This paper details an initial exploration into the development of a breathing building skin. This research proposes a system of diaphragms as an alternative to the use of fans for distributing volumes of air. The driving concepts for this project are the three types of evolutionary adaptation: flexibility, acclimation, and learning. Of particular interest is how these biological concepts relate to architectural design. Parametric modeling was used throughout the project to study a family of folding geometry. This allowed for the iterative development of a complex part that is capable of being manufactured from a single sheet of material. Preliminary calculations point to this system being several times more energy efficient than a fan at moving a given volume of air per Watt of electricity. This research is significant as it puts forth a potentially energy efficient and highly integrated alternative to fans, while also illustrating a way of relating biological concepts of adaptation to architectural design.
1 Introduction

1.1 Biological Adaptation

In architecture, change is a novelty often associated with ideas of fashion, weathering of materials, or other topics related to time and aging. Change concerning building systems is an idea found on the fringes of architectural practice. However, change is an important factor in design because the cultural, environmental, and technological context of architecture is in constant flux.

Biology is often used as an inspiration for architectural design because of the complex behavior and integration of living systems, which have been fine-tuned over the course of generations. In biology, change is the rule. Biological adaptation is the process which guides organisms through changes over a range of temporal and physical scales. Change occurring over the life of an individual organism is referred to as acclimation and learning, but it also occurs over the course of generations, which represents the species' flexibility.

Key to these types of adaptation is the relationship of organisms to their environment and the contextual forces that shape their development and behavior. These three types of adaptation formed the foundation for exploring the possibilities of this project.

1.2 Ventilation Systems

The development of a diaphragm based ventilation system arose in response to three contextual forces (Figure 1).

Air is a grossly inefficient medium for transferring heat in comparison to water, and in the book Thermally Active Surfaces in Architecture Kiel Moe makes the argument that buildings should instead be hydronically heated and cooled (Moe, 2010). It is then no longer necessary to deliver conditioned air through long, tangled runs of duct work, but there is still the requirement for expelling air that is high in CO2 and other pollutants, while providing new air to replenish O2 levels.

Natural ventilation would likely be the first choice for delivering fresh air due to its low energy requirements. However, its implementation depends on the presence of certain key conditions such as wind speed, sufficient pressure differences, and floor plate size. Not meeting these conditions or occupants not operating a building according to the system requirements can cause a building to become over concentrated with CO2, creating an environment which negatively affects worker comfort and respiratory health. For that reason, buildings standards are being rewritten to require at least some form of mechanical ventilation to be present in most buildings (ASHRAE, 2007).

The third reason is a broader concern for the quality of the built environment. Building systems that are more tightly integrated can have impacts ranging from the energy embodied in the materials and operations of building systems to the comfort and interaction that occupants share with a space. These three forces in combination with other requirements for ventilation established the context that influenced the initial shaping of this project.

2 Breathing Building Skin

The primary function behind this project was to provide ventilation. Fans and compressors are capable of moving large volumes of air at high flow rates, but this comes at the cost of noise and potential discomfort from sensible air movement. A fan will typically use 1 Watt of energy for every 10–20 cubic feet of air that it moves every minute (40-100 mW/cfm) (Clarke, 2006). The high flow rates of a fan-based system are distributed through a series of ducts, which can represent a large amount of embodied energy, both in terms of the materials they are made of and the space they occupy within a building.

The proposed ventilation system for this project uses a diaphragm for moving air, functioning in the same way as lungs by moving a volume of air through the expansion and contraction of a flexible form. Diaphragms and bellows move air with little noise but tend to output low volumes at low flow rates. The initial investigations of the project focused on the integration of the diaphragms into a space frame structure because of its optimized structural qualities and geometric rigidity. The volume of air within the space frame structure is used to create a plenum, which can be increased and decreased through the actuation of the diaphragms. The plenum also opens up to the interior or exterior environment of the building, allowing air to be inhaled or exhaled.

A gymnasium was used as a test case for comparing the proposed system to a fan based system (Figure 2). Each diaphragm in the gymnasium's roof is capable of moving 2.9 cf and weighs between 0.75–1.5 lbs, depending on
Based upon the above information, the predicted energy consumption of the diaphragm using a pneumatic cylinder ranges between 9–25 mW/cfm, which is roughly 2–4 times more efficient than large industrial scale fans. The distributed nature of the system creates energy efficiencies by requiring a minimal amount of force, but it also requires a large number of components. This poses a potential maintenance issue because of the large number of moving parts that are nested within the structural system. There is also the issue of cost and the necessity to keep the diaphragms and their actuation mechanism modest in price, since hundreds of them will need to be used.

A tetrahedral space frame consists of two types of polyhedron, a tetrahedron, and an octahedron. Early on in the project it was decided to locate the diaphragms within the tetrahedrons because this would allow an actuator to be anchored to one vertices of the tetrahedron and then be able to push or pull the diaphragm. Bellows were explored as an initial way of moving a volume of air, but the limitations of integrating them into a space frame lead to a search for other possible forms. The first limitation was that the bellows would need to be tapered to fit within the tetrahedron, thereby limiting the volume they displace. Another issue was the fact that a linear actuator only allows for a length of movement that is less than half the depth in which it is located because when collapsed, the cylinder of the actuator must hold the length of the piston. The fabrication of bellows is a well-known industrial process, but their large number of folds and the fact that multiple folds intersect at a single point were seen as issues that could affect the life of the part.

3 Flexibility

In biological adaptation, a species' flexibility is its ability to adapt to a new environment over the course of generations. The more flexible a species' DNA, the more variation it can adapt to. The equivalent of a generation in design is an iteration. The more iterations explored during design, the more likely that a viable solution will be found. In the book *An Evolutionary Architecture*, John Frazer claims that the major difference between natural selection and the process of design is that evolution operates without the preknowledge of what is to come whereas design is guided by preconceptions and an incrementally developed insight into a problem (Frazer, 1997).
3.1 Parametric Model—The DNA of the Diaphragm

Parametric modeling was an essential tool during this project due to the complexity of the diaphragm’s folding operations. After exploring the possible use of bellows an attempt was made to design a flexible form that when collapsed would lay flat and when expanded would be able to displace a larger volume of air than the bellows. The parametric model began with a polygon with any number of sides that would then be subdivided into petals by connecting the vertices of the polygon to its center point. The petals would then be rotated around their outer edge in order to open and close the diaphragm.

The challenge of the project became finding a way of infilling the space between the petals as they opened. To do this, a series of folds were developed by intersecting circles or spheres whose radius determined the length of each fold (Figure 4). The main parameters or genes of the design were the values for each radius. Different combinations of radii led to different characteristics of the diaphragm. The parametric model allowed for an evolving understanding of how each fold influenced the properties of the diaphragm.

The parametric model was also used to unfold the diaphragm into a single form. This not only sped up the fabrication process, but also served as a means for better understanding the geometry of the diaphragm. When the geometry was digitally unfolded and examined over the range of positions, from being fully closed to fully open, it was revealed that there were folds that changed slightly in length. The organization of the parametric model was redeveloped until there was only one fold that changed length, but this change was less than 3% of the fold’s overall length.

3.2 Interaction between Digital and Physical

Physical prototyping was key to understanding the limits and behavior of the diaphragm. There were several instances at the beginning of the project where an iteration that seemed to behave properly in the parametric model turned out not to work physically due to issues that were not evident in the digital model. This informed changes to the parametric model as well as an increased insight into constraints of the diaphragm’s geometry. For example, it was discovered that two panels sharing a fold line should never approach parallel because this could cause the fold to flip its orientation, which might not automatically flip back.
The physical prototypes also highlighted that the change in length of the one fold line was a potential advantage. Through modifications of the radii parameters it was possible to generate iterations where the changing edge was shortest when fully expanded or collapsed, but longest when midway between the two extremes. This behavior causes the center of the diaphragm to become compressed as it is actuated towards the midway point, but then it springs the remaining distance once it passes that point. This behavior helps to reduce the amount of energy to completely move the diaphragm while holding the diaphragm tightly closed.

Iteratively exploring the geometry of the diaphragm made it possible to move beyond what at first seemed a very complicated problem and instead, begin to understand the complex relationships between the radii parameters of the design. Nature uses the process of incremental changes to develop complexity, and within design, this ability to explore iterations has powerful implications as long as those parameters can be recorded, tested, and altered in a reasonable manner.

4 Acclimation

Acclimation is the behavioral response of an organism to changes in its environment. In biology, active systems are optimized to use less energy and limit the stress on a joint by minimizing weight and friction between moving parts. A key difference between a biological system and man-made systems is the ability for the biological system to repair or heal itself. A kinetic building system must address the conditions of wear and failure. The motion of the diaphragm requires the use of a sheet material that is capable of being repeatedly folded along its joints while also needing to be semi-rigid to retain the overall shape. The ideal material would be lightweight, to minimize the energy required for actuation, and be able to be continuously flexed along fold lines, while also capable of being recycled once a part reached the end of its life.

4.1 Material Systems

Two material types were chosen with these constraints in mind; plastics and fabric composites. Both materials have the advantage of being able to act as a living hinge, where a portion of the material is altered to allow it to continuously bend without failing (Osswald, 2006). Polypropylene does this through a reduction in the material thickness at the location of the folds. In a composite material, such as fiberglass or Kevlar, the fold lines are coated with silicone, before the entire piece is set with a rigid resin.

It is possible to make one of the proposed diaphragms from a single sheet of material, but this wastes 51% of the material (Figure 5). The form nests more efficiently by breaking the diaphragm at the seam between each petal, wasting only 24% of the material. Assembling the diaphragm from multiple petals opens the opportunity for better control of how the outer seam between petals come together. There is also the ability to repair a diaphragm without replacing the entire thing. The choices were concerned with flexibility, lightness, and waste because these three criteria have a large impact on the initial cost and the energy cost of actuating the system.

4.2 Motion Systems

The breathing cycle of the system relies on the use of an actuator to open and close the diaphragm. The design started with pneumatic cylinders that were anchored to an exterior hub of the space frame structure and the center of the diaphragm. When the pneumatic cylinder is supplied with sufficient air pressure it collapses the diaphragm, increasing the volume of the space frame’s air plenum. The final linear force generated by the actuator is dependent on the cross sectional area of the cylinder and the supplied pressure. Those parameters also influence the actuation volume, which has energy implications. The tension force of the spring return pulls the diaphragm open once the pneumatic pump is turned off, decreasing the volume of the plenum. The pressure or the surface area must be increased to overcome the spring force.

While experimenting with the pneumatic cylinder, it became apparent that there were panels within the diaphragm that experienced a large angle of change between their faces over the course of the breathing cycle. In response, a new actuation system was designed. Panels from the center of the diaphragm were offset and shortened, creating an air cavity. When the diaphragm is closed, the cavities are just big enough to fit an inflatable bladder inside. As this bladder is filled with air, it pushes against the sides of the diaphragm, attempting to find extra space. This forces the cavity to increase its cross section, causing the rest of the diaphragm to open up (Figure 6). The advantage of this system is that it could potentially replace an expensive
component like the pneumatic cylinder with something that is the equivalent of a balloon. The bladder is able to create a greater amount of force than the pneumatic cylinder with the same pressure because of its larger surface area, creating additional energy savings.

This system of actuation allows for alternative configurations of the diaphragm system, either within the current space frame or other building systems. One option would be to seal a grid of diaphragms between ETFE cushions and insert this assembly into a curtain wall.

5 Learning

Learning is when an organism goes beyond instincts, and develops insight about the environment through the recognition of patterns and cause-effect relationships. The distributed nature of the proposed ventilation system provides the opportunity to finely tune its behavior in response to environmental changes, but the challenge becomes about knowing how to properly control those behaviors. The most straightforward operation would be to set the necessary number of actuations per minute to achieve the required ventilation rate. In that case, the system would run regardless of CO2 and thermal conditions within the building or surrounding environmental.

A better approach would be for the system to learn to recognize relationships between environmental changes and the performance of its behavior (Figure 7). The Adaptive House has demonstrated the ability to create intelligent building systems with artificial neural networks (Mozer, 2005). The system would need a series of sensors to monitor environmental conditions, including wind, solar radiation, temperature, building activity, and CO2 levels. The ventilation system could initially be programmed with a set of base conditions that established the acceptable bounds of performance such as the maximum acceptable CO2 levels. The system would then respond until the desired levels were reached and then maintain this balance. There may be times when the wind alone would be enough to provide ventilation, in which case it wouldn’t be necessary for the system to be turned on. The sun will also influence the temperature of air across the roof surface. Zones of the roof that are oriented perpendicular to the sun will heat up faster than those oriented away and this difference could influence which zones draw in air. These forces could incrementally be introduced to the control system once it is evident that it was properly responding to the previous stimuli. Over time, a complex set of relationships would arise between the behavior of the system and the surrounding environment.

6 Summary and Future Iterations

The research presented in this paper introduced the design of a breathing building skin that utilizes a large number of diaphragms to move volumes of air. While many aspects of a functional ventilation system, such as...
as air filtration, were left out of the project to simplify the initial scope, there are still promising discoveries. Over the course of the project new ideas emerged, about different types of actuation that could be used or other configurations that the project might take on.

A similar statement could be made about how the three types of adaptation were referenced during this project. Architects are most familiar with confronting the concept of flexibility, but there is the potential to extend this flexibility by using design tools that allow for iterations to be more easily and systematically explored. It is important that these tools allow for the parameters or genes of the design to be easily manipulated so that the designer can begin to understand the complexity of the relationships between these parameters and the performance of the design. Without that experience and time, the complexity of the problem is instead seen as a complication.

The design of active building systems are largely left to outside consultants, but there is potential for architects to engage with these systems at a deeper level, in collaboration with engineers, to design more integral building systems. The responsiveness, maintenance, and life cycle of the system must be considered in conjunction with its energy usage. The ever increasing power of computation tools opens opportunities for building systems to learn and adapt on their own to environmental changes, but this ability requires significant changes in how systems are designed as well as the way they are programmed to behave. The three types of biological adaptation—flexibility, acclimation, and learning—have served as the inspiration for this project. There are distinct differences between the biological process of adaptation and design, but there are enough similarities that lessons can be learned in aid of the designing adaptive architecture.

References