically adjusts its thermal resistance to reduce further thermal impacts. Numerous dynamic shading technologies capable of changing the envelope's formal characteristics to control solar radiation absorption have been proposed. For instance, Al Bahr Towers, located in Abu Dhabi, applies a kinetic solid solar barrier that dynamically covers all direct solar access to block a very large solar insolation on a fully glazed building (Karanouh 2015). As a result, significant cooling loads are avoided in this extremely hot climate region. Other representative cases of this approach are the thermo-activated envelope systems. An innovative louver system called *BioSkin* of The Sony City Osaki building (Yamanashi 2011) used evaporative cooling

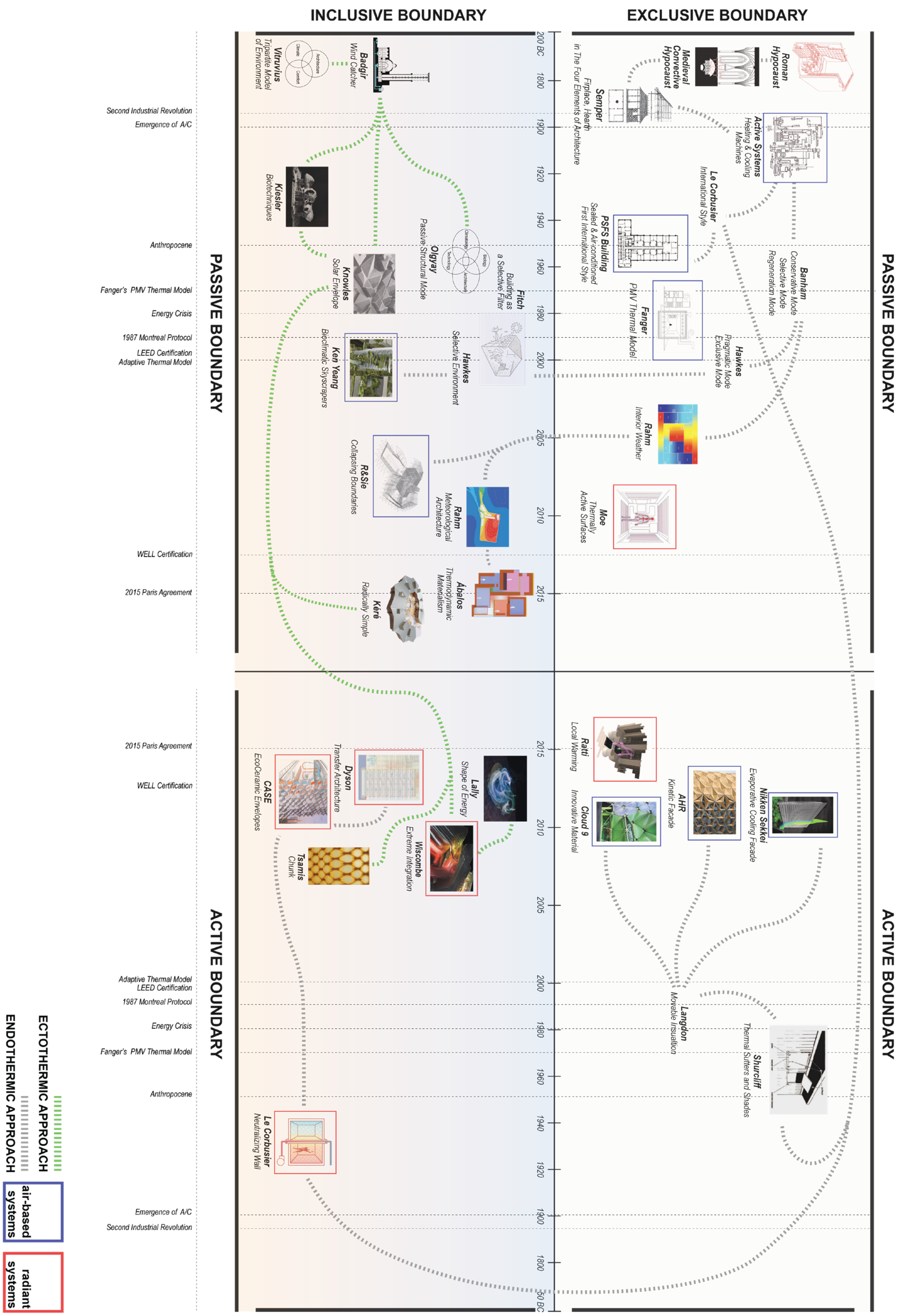

Figure 2. Historical analysis of building envelopes with emphasis on the relation of the weather, heating and cooling technologies, and design.

technology, which adds the cooling impact on the envelope by dropping the ambient surface temperature to reduce convective heat gain on the envelope. The inflatable ETFE skin of Media-TIC in Barcelona, which has dot patterns on both the inner and outer layers of the ETFE designed to cover a specific range of the surface to control incident solar radiation, can add an improved insulation value while controlling the amount of solar insolation depending on the change in climate conditions (Juaristi 2016) .

While the exclusive boundary models are dominant in the building industry, numerous projects based on passive inclusive envelopes have also been introduced. The passive inclusive envelope is designed based on a statistically averaged climate and has a fixed form as well as fixed material thermal characteristics. All types of envelopes designed based on passive strategies belong to this building model, regardless of the dependency on heating and cooling systems. For instance, Ralph Knowles's *solar envelope*, an urban design method for the direct use of solar energy through a form "coordinated" based on solar access and orientation (Knowles 2003), showed how to determine the building envelope's size and shape with various sloping lines so that buildings do not overshadow each other during the critical periods of solar access. Iñaki Ábalos proposed extended passive design approaches with various climatic factors, such as wind and humidity, and developed their relationships with building materials and building geometry through newly established tectonic expressions and material compositions (Ábalos 2015). Recently, Rahm extended his early *interior weather* idea to the broader concept of "*meteorological architecture*". He considered the weather as a fundamental design element when shaping a building's form (Rajagopal 2014). He allowed it to interact with the interior space and thermo-electrical devices to determine the spatial function and a place with diverse atmospheric qualities.

Unlike both passive and active exclusive envelopes, which are entirely based on the endothermic heating and cooling approach, the passive inclusive envelope archives thermoregulation by incorporating the weather. However, meeting the heating and cooling energy demands of a building through passive building components, has proven to be in most cases challenging. For this reason, the endothermic approach –the exclusive model– is still dominant.

An active inclusive envelope has a significant potential to impact both the way we design as well as the way we develop heating and cooling technologies. This type of envelope can be understood as a thermally transient one that intelligently exchanges heat directly between the interior and exterior environment depending on the weather. Interestingly, the first project we identified that exhibits these characteristics and outlines the potential of such a model is Le Corbusier's Neutralizing Wall from the 1930s. It aimed to dynamically regulate heat exchange between spaces by optimizing their temperature difference through a dynamic thermal mass. About 60 years later, a few built and conceptual projects have been introduced as active inclusive models. For example, the Center for Architecture, Science, and Ecology (CASE) has developed and validated a thermally active ceramic envelope module, called *TACE* (Gindlesparger 2018). It can heat and cool water using the ambient exterior environment through an array of ceramic tiles that maximize both thermally conductive and convective heat transfer.

Only a few conceptual and theoretical projects show a potential that could be developed as an ectothermic model. For instance, Tomb Wiscombe proposed a unique multi-functional building prototype, called *Batwing* (Wiscombe 2012), which integrates a heating and cooling system with a building structure and an envelope. This prototype is composed of multi-layered skins that delaminate in between the skins to create hollow micro-capillaries. Fluid would pass through these hollows and is heated and cooled by ambient climates to control the interior environment. Alexandros Tsamis proposed a conceptual active vacuum envelope with the concept of a functionally gradient material in his *Chunk* project (Tsamis 2012). In *Chunk*, active thermoregulation is achieved by controlling the amount of air pressurized within the wall section. a complete vacuum would result in maximum insulation. A few theoretical projects, such as a thermodiode loop-embedded envelope (Zhang 2014) and a thermo-electric device-based envelope (Ibáñez-Puy 2014), have also been proposed, but none have delivered an actual heating and cooling system or design as an ectothermic heating and cooling system (Martín-Gómez 2019).

SYSTEM PROPOSAL

We propose a climate-adaptive opaque building component developed based on the ectothermic approach. This active exclusive building envelope system, aims to significantly reduce energy demands for heating and cooling through maximizing the direct use of ambient low-grade renewable energy sources. This paper outlines a novel climate-adaptive design and building technology approach using the proposed system.

From a general design perspective, we propose a structurally integrated heating and cooling module, which can be applied to various opaque building elements, including a slab, interior partition and envelope (Figure. 3). This modular structure consists of a unique double-sided micro-capillary hydronic heating and cooling layer embedded in a composite structural insulated panel. A cyber-physical system, an integrated computer module, regulates the dynamic thermal behavior of the double-sided heating and cooling layer according to the changes of surroundings, available renewable energy sources, and occupant's thermal demands. To be specific, it aims to be used in conjunction with ambient renewable energy resources, including solar, wind, and geothermal energy, as well as low-temperature waste heat produced by building

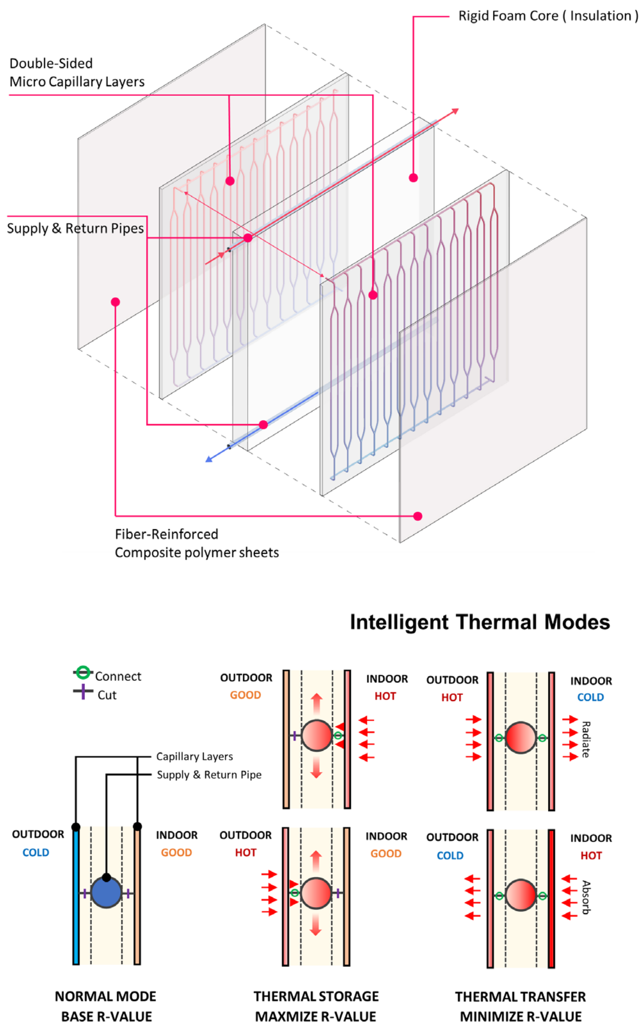

Figure 3. Structurally integrated heating and cooling module and its dynamic thermal mechanisms.

services and occupants. The structurally integrated micro-capillary hydronic layer in both the inner and outer layers of the module dynamically receives and intelligently distributes ambient heat via an optimal path through the opaque building elements. For example, on a cold, sunny day, the system evaluates if available solar energy can pre-heat the water in the outer capillary layer adequately and if yes, redirects it to the inner layer first to deliver the heat to the interior. Otherwise, if a geothermal source is available, water first flows deep underground and then gets distributed into the building. On a hot day, if there is wind, water is redirected to the windy side of the building first, and heat is allowed to escape from that side.

An ectothermic approach-based adaptive opaque building component herein does not refer to a gadget that is considered as an add-on to building envelopes; rather, it refers to an integrated part of a building. State-of-the-art climate-adaptive building technologies are limited to building exterior walls (i.e. they do not extend to roofs, slabs, or interior partitions) (Antretter 2019). Consequently, they focus only on limited connecting between the exteriors and interiors. By the application of the proposed system, all types of opaque building elements —such as slabs, interior partitions and exterior walls— can form dynamic relationships to exchange heat in real-time with their surroundings as well as between building elements. Hence, all opaque building elements can be joined as one thermally integrated building vascular system that can move heat at different locations where and when needed (Figure. 4).

From a technical perspective, Kiel Moe illustrated advantages of surface radiant heating and cooling systems in comparison to conventional air-based systems with an emphasis on the relation of technology, design, human metabolism, and comfort (Moe 2010). The advantages are high heat capacity, the ability to be seamlessly integrated with building construction, low-temperature heating and high-temperature cooling level close to the optimal room temperature, and feasibility to directly use low-grade renewable energy resources, such as solar thermal and geothermal energy. Micro capillary technology is the state-of-the-art hydronic radiant technology that can improve thermal performance and reduce energy consumption when compared to conventional hydronic radiant systems (Khrestianovskaia 2017).

For these reasons, many novel building technologies and designs associated with hydronic radiant heating and cooling systems have been proposed, such as a structurally integrated fluid-based adaptive insulation component (Yu 2016), a pipe-embedded thermal mass to be directly coupled with ambient renewable energy resources (Bockelmann 2013), and a movable bi-directional thermodiode envelope (Chun 2009). However, all these proposals including the advantages of the design perspective described by Moe are fundamentally designed based on a hypothesis that a building has central thermo-electrical heating and cooling systems —the endothermic building model— and the proposals aim at alleviating its heating and cooling energy demands. We want to extend this interaction further through our proposed double-sided system that allows a building envelope to interact with the external climates.

RESEARCH METHODOLOGY

A successful development of climate-adaptive —active inclusive— envelopes is challenging due to an insufficient ability to quantify their benefits. To be specific, the lack of computational simulation methods and validation through physical experiments are significant barriers (Antretter 2019). We are currently developing simulation and validation methods to deliver the value of the proposed ectothermic envelope system. In this paper, we summarize what our approaches are and how we have arrived at the proposed methodology.

Although the use of building energy modeling (BEM) and simulation can accelerate the development of adaptive

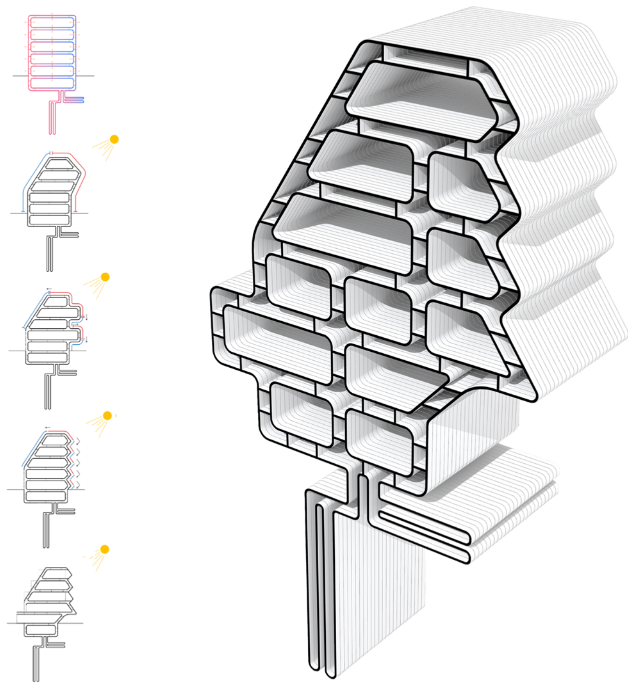

Figure 4. Thermally integrated ectothermic vascular system.

envelopes, current major stand-alone BEM tools are exclusively developed for the predominant static building model. The primary goal of the current dominant tools is to provide a universal modeling environment for energy analysis using a fundamental hypothesis that material properties of building elements remain unchanged over time (i.e. they are based on time-invariant thermal behaviors). The concept of adaptive envelopes did not exist until recently; consequently, thermal adaptability and dynamic response of building elements were not considered when those tools were in development in the 1980s (Oh 2015). Only a few BEM tools have added application-oriented modeling and custom script-based features for a few adaptive technologies (Favoino 2018). Further, a simplified load-based energy calculation model using hourly simulation time-step and idealized control schemes requires and delivers fundamentally different information from those required for fast dynamics and operations of adaptive systems.

To meet the changes brought by the adaptive envelope concept, a Modelica-based simulation technique is being developed as a novel alternative providing flexibility, replicability and modularity by separating the model's physics-based description from the simulation method. Modelica is an equation-based, object-oriented system modeling language that can offer complementary means to address the critical needs of modern BEM tools for advanced and domain-independent system modeling (Wetter 2016). Recently, many novel methods that use Modelica for modeling advanced HVAC controls (Sterling 2019) and enhanced simulation accuracy (Hongtao 2019) have been introduced in the BEM community. A few novel approaches using Modelica for modeling multi-functional building envelope systems have recently also been proposed (Gindlesparger 2018).

A digital twin module is developed to represent the dynamic thermal behaviors of the proposed adaptive system by using Modelica. Although this Modelica-based model can provide highly accurate and flexible modeling and simulation environments, modeling a whole building and its operation and controls are time-consuming and complex when using Modelica. Another core idea of the proposed simulation method is to use co-simulation that allows users to couple models developed in different simulation tools. While modern stand-alone BEM tools are not suitable for modeling and simulating adaptive building technologies, the simulation methods —numerical integration routines known as solvers— in these tools are well established and validated through much research. Co-simulation can partially improve the structural issues of the modern tools (Wetter 2015). To illustrate the value of the proposed Modelica module and the co-simulation approach, EnergyPlus is used for establishing a building's geometry and general building operations while being coupled with the Modelica-based module that represents dynamic thermal transfer modes. To this end, the Functional Mock-up Interface (FMI) standard for co-simulation is used in this coupling process.

An experimental validation method is also developed simultaneously. A large-scale test facility that aims to explore the actual adaptive thermal performance of the proposed physical prototype, energy impacts of thermal distribution and network between modules is developed (Figure. 5). The test facility consists of three different parts. Four individual scaled rooms will be constructed with eight connected physical 1/1 models of the preliminary physical prototype to represent a building prototype. This building prototype has four temperature-controllable water tanks representing geothermal loops and roof solar energy systems. On the right side of the test facility, an artificial weather chamber is designed to accurately reproduce 99% of historical climate conditions in the U.S. It can manipulate air temperature, humidity level, solar irradiation, wind speed and wind orientation generated with a prescribed weather file. This experiment will serve as the physical counterpart to the proposed simulation research. A feedback loop will be implemented between the computational simulation outputs and the function of the physical elements in the test facility to update each other.

The proposed two research methodologies will be the foundation to prove energy benefits of an ectothermic heating and cooling system over a relevant endothermic state-of-the-art heating and cooling technology in future research. Further, the research will examine the accuracy of the proposed simulation technique through large-scale physical experiments toward reliable adaptive building component modeling.

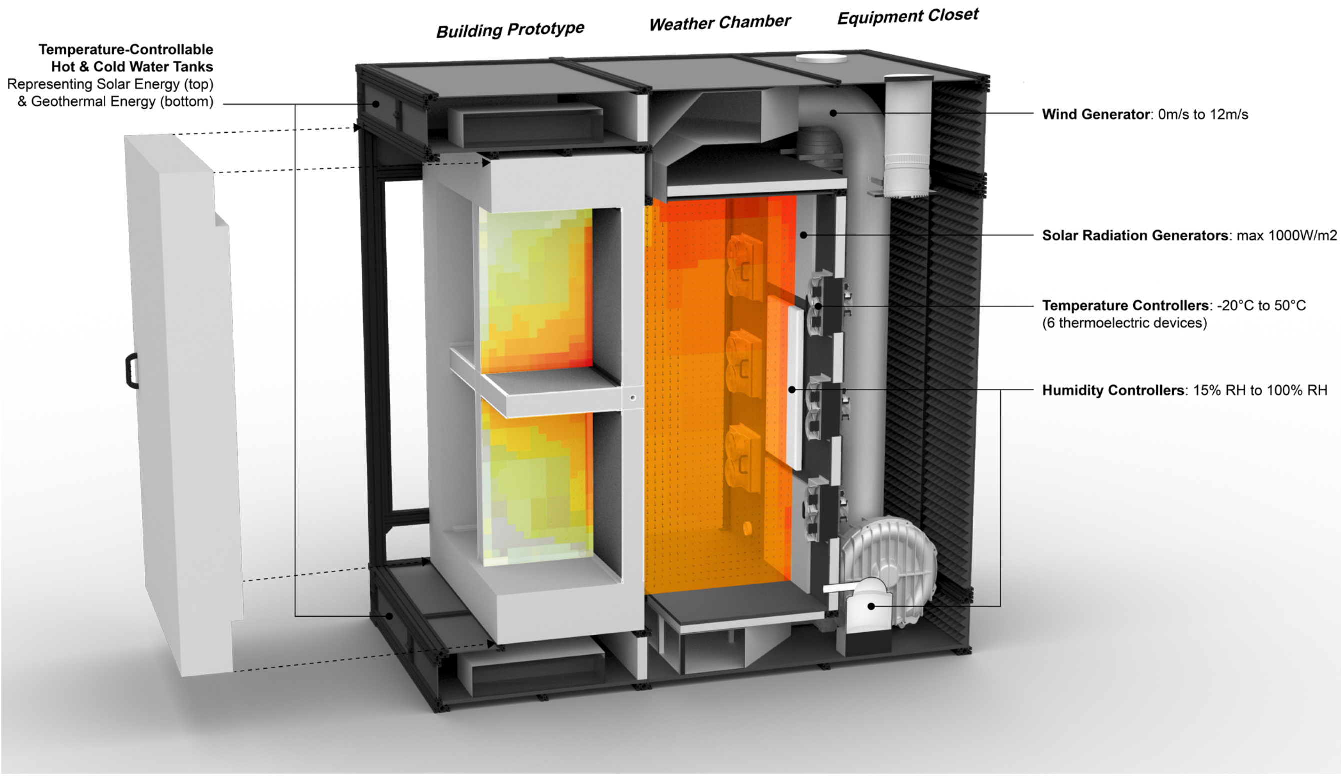

Figure 5. Test facility for experimental validation with physical 1/1 prototypes

CONCLUSION

This paper introduces a new design paradigm and building thermoregulation called the ectothermic heating and cooling approach that can actively exchange heat between the interior and exterior climate. In order to address its significance and potential, we examine design paradigms of building envelopes with emphasis on the relation of the weather, heating and cooling technologies, and building design. As a novel ectothermic opaque building envelope model, we present a climate-adaptive opaque building component that can significantly reduce energy demands for heating and cooling through maximizing the direct use of ambient low-grade energy sources. A novel simulation method using Modelica and co-simulation is illustrated to fill the gap of modern BEM tools for advanced and domain-independent system modeling, and the large-scale test facility is also introduced as a counterpart of simulation. The proposed simulation and validation will be integrated under a unified platform, and ultimately, it will significantly influence system configuration and design of the proposed system. The proposed system exemplifies a holistic design-technology approach that addresses energy supply and demand for the built environment.

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