DYNAMIC BUILDING ENCLOSURES:

The design of an innovative constructive system which permits mechanically-driven, computer-controlled shape transformations to the building envelope

by

Eric Nelson

Submitted to the Department of Architecture
in partial fulfillment of the requirements for the degree of
Master of Science in Architecture Studies
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Abstract

Dynamic Building Enclosures is a system of prefabricated, lightweight, kit-of-parts wall and/or roof elements. This system has the unique capability of dynamically altering, or mutating its shape in reaction to changing user requirements or site climate conditions through the manipulation of a mechanically-driven, computer-controlled frame.

The system’s ability to actively accommodate multiple functions (potentially with high-performance specifications) within a single space would make it appropriate and desirable for application to a broad spectrum of building typologies. It is postulated that industrial fabrication of standardized elements will increase its economic viability—especially when compared to the multitude of expensive, static, specialized building components it would replace. Since it reacts to optimize environmental performance (temperature, humidity, acoustics, ventilation, and lighting) in changing site conditions it will also be more environmentally responsive and energy-efficient than conventional systems.

The objective of this research is to explore the potential gains to users and the building industry of developing an industrially produced building system without the generally associated drawbacks of monotonous, repetitive layouts; inflexibility to changes of use, and the inability to adapt to varying site conditions. The prefabricated kit-of-parts which comprise the system will overlay the complementary structural behavior of form-active structures (cable, tent and arch systems), and vector-active structures (trusses and space trusses). The building system design will include: a strut; a node, which will allow the rotation of the struts to accommodate non-regular geometries, and an enclosure system which maintains the desired separation of interior and exterior environments for the various spatial configurations.

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INTRODUCTION

1.1 Manifesto for Change

The genesis of this research was the search for the answers to two questions: 1.) Do the static, non-adaptive building enclosures which represent the norm in the United States building industry adequately respond to the constantly changing demands of life in a dynamic society? 2.) Would a building enclosure system that is inherently flexible and adaptive to changes be more appropriate?

Buildings, and more specifically to this study building enclosures, that don’t have the capacity to expand, contract, or change in response to the dynamic requirements of their users tend to become obsolete and dysfunctional long before they have reached the end of their projected useful life span. (Figure.1) This point, the inevitability of change, and the importance of any system’s capacity to actively adapt to change are illustrated in the following quotes. “Nothing is permanent. Everything is in constant flux and change. (Figures.2&3) Through day and night, through winter and summer, year after year, from birth to death, life flows in a timeless cycle—life in the soil and on the ground, in water and air, life of man and animal and plant—always in change and transformation, in rise and fall, in growth and decline, so that in all nature nothing is the same at day’s end as it was at day’s beginning.”

“We know that all living systems exhibit adaptive behavior... A self-organizing system maintains its existence through a continual interaction with its environment. Changes within the system or in the larger world invoke an automatic response aimed at restoring a favorable balance, or homeostasis, between internal and external conditions.” And more specific to
the building industry, K. Lonberg-Holm had this to say, “Most industrial products are today manufactured for useful life spans much shorter and costing less than those which only recently were considered essential and economical. But immovable human shelters and cities are manufactured for a physical life far beyond their socially useful life on the original site, in spite of the obvious impossibility for any ‘planner’ to predict technological progress and socio-economic changes and to define future needs. The procedure imposes heavy liabilities on future users and creates expensive obstructions to growth.”

The enclosures most commonly used in the United States (Figure 4) are often designed and built to the specific requirements of a unique client and site, or more commonly, built for a generic client and site. The functional requirements of the enclosures and the spaces they define are perceived as fixed and unchanging even though the occupants activities change daily, or even hourly. Their layouts are generally based on tradition and the experience of those involved in their design instead of a careful analysis of the requirements of the users and how these will change in time. In the construction process, many specialized tradesmen must use imprecise tools to field-modify and assemble hundreds of different materials into a fixed configuration. Once built, these expensive, time-consuming assemblies are not easily changed without the demolition of the area to be changed and potential destruction of adjacent finishes. The fact that the majority of common enclosures fall into this static, non-adaptive category implies that a vast number of people are living and working in buildings which are too difficult and costly to modify, but don’t meet their spatial performance requirements.

Controlling access between interior and exterior environments through doors, windows and skylights, weather protection from precipitation, solar radiation, wind, and thermal resistance are the primary environmental tasks that an enclosure must perform. Many common assemblies, when performing optimally, accomplish these
tasks in a relatively static manner, generally small windows may be opened a little, a shade may be lowered and the heat or ventilation may be increased. While these adjustments may provide a minimum standard of comfort, they generally don't respond very effectively to diurnal or seasonal changes. As essentially sealed, mechanically regulated environments, they fail to make use of the healthful, energy-saving effects of exposure to the natural environment, when weather permits. Due in large part, therefore, to their inability to adapt to varying conditions they often produce and stoically maintain unhealthy environments which do not emit light when and where it's needed, are unevenly heated, cooled and poorly ventilated.

Based on the state of affairs described above, the degree of accelerating change evident in our dynamic society, and the ever dwindling land and material resources for construction projects, a new paradigm must be investigated which directly addresses the conflicts created by the static solutions of the past. The balance of this research will propose an enclosure system, Dynamic Building Enclosures, which redefines the relationship between the users, the enclosure and the outdoor environment from a rigid, static barrier to a responsive interactive separation. (Figure 5) While a system with such uniquely adaptable properties, may in fact be especially suitable to special uses, multi-functional spaces or critical climates, a direct identification is avoided due to a tendency for these to become a limiting frame of reference.
1.2 Objective of the Research

The concept of a dynamic or mutable building enclosure is a relatively radical, unexplored area in architecture and engineering and as such should be considered a new paradigm. Because of this, the research presented in this thesis will be broad in scope and necessarily limited in detail. Due to time and resource constraints some areas have achieved only a limited degree of development. It is hoped that this body of work will become the basis for additional, more extensive research. As a new paradigm, its appropriateness and viability in providing an economical, efficient solution to a problem (or set of problems) must become a central issue of the research.

This issue will be evaluated in the context of the following three performance goals:

1 Systemic and Spatial Performance:
   (Figure 6)
   - Maximize the potential for adaptability to diverse programs and scales of use
   - Optimize spatial flexibility with respect to mutability and the potential variety of configurations

2 Static and technological performance:
   (Figure 7)
   - Provide the minimum weight-to-span ratio of an efficient supporting system
   - Facilitate sustainable use of materials and energy
   - Take advantage of efficient kit-of-parts industrial manufacturing
   - Develop a simple, low-skill and time-efficient site erection strategy

3 Environmental performance:
   (Figure 8)
   - Introduce maximum number of beneficial affects on the inhabitants in terms of increased comfort and flexibility
• Facilitate low impact land use—Ability of the system to harmonize with the contextual character of a site and make the most of natural topographic and climatic phenomena in increasing the efficiency of its operation.

In general terms, the research explores three aspects of the system design process. A kinematic analysis, the first phase, identifies the appropriate level of mutability in response to the first and second performance goals. A sectional model of a space is used to study the changing ergonomic relationships of the various shape mutations and full-scale prototypes are used to evaluate movements in the components and ensure they are capable of delivering the required mutations. The system's ability to produce the widest possible range of spatial solutions in response to diverse site conditions and user preferences will be critical. The second phase includes a detailed, robust design of the frame and enclosing system. An evaluation of the construction efficiency [manufacture, transport and erection] and structural efficiency establishes the third, fifth and sixth program goals.

Control and mechanical systems are also identified and conceptually designed, but a robust exploration of these areas—while crucial to the ultimate performance of the system—fall outside the scope of this research. The third and final phase of the design will be the development of two prototype building projects to explore the architectural ramifications of the system in use and explore the land use implications.
1.3 Thesis Organization
The first chapter introduced the concept of dynamic change and how a new paradigm in architecture—the dynamic or mutable building envelope offers certain advantages over conventional building technologies. Chapter two will evaluate the performance of precedent designs that have similar problem statements and identify elements that may serve to guide the design of this system. Chapter three includes a description of the system, two prototypical building designs and a summary of various options that weren't used in the final solution. Chapter four evaluates the final system's performance and chapter five, the final section, will consist of a brief summary of the research, and some suggestions for future work.
2.1 Natural Systems

There are many examples of adaptable behavior that causes shape mutations in natural systems. In all cases the plant, animal, or even human changes its shape to improve its performance under a variety of dynamic conditions. Two examples that are directly applicable to the kinds of changes that occur in Dynamic Building Enclosures (D.B.E.) are the shape mutations of a common house cat (Figure 9) and a tree (Figure 10). In the case of the cat, it is common knowledge that they curl into a ball shape when they sleep. Cats do this to reduce their exposed surface area for security and the reduction of heat loss. The D.B.E. system, by altering its shape during times of minimal activity or severe weather conditions, has the ability to reduce the interior area it defines. This reduction in area will minimize heating and cooling loads. Under heavy winds trees twist and sway, their leaves rotate parallel to the wind direction to minimize drag and reduce the surface area that the wind may load. They do this to achieve a more aerodynamic shape and reduce the stress on the roots, trunk and branches. This becomes a clear analogy to most building enclosure designs when considered in reverse. If the tree didn’t have this dynamic capacity their leaves would act in unison like an enormous sail and force the branches, trunk and roots to become much larger and more rigid in order to resist this load. The D.B.E. has the ability, similar to the tree, to automatically reduce and reconfigure its wind resistant surface area. While this may reduce the shear mass and cost of the required structural system in low-rise buildings, it will be a very significant reduction in high-rise buildings and building sites with severe climates.
Movement in plants is called tropism. Different forms of tropism are defined by what force actuates the movement. Two examples are heliotropism and haptotropism. In the example of the sunflower, which is a heliotrope, irregular cell growth and decay cause diurnal rotational movement in response to the location of the sun. The D.B.E. has the ability to track the sun for power generation (with the addition of photovoltaic collection system) and light. Its ability to automatically adjust into a projecting surface will allow the dynamic control of shade patterns throughout the day regardless of the season, controlling light penetration and heat transmission.

"Some of these [plants] growth movements can be moderately rapid, observable by the unaided eye over the course of several minutes. Rapid movements as in the cases of the Venus flytrap (Figure 11) and the mimosa stalk require a different activating mechanism. This mechanism is fluid osmotic pressure. These plants ingest nutrients and defend themselves, respectively, with built-in chemical and mechanical devices that sense stimuli and react with a controlled motion. In the case of the D.B.E. a network of sensors will detect sunlight, temperature, humidity, wind pressure variations and the presence of precipitation and, similar to the Venus flytrap, actuate a mechanical response.

While the two examples above have related to the D.B.E. system in the kinds of movements made in response to certain stimuli, natural systems may also provide clues to the composition and configuration of materials to comprise the moving surface. The jointed bands of overlapping armor on the armadillo (Figure 13) are an example of this ability to control the coverage of an enclosure during movement. Mankind has already made use of this overlapping configuration in the ailerons of jet aircraft wings, which have a similar ability to extend when greater surface area is needed or retract to a more compact configuration. The D.B.E. uses a similar assembly to allow mutations of a rigid panel enclosure surface.
Perhaps the closest natural example, in all respects, to the design of the Dynamic Building Enclosure system is the human hand. Each of the four fingers has an interior skeletal structure of four segmental bones (Figure 14) arranged in a line. The ball and socket joints, or knuckles—spaced by cartilage and joined with ligaments—are essentially pinned connections; allowing rotation in one direction only. Rotations are actuated by nerves that stimulate the muscles (Figure 15) wrapped around the skeletal system into contracting, or relaxing. “The skin (Figure 16) is the principal seat of the sense of touch, and may be regarded as a covering for the protection of the deeper tissues; it plays an important part in the regulation of the body temperature, and is also an excretory and absorbing organ.” The skin that envelops each finger has varying degrees of malleability and porosity depending on where it’s located. For example, the skin on the posterior (inner) side of a knuckle is relatively tightly secured to the deeper tissues. On the opposite side (outer) there is a creasing, or folding of extra skin which is not attached to any substructure. As the fingers are closed into a fist the skin on the outside of the knuckle stretches taunt while the skin on the opposite side bunches up. In effect, the surface area of the outside has increased and the surface area of the inside has decreased. This allows a change of length in this area to maintain coverage over the knuckle during rotation. In addition, the fingers are articulated in such a fashion that each can move independently of the other. The skin which connects the base of one finger to the next is quite malleable and allows larger changes in length—both horizontally and vertically—than any of the other finger joints. The D.B.E. makes use of almost all of these attributes, from its skeletal system.
of a linear, pin-jointed frames, nerve and muscular systems of sensors and nodal drive units to its skin of flexible membranes and panel expansion joints.

2.2 Industrial Design

Industrial design is an important precedent resource for Dynamic Building Enclosures because buildings aren't generally designed to move. Many industrial products, however, such as wrenches (Figure 17), bicycles (Figure 18) and automobiles (Figure 19) are designed for movement. Three common characteristics to each of these industrial products are: 1.) A compact shape where the center of gravity of the system with respect to the moving elements is critical, 2.) A streamlined, aerodynamic form and 3.) Minimized mass of elements that must be moved. Each of these characteristics has been carefully incorporated into moving system designs as knowledge of the design process, material properties and technological processes have progressed.

Compact shapes are efficient in moving systems because any significant mass that has a distance from the center of rotation creates a moment force \( M = f \times d \) that requires support and stabilization. The further the mass is from the center of rotation the larger the moment. In addition, movement tends to create vibration and harmonic oscillations in the elements of the system, especially when they are a significant distance from the center of rotation. This has a destabilizing affect and therefore requires additional bracing and, in essence, wasted material.

Aerodynamic shapes are efficient in that any moving object, or mass has a certain resistance to air molecules flowing around it. These molecules [collectively known as the atmosphere] are always in motion and may be flowing in the same direction as the moving object, in the opposite direction, or any number of angular relationships with respect to the object. When the direction of flow and the direction of object movement is known, a tapering, or wedging of the form in the direction of motion will reduce its re-
sistance to the passing molecules. Even though buildings don’t generally move around, architects use this fluid dynamics concept in the design of tapered or rounded high-rise buildings because it reduces the lateral wind loading [flowing of atmospheric molecules] on the envelope. If, however, the flow of molecules or the moving object changes direction, adaptable, or multi-sided tapering must be utilized to maintain efficient operation. This aerodynamic, multi-directional tapering is illustrated in the smooth, double-curved surfaces of automobiles, aircraft (Figure 20) and racing yachts (Figure 21).

Minimization of the total mass of the system is critical because an object that moves has a resistance to this movement due to gravitational forces. Resistance to movement increases proportionally to the mass of an object. In mechanical terms, moving extra mass requires extra power and, therefore increases the cost of the system. R. Buckminster Fuller raised his concerns about the “price per pound of performance” in the building materials of his era. Comparing buildings to automobiles and aircraft, he claimed that most of the weight of building products used at that time was unnecessary and ineffective. This observation becomes much more critical in the need to minimize the mass of the Dynamic Building Enclosure system.

Movement in mechanical design occurs as the result of an applied force of rotation or translation. Worm drives, cable drives and gear drives produce rotations, whereas hydraulic pistons produce translations. Each of these devices essentially converts energy in one form (i.e. electric, steam, combustion, etc.) and applies it to the driving mechanism to produce a force that may take the form of a rotation or translation.
which is used to push, pull or turn another portion of the system. The forces produced by these energy conversions become particularly efficient—multiplying the input force many times—when coupled with a lever. The wrench uses this principle in a very simple way. The human hand turning a nut on a bolt relies almost entirely on the force of the hand to drive the nut because the distance between the hand and the nut is negligible. The wrench extends the point of application of the input force, based on the length of the handle, a certain distance away from the nut, thereby increasing the moment force that drives the nut. (Figure 22) In a similar manner, a large gear attached to the pedals of a bicycle (Figure 26) creates a large moment force that drives a small gear and spins the tire. A single rotation of the large gear can rotate the tire several times. Mountain bikes, having both small and large pedal gears, can reduce the amount of force the rider needs to apply to start the bike [with the small gear] and once the bike has enough momentum, switch to the larger gear to increase the moment spinning the tire.

*Kinetic Architecture* 10 offers some additional information on variability and the associated complexity of the motions of single and multiple function machines. In the list below the authors have classified man-made machines or industrial designs by variability and control into the following four levels of adaptability:

- **Level One**
  Singly-variable, human controlled (Figures 23 & 24)
  These are single, repetitive operation machines; simple tools such as the lever, or pulley.

- **Level Two**
  Multi-variable, human controlled
  These machines began to be developed in the nineteenth century; they were more complex and performed multiple func-
tions. Examples include the sewing machine and typewriter. Automatic controls were developed early in the twentieth century.

- **Level Three**
  Multi-variable, automatic control
  Sensors to detect input data and computers to evaluate and actuate a response are added to these machines to allow automatic control. They include: CNC tooling, automobiles and aircraft

- **Level Four**
  Multi-variable, heuristic control (Figures 27&28)
  These machines are similar to level three, with the addition of a learning capacity. They fall into the fields of robotics and cybernetics.

In general, as the level of variability and autonomy of control increases, the complexity and cost of the associated machinery increases.

Considering the list, the general information above and the principal operational goal of facilitating the maximum spatial diversity with the minimum amount of mechanization (Figure 29), three design objectives for the Dynamic Building Enclosures system become apparent. Keep the mechanical system compact, lightweight and simple to simultaneously reduce the complexity and cost of the system and increase its effi-
ciency. (Figure 25) Utilize a linear frame to facilitate simple, efficient rotational movements and minimize kinematics complexities. (Figure 25) Take advantage of small, high-performance unit-type drive assemblies to make more effective use of input power and increase flexibility.

The level of variability required by the system will depend on what types of motion are required and this will be explored in chapter three, but from an efficiency standpoint, level one adaptability would be the most appropriate since the task is to produce a rotation. Control requirements are more complex. Two types of control—one manual and one automatic would be appropriate in the system based on the fact that it should respond to user input and climate changes. The control for user input could be voice activated, or by interfacing through a control monitor. Shape transformations in response to climate changes would most efficiently be controlled with sensors attached to various points of the enclosure, both inside and out. Some kind of safety device, or warning system would be required to arbitrate between conflicting user desires and climate changes.

2.3 Architecture
The developments of building enclosures that actively adapt to program and climate changes have historically taken one of two directions. Either the enclosure was made to move from site-to-site, or became a stationary system that incorporated a range of flexible elements. Two precedents of the former are nomadic tents (Figure 30) and teepees. These enclosures were developed to be quickly erected from a small number of lightweight components on a variety of different sites. Since the inhabitants migrated to maintain climatic stability and their activities didn't significantly change, the form and penetrations of their enclosures remained essentially the same in each place. Stationary enclosures, (Figure 33) on the other hand, were fundamentally different because they were erected to withstand the ravages of seasonal climate changes and time. Elements of these enclosures that formed the beginnings of an adapt-
able capacity included operable doors, windows and shading devices. In essence, these elements allowed the inhabitants to experience the controlled affects of the exterior environment from inside producing some healthful benefits of natural ventilation, thermal control, natural day lighting and shading from the bright sun. While there were obvious environmental benefits to increasing this flexibility, technological limitations of heavy, load-bearing building enclosures severely restricted development.

These two enclosing approaches of light, transportable membranes, or heavy, stationary barriers remained disparate and relatively unchanged until the technological developments of the Industrial era began to remove some of the constraints. Chris Abel in his article on the works of Norman Foster, *From Hard to Soft Machines*, describes the advances after this era, the last century and a half, as two “Machine Ages”.

In the first Machine Age, which roughly began in 1860 with the construction of the Crystal Palace, (Figure 37) architects responded to developments in industrial products such as electrical generators (Figure 35) and locomotives (Figure 34) by replacing the art and craft of architecture with the modular components of industrial production. Development of the load-bearing frame (Figure 36) removed many of the previous technological restraints to enclosures, allowing them to become lighter, thinner and more open. This is evident in the work of the Constructivists, (Figure 38) Futurists and De Stijl that exploited the new materials and constructive techniques developed by these industries to develop open plan spaces and glass curtain walls. By the late 1920’s the work of Mies Van
Der Rohe, (Figures 39&41) Walter Gropius (Figure 40) began to investigate universal, or idealized building forms which vastly simplified certain aspects of the construction process through prefabrication and simplification of finishes. Although these universal forms often accommodated changes [within the enclosure only], they tended to provide an uncomfortably loose, sterile fit for any program. Another example of adaptability, while not directly applicable to this research topic, developed during this period was the Schroder house. (Figures 42&43) This project, designed in 1924 by Gerrit Reitveld, exploited the space saving devices of movable partitions and furniture. In addition to allowing the house to have a smaller, more economical footprint, they accommodated the dynamic potential of using large open space, or closing off zones to divide the floor into smaller rooms. While the envelope is still a static element in this example, the movable partitions and furniture are appropriate for use in the D.B.E.

The two changes in the architecture of this period that had the most profound impact on the adaptability of building enclosures were the use of lightweight prefabricated components and the development of flexible interior space. Both of these changes were made possible by the technological development of the load-bearing frame. In addition, due to the simplification and uniformity of the finishes, or adjustability of interior partitions and furniture, it was proposed that changes in the lifecycle of the buildings would be less destructive than those of earlier periods.

In the second machine age, brought about in the late 1950's by the space programs of the former Soviet Union and the United States, architects were again looking toward the advances in other industries to improve building design and construction. This time as Chris Abel describes, "it is around the versatile microprocessor, (Figure 45) rather than the inflexible mass-production line, that the emergent architecture of the Second Machine Age centers." Two projects that exemplify the adaptability achieved in the buildings of this era and the resulting develop-
The Hong Kong and Shanghai Bank, a thirty-six-floor bank and office high-rise in downtown Hong Kong, effectively applies many principals of adaptability. Its perimeter walls (Figure 44) incorporate operable interior shading devices, exterior sun louvers, variable mechanical ventilation diffusers and large modular glazing units into an integral prefabricated assembly. A computer-controlled tracking sun scoop (Figure 46) is incorporated to actively reflect sunlight into the multi-story banking hall. Utility systems and toilets are housed in articulated box-type modules that may be efficiently removed from the building for servicing or upgraded for expansion. In addition, efficient flexible manufacturing systems and CNC machining processes are used to prefabricate a large percentage of building systems.

In contrast, the IBM Traveling Pavilion—a small, demountable shelter—visited nineteen countries throughout Europe in the late 1980s displaying the latest wares of IBM. This building, including segmental arched enclosure, floor panels and utility systems, was entirely prefabricated. (Figure 48) The polycarbonate pyramids and laminated wood strut components of the vaulted enclosure system (Figure 47) were selected for weight reduction, transparency and simple erection. The entire sixty five hundred square foot building could be efficiently loaded on to eighteen forty-foot long trucks and moved to another site where fifteen workers would reassemble it in three weeks.
Both of the previous examples are extremely appropriate precedents for the D.B.E.—using materials selected for performance, taking advantage of innovative manufacturing and erection techniques and providing the flexibility of an open plan and mobile, adaptable elements. While this is true, few truly mutable building enclosures exist. Most of this work is not truly mutable, but deployable, or adaptable in the sense of having two configurations: open and closed. The traveling theaters of the Spanish architect, Emilio Perez Pinero (Figure 50) and the more recent Iris dome (Figure 51) and expanding geodesic dome of Chuck Hoberman are examples of these structures. These constructions tend to be either small, temporary shelters, or the operable roofs of very large public stadiums. In addition, none of these constructive systems have the ability to adapt to site climate changes. Based on this assessment, much fertile ground for research exists in the area of truly mutable, adaptable building enclosures.

From the initial disparate enclosing approaches of light, transportable membranes and heavy, masonry barriers to the lightweight modular materials and operable climate control devices of later systems a common line of development has been consistent. New materials, fabrication processes and constructive techniques have been used to provide adaptability to accommodate specific requirements of diverse functions, maintain control of the interior environment while reducing the barriers to the healthful effects of the natural climate and simplify the construction process. While all of the examples cited in this section have in some way demonstrated aspects of this line of development, the Dynamic Building Enclosures system has directly addressed all of these issues in its design. As a synthesis of the lessons learned by adapting appropriate natural processes, utilizing the latest technological developments in industrial products and gaining experience from related architectural developments, the D.B.E. attempts to pave the way for the next wave in intelligent design and building construction.
THE SYSTEM

The encyclopedia of Architecture Design, Engineering and Construction describes building envelopes [or enclosures] in the following passage: “The main function of building envelopes is to separate the interior environment from the exterior. In this respect, envelopes have been described as the skins of buildings. Building envelopes consist of components with specific functions and properties. Envelopes often serve as a part of the structural system, accepting loads from the building itself and from occupancy. Envelopes must be designed to withstand structural loads from wind and snow. In earthquake zones, special structural requirements apply.”

3.1 Description

The Dynamic Building Enclosures constructive system (D.B.E.) (Figure 52) is composed of six major elements: the strut, end nodes, outriggers and lateral beams, an enclosure (membrane or panel) and connective elements that join the assembly together. These may be assembled in many different combinations to achieve varying building configurations. In addition to these elements, there are mechanical systems including unit drive assemblies, safety breaks, locking mechanisms and a control system. A functioning building would, of course, have additional components such as flooring, ventilation, climate control (depending on climate requirements) plumbing, electrical and telecommunication systems. Each of these systems, while necessary for the proper functioning of the building, falls outside of the scope of this research. Although they will not be designed specifically for this enclosure system, provisions have been made for integrating a variety of available systems.
Architectural implications of the use of this system may range from the relative anonymity of a few small experimental facilities in extreme climates to communities of suburban tract houses and urban office towers subtly undulating and shifting as the hours of the day pass. It is an unusual architectural design due to its "shapeless" character. While this shapeless character and intermittent motions will initially tend to catch the attention of passersby—the human eye is extremely perceptive of motion—the intimate, somewhat symbiotic relationship the system will have with the building site and changes in climate may ultimately reduce perception. The building enclosure, as an assembly of mechanical bones, muscles, nerves and skin, will be a cybernetic machine, but may, through its connection and dependence on the natural environment, begin to blur the boundaries between the man-made and the organic. Human beings have used machines to add comfort and simplify their lives for centuries. The functional aspects of this particular machine, the D. B. E., will allow users to enjoy the healthful benefits of the natural environment as it changes in an unprecedented manner. Within the enclosure, users performing everyday tasks, or highly-specialized procedures all of which require varying volumetric, acoustic, lighting or climate conditions, will benefit from the ability of the system to provide custom-tailored spaces on demand. Changes that occur to the building, or the users during the system's projected useful life will be easily accommodated by adjustments in the mutable surface, or by adding, changing, or removing modular components.

The following paragraphs describe the major elements of the system, how they are connected together and how they function as an integrated assembly.

3.1.1 Strut
In addition to being the primary supporting element, the strut is the workhorse of the system, (Figures 56&57) providing attachment points for the mechanical components that drive the system, electrical raceway, interior and exterior fin-
ish surfaces, and required thermal insulation.

The strut is a 2.5-inch diameter, 48-inch long hollow pultruded carbon fiber tube. Wall thickness varies between 0.125-inch and 0.25-inch depending on internal stresses; the tube is thicker at the ends where it becomes bonded to the stainless steel sleeves. Material thickness must be varied due to the fibrous composition of carbon fiber that tends to make it delaminate and fragment under high, localized bending stress. Carbon fiber was chosen due to its unusually high performance per pound, having a yield strength of 150,000 psi (pounds per square inch), modulus of elasticity of up to 20,000 psi and density of 0.0477 lb/cuin (pounds per cubic inch). In comparison to Grade 50 structural steel, it is three times as strong, seventy-percent as elastic and six times lighter. Weight reduction was an important goal to minimize mechanical stress, reduce the necessary size of the supporting frame and simplify site erection. In addition, carbon fiber is not adversely affected by the presence of moisture in the atmosphere. Its cool, metallic gray surface needs no additional finishing. Each thickened end is bonded with an adhesive to a high-strength stainless steel threaded sleeve. This sleeve has a large surface area for bonding to the inside of the carbon fiber tube and allows simple attachment of three different end nodes.

3.1.2 End Nodes
The end nodes (Figures 58-60) have three different forms, a male and female end for pin connecting one strut to another and one to terminate the system at an edge. These nodes control rotation and therefore mutability in the sys-
tem. In addition, the nodes provide attachment points for the mechanical components that drive the system and elements to secure the ends of the outrigger assemblies. Connecting nodes are composed of milled high-strength stainless steel plate [approx. 0.25-inch thick]. This is thickened into a conic shape the diameter of the strut and milled into a two-inch diameter threaded rod at the end which will fit into the corresponding tapped end of the strut sleeve.

The male connective node (Figure 61) is a 5-inch diameter disk in elevation with a 0.5-inch inside diameter roller bearing set in its center. This disk has a centered, 3.5-inch diameter [approx. 0.25-inch thick] geared ring milled out of it and a series of 0.1875-inch diameter holes which ring the disk 0.375-inches from the edge. The geared disk, the element that will be mechanically actuated to rotate during shape transformations, will fit into a counterpart disk in the female node. The series of holes accept a pair of locking pegs (opposite ends of the disk) that are mechanically pushed into the holes when the desired rotation has been achieved. As a measure of safety and efficiency, the pegs allow the drive assembly to shut down when the transformation is complete and the has finished rotating.

The female connective node (Figure 62&63) has two plates, roughly oval in elevation [7.5-inch long, 5-inch high and 0.25-inch thick] that are similarly thickened and joined at the end that attaches to the strut sleeve. The space between the plates allows access to the male end of the next strut. A 0.5-inch inside diameter roller bearing is also set into each plate on this end, however this is offset from the center of the oval to allow space for the drive assembly and outrigger attachment. This node includes hardware to secure the unit drive assembly, roughly at the center of the oval and the locking peg mechanism. In addition, the outrigger sub-assembly is also secured to the plates in a triangular configuration, centered on the 0.5-inch roller bearing or the center of rotation.
3.1.3 Outriggers and Lateral Beams

The outriggers maintain lateral stability, provide a means for connecting one line of struts to another and, most significantly, permit variations to the plan layout of the D.B.E. system. These outriggers are three 0.75-inch diameter hollow, high-strength stainless steel tubes which have varying lengths [from about three-inches to eighteen-inches]. They are welded into a cast node at the apex of the tetrahedron and fitted with milled pin connections at the other three ends from which they are secured to seats in the oval plate of the female end node. The apex cast node incorporates a 0.5-inch roller bearing to connect another line of struts and welded tabs that receive lateral beams which are pin connected to the 1.25-inch diameter hollow, high-strength stainless steel tubes. These tubes connect the end of one outrigger to the end of the next producing the triangulated configuration necessary to laterally stabilize the system.

3.1.4 Enclosures

Two types of enclosures are appropriate for use with the D.B.E. system, membranes and panels. Both soft and hard surfaces, respectively, offer a broad range of finishes, textures, light transmitting values and operability options. Length changes that occur in the enclosure as it mutates into a desired form are particularly critical to the proper functioning of the system. The surface area of the enclosure must increase in some areas and decrease in others. This is very similar to the behavior of skin on the human hand described in chapter two. This phenomenon is variable, but predictable. The two basic types of length changes are 1.) Planar changes; at the nodes as they rotate, and 2.)
Bi-planar changes; between the lines of struts which are rotating out of plane. In contrast, the areas surrounded by outriggers and lateral beams can be relatively stable. While areas that are subjected to length changes may be accommodated with a highly elastic membrane or rigid panel system with a special type of expansion joint, neither solution is simple.

Membranes with the degree of flexibility required to provide the full range of system transformations are not currently available in the building industry. Since building enclosures are generally not designed to accommodate shape mutations and building membranes (Figures 64 & 67) are generally designed to stretch only to accommodate the desired load-bearing tension in an articulated configuration, there has been no need for a membrane with such properties. The fashion industry however has done extensive research and development of highly malleable textiles. Although textiles in the fashion industry are developed for use as clothing (Figure 66) many of the products made for outdoor use (Figure 65) have properties, waterproofing, insulation, resistance to ultraviolet degradation and the ability of accelerating evaporation, which would be appropriate for use in the building industry. As an example, Dupont Lycra, a high-performance, man-made spandex fiber, which stretches up to five times its original length, displays the level of malleability required by the system. Since spandex fiber has the ability to be combined with other fibers, a building membrane that accommodates the required length changes with the additional properties necessary in a building envelope may be engineered. The potential to further penetrate the building industry market may induce textile manufacturers such as Dupont, Gore or Goodyear to make the substantial investment in research and testing that would be required before a membrane could meet the building industry performance and code requirements.

The membrane forms a continuous interior and exterior surface over the frame integrating weather protection, thermal insulation, lighting and interior and exterior finishes. (Figures
Stainless steel grommets at the connection points and material reinforcing in areas subjected to high stress are elements of its design. Connection points are provided on both interior and exterior surfaces at the node through a small attachment device. The device, a semi-spherical stainless steel clip, is threaded and pinned into a plate that is secured to the backside of each of the outrigger seats. A membrane is secured by placing the grommet hole over a tapped hole in the center of the spherical clip that is spaced with compressible neoprene washer seals. Another clip section (opposed in direction) is then screwed into the tapped hole. Compression of the neoprene washers creates a watertight seal. Both convex and concave articulations are accommodated due to the opposed, semi-spherical configurations of the clips that allow the membrane to stretch evenly (without any sharp angles or points) over their surface. With the addition of a small attachment device lighting may also be integrated within the membrane, or at panel joints at the line of struts. This is especially effective when the interior membrane is present because the entire surface may be back illuminated similar to the luminescent ceiling panels on Renzo Piano’s Kansai International Airport terminal (Figure 70) or the translucent metallic skin of Toyo Ito’s Tower of the Winds. (Figure 71)

Panels, which may be selected from a variety of available manufacturers, include point-supported glazing, aluminum and glass curtain wall and lightweight insulated metal systems. In this case an open systems approach was achieved with the design of an attachment device that could accommodate several different types of panel systems. Most of these panel systems have standardized rectangular dimensions.
D.B.E. systems with rigid panels (Figure 73) do not provide the same degree of mutability as those with membranes due to the rectangular grid configurations and rigidity of the panel systems. Since the grid is rectangular, one line of struts and its associated rigid panels must be tied along its entire length to the next and a series of cross bracing members must be added to maintain lateral stability. This necessary rigidity eliminates the shape flexibility of bi-planar mutability achieved with membranes and allows only planar rotations about the nodes. Even this degree of mutability, however, requires length changes at the nodes. These are accommodated with the use of one of two specially designed expansion joints. A "hard" joint (Figure 74) has been developed borrowing concepts used by two of the precedents mentioned in chapter two, armadillos and jet aircraft ailerons. This assembly is a cylindrical form [three-quarters of a circle in the open position] composed based on a sixteen-inch accepted building industry material standard, or a multiple thereof. Although generally reliable, this standard is not universally accepted. The strut length and outrigger spacing accommodate the standard allowing forty eight-inch square panels, a common size commercial window or insulated metal panel, to be used without any site modifications. The potential to use varying strut and outrigger lengths within a defined range will also contribute to the ability of the system to adapt to various manufacturers' unit standards. Attachment of the panel to the frame (Figure 74&75) is made with a stainless steel C-clamp that has a 2.25-inch tapped post milled out of one end. This C-clamp is bolted to the exposed portion of the strut sleeve. A T-shaped stainless steel seat, threaded into the C-clamp, forms the platform that supports the edge of the selected panel. Another T or L-shaped extrusion, with identical dimensions is side bolted into the seat, capping the assembly. In addition to providing a blind bolted finish mullion to the panel system, this element also serves to compress the panel edge—keeping it secured to the system in shape configurations that might otherwise cause the panel to fall out.

D.B.E. systems with rigid panels (Figure 73) do not provide the same degree of mutability as those with membranes due to the rectangular grid configurations and rigidity of the panel systems. Since the grid is rectangular, one line of struts and its associated rigid panels must be tied along its entire length to the next and a series of cross bracing members must be added to maintain lateral stability. This necessary rigidity eliminates the shape flexibility of bi-planar mutability achieved with membranes and allows only planar rotations about the nodes. Even this degree of mutability, however, requires length changes at the nodes. These are accommodated with the use of one of two specially designed expansion joints. A "hard" joint (Figure 74) has been developed borrowing concepts used by two of the precedents mentioned in chapter two, armadillos and jet aircraft ailerons. This assembly is a cylindrical form [three-quarters of a circle in the open position] composed...
of overlapping extruded aluminum leaves. The leaves, four on each side of the node, are screwed into the panel seat T opposite the panel edge. This connection is finished with an extruded stainless steel trim that clips into the T. Each leaf is secured to the next in the assembly by clip angles that use roller bearings and a molded rubber lip to ensure proper alignment, smooth action and a continuous, watertight surface. As the open assembly closes, pivoting around the rotating node, a small ledge secured to the base of the C-clamp makes contact with the leading edge of each leaf and pushes it into its closed quarter circular form.

The "soft" joint (Figure 75) uses double sections of membrane with expanded or piped edges which slide into extruded clamps. These clamps are secured to the opposite side of the T-extrusion between panel sections so they cover the area of the node. The malleable membrane stretches to accommodate the mutation.

The addition of photovoltaic cells (PV) to the enclosure surface could provide electrical autonomy, powering the mechanical elements of the system and potentially the additional electrical systems in the building. In addition, as a mutable surface, the D.B.E. would have a unique ability to optimize solar collection by tracking the sun. Since recent developments in PV technology have made thin film applications possible they may be adhered to very demanding shapes such as doubly curved surfaces of tent structures, or the membrane enclosure of the D.B.E.
3.1.5 Mechanical Systems

While most of the mechanisms in section 2.2 were considered and several were applied and tested, the D.B.E. system (Figure 78) in its final form adopted a simple geared mechanism to produce a rotational force at nodal points in the linear frame. The mechanical system includes: unit drive assemblies, safety breaks and locking mechanisms. Unit drive assemblies are small, high-performance electric motors, mounting seat, gear drive components (Figure 79) and a lightweight housing. One assembly is secured to each node on the female end and is designated the task of facilitating the rotation of that node. This nodal drive concept, as opposed to a central drive for many nodes, was adopted early in the design process. Reasons for this decision include the following: 1.) The system would not need to be tethered to a large central drive, limiting layout flexibility and occupying valuable floor space; 2.) Coordination of central drive unit sizes with the maximum number of struts it could operate would be eliminated; 3.) Mechanical problems with nodal drives would only affect a single node, as opposed to the entire system and 4.) Maintenance of nodal drives would be easily accommodated by lowering the drives to a height where they could be serviced, or replaced.

As a result of the decision to use the nodal drive concept, minimizing the size and weight of the drive units was critical to the design of the system. In a rough calculation, based on the estimate that the weight of a single line of struts in an arched configuration [38ft. dia.] would be approximately two hundred fifty pounds, the power provided by each nodal motor was sized to two hundred fifty watts. This power requirement could be easily handled by a single horsepower motor [1hp=745W], which could be as small as a two inch diameter cylinder, two inches in height and weighing as little as 4.5lbs. Given the minimal size and compact shape of this unit, it could easily be attached with a mounting seat to the outside face of the female node surrounded by the outriggers. In addition to this being a convenient and protected mounting position, it would
not substantially offset loading and potentially destabilize the system since it is only two inches from the pivot point of the node. Including the associated mounting seat, gear drive components and a lightweight housing, this would only add approximately six pounds to each node, or a twenty-five percent increase to the system.

The other two major elements of the mechanical system, the safety breaks and locking mechanisms are components which prevent the nodes from rotating during a power failure or mechanical problem and lock the node into a particular angle when not in rotation. Safety breaks are common elements of many mechanical devices such as cable cars and elevators—they may be magnetic, or use friction to impede movement. They are triggered by a loss of power or a sensed anomaly in the system. The locking mechanism used in this system is a pair of electrically activated plunge pins that protrude out of two tubular stainless steel housings. These appendage housings extend in opposed directions from under the drive unit beyond the edge of the female node where they are centered over the holes along the male nodal disk. In operation, the node rotates in increments defined by the spacing of these holes to the desired position and stops. The pins in the locking mechanism are then extended through the holes on opposite sides of the disk and into a receiving housing attached to the opposite side of the node. Once the pins are in place, the motor of the drive assembly powers down and the pins maintain the position of the node.
3.1.6 Control Systems

Control systems (Figures 82&83) are the electronic networks which sense interior and exterior climate changes, interpret user input, and communicate instructions to rotate the nodal drive units. Control systems in “Level 4” adaptable machines, (Figure 83) as described in the book *Kinetic Architecture*[^14], include continuous input to a sensor which is relayed as a set of instructions to an energy conversion unit for activation. The level of sophistication in this kind of a system would be appropriate for interior and exterior climate (precipitation, temperature, humidity, ventilation, wind loading and potentially lighting) control. In the case of user preferences, however, a much simpler system, (Figure 82) potentially activated through voice control, a manually operated control panel or computer station, would suffice. Based on this, a dual control system is being proposed with an override capability. The override would monitor potential conflicts between user-input control and the climate controlled shape optimization. This would be especially critical in climate changes including heavy precipitation, or wind loading, or user input that might affect the structural capacity of the system. The system could respond to such conflicts with a warning signal, or in potentially critical situations automatically adapt the form of the enclosure to eliminate the threat.

A final element of this section, electrical and data wiring will be kept to a minimum through the use of “no new wire” technology[^3]. Wiring will run along each line of struts, powering the nodal drive units and locking mechanisms. This presents the benefit of using the enclosure as a source of power for lighting (Figures 87&88) and other peripheral electrical systems generally associated with building spaces. A system of organizing and protecting the wiring will be a necessary element in the design. Connections and splices will need to be accessible and some provision for later additions or modifications to the system will need to be included. Due to the mutability of the system provisions must be made for allowing flexibility at the nodes. Three general concepts, which need to be further evaluated,
should be considered, 1.) Use the carbon fiber struts as raceways, milling out sleeves into the nodes for connections and splices; 2.) Add an appendage to the strut in the pultruding process that will house the wiring, or 3.) Develop a clip or spine (Figure 85) that attaches to the strut sections.

While the mechanical and control systems in the D.B.E. are still underdeveloped, it is intended that the information presented here represents a basis, establishing a credible path of further research.

3.2 System Configurations

This section describes mutability and the diversity of configurations the system, as a prefabricated kit-of-parts, may produce when its elements are assembled in different combinations. In addition, the section establishes a range of acceptable “scales of use,” or relative sizes of enclosures the system may produce.

Mutability (Figure 89) occurs as a result of the nodes rotating in the frame. Each strut in an articulated configuration may rotate one hundred eighty degrees, ninety degrees clockwise and ninety degrees counter clockwise, about an adjacent strut in a connected line of struts. (Figures 86&90) When several lines of struts are joined together a plane is formed which defines the enclosure and mutable plane. With concave, convex and combinations of sectional configurations a broad range mutability is achieved. The rotations of struts may occur “in plane,” where all the adjacent nodes on each line rotate with the same direction and angle. This type of mutability may occur with membrane or panel enclosures. Several lines of struts may
also produce bi-planar rotations, where adjacent nodes in each line may rotate in varying directions and angles, but this is only possible with a membrane enclosure system. Although bi-planar rotations limit enclosure material selection, an entire dimension of mutability is added to the enclosure including complex, three-dimensional synclastic and anticlastic curvatures. (Figure 91)

An important objective of the research was to develop an efficient, industrially produced building system without the generally associated drawbacks of monotonous, repetitive layouts, inflexibility to changes of use and the inability to adapt to varying site conditions. As described in section 3.1, lines of repetitive elements (struts and outriggers) are connected into a grid configuration that forms the mutable, enclosing surface. (Figures 91, 94&96) This grid, by varying the lengths of either struts, or outriggers may enclose space in an Euclidean (rectangular or triangular), or non-Euclidean (curvilinear) form. (Figure 91) The example of a thirty-eight foot wide by forty-four foot long barrel vaulted enclosure will be used to illustrate the range of forms the system may take. If, for instance, the outriggers on one side of a line of struts are longer than those of the other side, the enclosing plane will curve toward the longer side. This device makes a multitude of plan configurations possible including L-shapes, C-shapes, H-shapes and O-shapes (Figure 93) in addition to the I-shape displayed by the reference example. (Figure 94) Several different types of edge conditions—where the system meets another surface, such as the ground, are possible including open and closed ends perpendicular to the lines of struts. These ends, if open, may have varying edge conditions by manipulating the outrigger lengths. In reference to the barrel vault, the edges shown as two triangles joined at a point in the center of the arch could be a straight edge, or a single triangle which is widest at the top, etc. By manipulating the nodal positions, varying heights and sectional forms are realized as an active form of mutability. An additional form of active mutability, the opening or closing of the side of the vault, may be accomplished with the addition of a secondary support. This sup-
port, connected to each node, runs along the length of the vault and is supported at each end with a laterally braced column.

Since the system is an enclosure, it may be used as a wall surface, or a roof surface, or both. (Figure 95) It may be used as a freestanding element, or in conjunction with another building system, such as a stone wall or load-bearing steel frame. This will permit use in retrofit work as well as new construction. The grid frame is capable of supporting load perpendicular to either axis (struts, or outriggers). This allows the system to be set on edge, with the outriggers bearing gravity loads, facilitating plan mutations as opposed to the sectional mutations provided when the struts are resisting gravity loads. In this configuration it may form a façade of a high-rise building. (Figure 96)

Since the façade is a mutable surface, the method by which the enclosure would meet the stacked floor planes, which would not mutate, must be considered in the following two examples. The D.B.E. could be used as the outer surface of a double skin, mutating independently of the inner enclosure. This would present the formidable challenge of minimizing the space between skins to facilitate the buoyancy driven air flows desirable in double skin designs while simultaneously mutating as required to reduce lateral wind loading. Another potential concept would cantilever the D.B.E. off the floor plates enough to facilitate the required mutations. It must be noted that the ability of the outriggers to support gravity loads is not as efficient as the capability of the struts. Because of this spans would be limited to five or six bays [approximately twenty to twenty-four feet, or two floors] as an infill system with a pri-
mary supporting system transmitting the loads to the foundations.

### 3.3 Interdisciplinary Design Process

Because this research topic essentially combined adapted technologies from several different disciplines an interdisciplinary approach was adopted. The broad range of subjects researched including architectural and product design, material sciences, structural and mechanical design, etc. necessitated direct contributions from members of each specialty. In addition, manufacturers were consulted on the constructability issues of manufacturing, transportation and erection. As a kit-of-parts design, the result would be multi-purpose and multi-configurational and elements designed by one specialty would have to be closely coordinated with elements from several others if they were to function properly as an integrated assembly.

In following passage of the book *Structural Glass* the authors describe the design process, which shares certain similarities with the development of the D.B.E., of the Serres or large glass enclosures at La Villette in Paris. "It is important to understand the design process used in the Serres project to appreciate how it works. This requires a clear understanding of the structure's behavior and its architectural objectives, plus a knowledge of the possibilities made available by industry. Such constraints demand a rigorous method of working and follow-up. The Serres is not simply a good idea conceived and then completed in the abstract. It is the result of long research into the behavior of glass, as well as the fixings, the cables and the structures that support it. The project evolved as understanding grew wider and deeper. The results of each design stage were compared with the aesthetic and architectural objectives and the necessary decisions taken accordingly. This type of design process is somewhat analogous to that for industrial products such as aircraft, motor cars, machinery and even skis." 

Loosely following this procedure, (Figure 97) the architect assumes the role of providing direc-
tion and organization to the research and assembles the team that will amass the knowledge and experience. (Figure 98) This was made possible in the case of the D.B.E. by the generous involvement of several faculty members from different departments at MIT, involving student participation from several different schools and disciplines and soliciting the advice of active professionals. Complementing small working sessions with various combinations of team members, a series of team meetings where design concepts were formally proposed and critiqued formed the core of the interdisciplinary process. These meetings were essential in keeping everyone involved up to date and developing awareness that specialists, having a thorough, but limited scope of knowledge, may provide essential information that does not have to be incorporated at the expense of other significant input. They also provided a general sense of sharing, cooperation and participation that is imperative to the members of a creative, energetic design team.

The following section is a rough chronology of the concepts developed during the project, some of which were used in the final product and some of which were not. While research from the start included kinematics studies to define the range of necessary movements and architectural research to identify appropriate spatial configurations and system uses, this section will be devoted to the development of the frame and its associated technology. This is included to give readers a base of knowledge of what was attempted before the selection of elements that comprise the final system and to assist in directing additional research.

Initial ideas about the research (Figures 99&101)
centered on a building system that used the spanning capability of a space truss but could produce universally variable forms ranging from orthogonal to three-dimensionally curvilinear geometry. This was adjusted to incorporate the aspect of mutability, (Figure 101) which would allow additional flexibility over a period of time specifically with respect to user preferences and climate changes. It was thought at the time that both rotations of the nodes and translations of the struts would be necessary to produce the range of spatial variations and adaptable mutability. A structural engineer made the observation from the initial concept sketches that a structural system that was designed to be inherently rigid and stable would be difficult to mutate. This realization provoked a geometric simplification of the solution to a linear strut system that was used in the final project. By eliminating the triangulation, the system mutability could be studied without the complexity inherent in a three-dimensional space truss. In addition to simplifying mutability it also led to the fortuitous discovery that the strut translations were unnecessary because the rotations in the nodes of the frame produced translations in the system. In addition to these initial simplifications, several types of drive systems, including worm drives and compressed gas, piston drives were being evaluated.

The initial strut scheme (Figures 102-104) was substantially more complicated than the final scheme. It had two sets of double struts pinned to a tapered outrigger. A closed loop of cable ran from the ends of one pair of struts through eyes in the ends of the outriggers to a drive unit on the outrigger pinned to the ends of the second pair of struts. By rotating the cable in either direction the end of the struts would correspondingly rotate to produce the desired shape mutation. This scheme proposed to use the cable as a load-bearing element and drive system of the mutations. It was thought that the space between the two struts could contain the enclosing system. Three problems with this scheme—destabilization of the rotations due to the eccentricity between paired pin joints, a limited maximum rotation of twenty degrees and the reduc-
tion of the section between struts during rotation that prevented insertion of the enclosing system—eliminated further development.

The second prototype (Figures 105-109) modified the first concept by eliminating the paired struts in favor of a single strut. The balance of the previous design was maintained. It was proposed that a single strut would eliminate two of the three initial problems and that the enclosure system would be attached to the outside of the system. In addition, this prototype included several lines of struts interconnected with straight beam elements forming a plane. While this design increased rotation of the struts to the required ninety degrees and was relatively stable, another problem was encountered. During rotations the outrigger, which splayed the cables, was not rotating in proportion (maintaining a bisecting angular relationship) with the struts. This tended to reduce the triangulation, or affective section depth of the splayed cables and therefore the system's load-bearing capacity. While the cables could be fixed to the outriggers by changing the fixed cable end connection to another rotational device, this still didn't ensure that the outrigger would rotate in proportion with the struts. In addition, the lack of triangulation in the parallel lines of struts which resists lateral loading necessitated cross bracing. Since the cross bracing resisted lateral loading it could not change length to allow out of plane mutations. This was the final strike against this prototype, except for one additional attempt to use it in a triangulated grid configuration. (Figures 110&111) This concept failed due to the large eccentricity between the two pin joints that separated each paired set of struts that completely destabilized the system. A substantial amount of space between two separate pin joints
was necessary to allow accommodation of the four additional pin jointed struts at the node of a six-sided triangular grid. In retrospect, it would have been interesting, with a functioning nodal design, to study the affect this triangular grid would have had on the mutability of the enclosure plane.

The third prototype departed from the first two by fixing the outrigger to the end of one strut in the paired system. Initially the outrigger was designed as a straight element perpendicular to the strut. With this scheme the cable didn’t need to be fixed to the outrigger ends, similar to the first and initial second prototypes, but the reduction of the affective section was still a problem, especially in the fully rotated position. In reaction to this the outrigger design was modified into a wheel configuration that would maintain the same triangulated section in any position.

A fourth prototype (Figure 112) radically departed from the third with a change of materials. Carbon fiber was substituted for the struts, which were previously modeled as steel. This decision was made to facilitate simplified fabrication of the more curvilinear form of the strut with attached circular outrigger and to reduce the weight of the system. (Figures 116&117) The asymmetrical, curvilinear designs of carbon fiber mountain bike frames (Figure 113) inspired this departure. In this scheme the strut with the rounded end was pinned to another identical strut and a closed loop of cable was secured to the tapered end of one strut and wrapped around the circular end (the outrigger) of the second strut. Initially this design had the same proportional relationship between strut length and outrigger length (approximately 3:1, or 4:1) as the initial prototypes. This proportion is substantially over designed (12:1, or 15:1 is more appropriate in articulated, cable-stayed beams or trusses) and with the relatively solid, monolithic form of the carbon fiber element it made sense to increase this proportion. The curved portion of the strut was reduced and the tapered end elongated. The newly proportioned section (Figures 114&117) almost eliminated the triangula-
tion of the effective section between the strut and cable. During this phase of the process it was also discovered that the cable required a small length change to accommodate the rotation of the strut. Therefore, the adjusted proportion and the necessary change in cable length virtually eliminated the possibility of using it as a load-bearing element of the design even if a spring was added to accommodate the length change.

Based on the elimination of the cable as a load-bearing element and the fact that a geared system could be set into the wider end of the strut, the cable and outrigger concept was scrapped altogether in the fifth prototype. (Figure 119) This vastly simplified the mechanics of the design, eliminated structurally ineffective elements and made attachment of the associated enclosure system much simpler. A small change was made to this prototype, eliminating the broad end and tapered section of the carbon fiber strut in favor of a straight cylindrical section with stainless steel male and female end nodes. This change allowed a simple pultruded section to be used instead of the more complex, expensive tapered section and permitted a variety of node designs to be used interchangeably, thereby increasing the total flexibility of the system. With this change the final strut design was adopted.

A final series of major refinements was made to the strut assembly through the development of the planar aspects of the system and the connection between lines of struts. (Figure 118) With the development of the fourth prototype it was thought that the lines of struts would be connected one to another in the same orthogonal method used by the second prototype. The
reason for this assumption was the desire to avoid the incredible degree of mechanical complexity created when one triangulated frame rotates about another. While the orthogonal configuration functioned properly in planar mutations, it didn’t allow the bi-planar mutations required in a three-dimensionally mutable enclosure. An initial attempt at triangulation connected two lines of struts at one end and splayed them at the other creating triangular bay. This configuration was never modeled, but it was supposed that there would be mechanical difficulties due to the triangulation. In addition panel enclosure systems couldn’t be affectively used with it because of the cost of triangulating the panels and the drive units on two sides of a relatively small bay were redundant. The illusive trick was to triangulate the frame without triangulating the rotating line of struts. A re-adoption of the previous outrigger system solved the puzzle. Instead of using the outriggers in the section of the struts, they were projected out from the sides of the line of struts in plan. If the lengths of the outriggers were varied in a triangular configuration and secondary, small-sectioned beams were pinned to the ends of the outriggers they would tie the line together in a triangular configuration without affecting the linear nature of the strut rotations. The redundant drive units could be eliminated. In this configuration, the lines of struts are pinned together in only one location, allowing the sections of frame above and below this connection to rotate independently—permitting bi-planar mutations.

3.4 Prototype Building Designs
The following section includes representatives of two prototype building designs utilizing the system.

The first scheme is a small detached dwelling or office using the D.B.E. system in a barrel vault configuration.

The second scheme applies the D.B.E. system to an existing facade of a mid-rise office building.
Plan of small residence or office with membrane enclosure
Plan of small residence or office showing articulated strut configuration
Section of small residence or office
Side elevation of small residence or office showing membrane enclosure
Side elevation of small residence or office showing articulated strut configuration
Section and side elevation of small residence or office
3D View of Frame
Plan and section through membrane enclosure system
Section through deformed membrane enclosure system
Plan and section through panel enclosure system
Section through deformed panel enclosure system
Plan of mid-rise office tower with double skin facade utilizing the Dynamic Enclosure System
Elevation of mid-rise office tower with double skin facade utilizing the Dynamic Enclosure System
Plan and elevation of the components of the Dynamic Building Enclosures frame
4.1 Introduction

As a new paradigm, the appropriateness and viability of the Dynamic Building Enclosures system in providing an economical, efficient solution to a well-defined problem (or set of problems) is a central issue of the research. The method of evaluation is crucial if the result is to be considered a credible basis for further development. Based on this assessment, two forms of evaluation, physical modeling and computer simulation, were used concurrently to test the system. Since the D.B.E. is a kit-of-parts multiple-use building system it may be combined in many different configurations for use in diverse contexts. Therefore, a lucid understanding of its performance is necessary to define clear limits to its potential uses. This issue is addressed by evaluating the system and testing it against a set of performance goals, previously mentioned in section 1.2, in the following three categories: 1.) Systemic and Spatial (Figures 120&121), 2.) Static and Technological (Figure 122) and 3.) Environmental. (Figures 123&124) Each of these categories is briefly described below.

The systemic category will assess the functioning of the components as a harmonious interconnected assembly. Areas of this category include potential uses, the efficiency of the component organization, its growth and flexibility. Another area being evaluated in this section is the system’s ability to be used in conjunction with other pre-existing building systems, or individual components. A series of diagrams and matrix of plan morphologies is included as a demonstration of this evaluation.

The spatial and geometric category assesses
the degree of motion and limits of mutability that the system will permit. A definition of the diversity of shapes and configurations are the ultimate goal of this section. Several representative section configurations with geometric and ergonomic analysis, forming a reasonable range of mutability, will demonstrate this definition.

Static and technological aspects of the system include its structural integrity and constructability, including manufacture, transport and erection. A very large component of this evaluation was carried out through the verification of strategies by physically modeling them. In addition, two computer simulation products were used, Multiframe\textsuperscript{18} and Phoenics\textsuperscript{19}.

Environmental performance, an important locus of the research, is an extremely large area and due to time and resource constraints was severely limited. Areas that were considered include wind loading, natural ventilation, natural day lighting, acoustic and thermal performance. Simulations were performed to test wind loading with CFD and day lighting with lightscape\textsuperscript{20}. The balance of the environmental categories was tested with simple numerical calculations and comparisons. The energy usage of the system in terms of input versus output concludes this section.

4.2 Systemic and Spatial Performance

4.2.1 Diverse Configurations and Spatial Flexibility

The D.B.E. is an adjustable kit-of-parts building system (Figures 125&127) that may actively change its shape delivering an extremely broad and efficient variety of configurations. Efficiency is, in this case, achieved by the limited number of relatively simple components necessary for articulation. Due to the separation and clear articulation of the linear mutable struts from the variable length stabilizing outriggers (Figure 126) orthogonal, triangular and three-dimensionally curvilinear configurations are accommodated. Users may select components to create several regular grid plan configurations including I-
shapes, L-shapes, C-shapes, Z-shapes, H-shapes and O-shapes. (Figure 128) By varying the outrigger lengths any of these configurations may be further deformed into asymmetrical configurations. This degree of flexibility, not including the mutability, allows the customization of building form to almost any program. It must be noted that physical modeling at one-eighth full-scale indicates that the outriggers with varying lengths function properly in a simple I-shape barrel vault configuration; the other shapes remain untested. In addition, while this degree of flexibility seems beneficial, further kinematics and ergonomics studies may indicate that simplifications and limits are reasonable.

The mutability accommodated by the system (Figure 129) in its present form is sufficient to accomplish the set range of program goals. Flexibility through the mutations therefore extends the range of program fit into the dynamic realm. Architectural design must take into consideration a perimeter that moves in and out, up and down within a predefined range. Open plan configurations with flexible, movable partitions and furniture would be a logical counterpart to the mutable surfaces of the enclosure. The D.B.E. system properly integrated with these partitions and furnishings simply and effectively responds to the changing use of spaces within buildings on a daily or even hourly basis. Grammar school rooms, for example, are used as painting studios and lecture halls in the morning, then recess play spaces and sometimes napping during the afternoon. In a similar manner, community centers have multiple-use functions that could be actively accommodated with ease. Providing a building system that adapts to the needs of each of these program uses,
not to mention the range of changing program requirements in residential, commercial and recreational typologies was essential to the system. The understanding of the kinematic aspects of the system has made a great deal of progress. When the D.B.E. was initially developed, the concept was based on an understanding that shape plays an important role in the performance of built spaces. In addition, it was thought that using the system as an enclosure, instead of an interior space defining element, would have a positive affect on the environmental performance of the built space. While these benefits seemed reasonable, the specific types of motions required or the technology necessary in providing them was unknown. Based on developments in studying the ergonomic relationships created by various movements; identification of parameters of what constituted comfortable, functional spaces and evaluating various technologies, the system mutations were limited to a range of 180-degree rotations (90-degrees clockwise and 90-degrees counterclockwise) at each node. These limitations seemed additionally appropriate based on the fact that nodes were subjected to disproportionately high levels of stress when they rotated more than 90 degrees and highly angular configurations produced no tangible spatial benefits. Mutability, as a range, is ultimately defined by the properties of the enclosing surface. While bi-planar mutability may be accommodated with a membrane, the special nature of this currently unavailable membrane severely limits its potential usage and therefore development. Panels, in contrast, may be selected from a range of currently available systems, but do not provide bi-planar mutability. These realizations have had a guiding affect of the design of the system and continued research will surely provide additional limitation param-

4.2.2 Diverse Scales of Use

Because the system can enclose a variety of surfaces, such as a roof, wall, canopy, (Figure 131&132) or freestanding autonomous structure, (Figure 133) it has many potentially diverse scales of use. The structural ability of the outriggers to resist gravity loads additionally al-
allows the system to be used upright, accommodating mutability in plan. This makes the system appropriate for mid-rise facades (Figure 130) and especially double skin facades. The device that permits use in different scales, more effectively than any other, is the additional primary supporting system. With this simple addition, attached at the outrigger nodes, the spanning capabilities of the system are multiplied many times. In addition, this concept effectively articulates the enclosure in large-scale uses as a series of inter-connected panels, permitting effective zoning of structure and mutations. It must also be noted here that while a primary structural system supporting the gravity loads of an enclosure system is not a new concept, it has not been physically modeled or tested with the D.B.E.

4.3 Static and Technological Performance

4.3.1 Supporting System Efficiency

The spanning capabilities of the struts and outriggers partially define the limits of the system configurations with respect to layout. These limits have been maximized to the material properties of the components with some concessions made for coordination with pre-existing enclosure systems and ease of transport and manufacture. The main concession in the structural design is the adoption of a universal node that, paradoxically offers the major benefits of being extremely convenient to manufacture and erect. This node provides a focal point for the internal forces of the system. Since the system achieves mutability by rotating the nodes at varying angles, stress levels in these nodes are also variable and each node must therefore be designed to resist the maximum level in the predefined range. Although this was a convenient start point, additional research has suggested that more acute bends generally occurring close to the ground must resist larger loads and higher levels of stress than nodes close to the top of the frame. This may lead to the adoption of slight variations in nodal design increasing the efficiency of the structure. Based on these developments the four-foot square grid
for the panel system and triangulated membrane system are the maximum strut spans. The twelve panel model [arched] system, with the struts resisting gravity loads, is an example of an optimal design in the sense that the material and sectional properties utilized are simultaneously sized to minimize weight and withstand the required range of loading conditions in any of the allowed spatial mutations. Minimizing weight was a critical aspect of achieving this efficiency, optimizing mechanical performance and permitting erection without a crane. The use of carbon fiber as the strut, the largest component in the design, was a key development in the accommodation of this goal and allowed the weight to be reduced to approximately one fifth the value of another comparable structural material. The miniature motors had a similar affect and also reduced bulk and noise.

Redesigning and re-sizing the components (including the drive units) could increase these, but it was decided that larger span uses would be accommodated through the addition of a larger, static supporting system. This decision was made to avoid redesigning the system for every use that would violate the design and for manufacturing efficiency which is essential in the concept. In the same way, smaller spans could be accommodated, but are considered unnecessary due to the tight ergonomic fit presently provided by the system.

The system has been computationally tested in Multiframe simulations of several configurations, with varying loading conditions. (Figures 134-137) The results of these simulations are promising. A program of additional simulations, physical modeling and structural load testing of full-scale prototypes, however, will be necessary to...
verify performance over the entire range of mutations. In addition, no testing of the structural performance during rotation and mutation has been attempted. This is an area of testing that is critical to ensure the proper, safe functioning of the system, but beyond the scope of this research. The mechanical design of the system has been conceived to ensure certain safety measures. The nodal drive units do not support the system if they are not rotating, instead the support is provided by the locking mechanism which doesn't require continuous power input. In addition, the nodes have safety breaks similar to those used in elevator cars, which arrest motion during power failures or mechanical problems. Although the system obviously needs a great deal of additional testing in this area, it is the intention of the author that a logical and appropriate level of development has been provided to indicate feasibility.

4.3.2 Sustainable use of Materials and Energy

Although carbon mining and steel mill production are generally not considered ecologically beneficial, the relatively small amounts of carbon used in the D.B.E. in comparison to most steel frame buildings being built today is quite economical and efficient. The pultruding process of the carbon fiber struts essentially uses small amounts of fibrous carbon (Figure 140) and weaves it into a geometrically stable, highly efficient configuration. The more solid form of carbon steel (stainless steel in the D.B.E.) is only used in smaller members and at the nodes because of the concentration of stresses which the carbon fiber is not well suited to resist. Another sustainable aspect of the D.B.E. design is the ability for its modular, adjustable components to be used and re-used in a variety of different situations. (Figure 138) The usable life span of the corrosion resistant frame components would presumably be longer than the standard fifty years assigned to most steel frame buildings. This might otherwise be considered a liability to future changes, but because the strut sleeves allow a diverse range of nodal designs these elements could easily be moved around into new configurations or reused in another building.
Arch configuration: frame and loads

Axial stress

Moment

Shear

Deflection

Wing configuration: frame and loads

Axial stress

Moment

Shear

Deflection
eters, making the system more efficient and viable.

4.3.3 Kit-of-Parts Industrial Manufacturing

All of the D.B.E. components (Figure 141) would be manufactured in a controlled factory environment that would provide many benefits to users, fabricators and constructors. Manufacturing standards of precision, uniform finishes, high-quality control of dimensions and material standards could only be assured if produced in a factory environment. This is due to the ability of factories to control climate conditions and utilize special machinery and processes that are not feasible on a construction site. In addition, factories are safer places to work than building sites and generally provide more stability to their labor force than the intermittent opportunities provided by the traditional building industry. Through the use of Computer Numerically Controlled (CNC) machining and flexible manufacturing techniques small factories could efficiently produce on-demand components customized to each unique project. (Figure 143) There are pros and cons to both large centralized production plants or small local facilities. The decision to adopt one approach over the other would depend on product demand, the potential for approval of the system by a nationally preemptive code, work force distributions, transportation costs and many other factors. One consideration that is unique to the D.B.E., the highly specialized work force which would be required to erect the system, would also need to be considered in the distribution of manufacturing facilities.

4.3.4 Site Erection Strategy

While erecting the lightweight frame (Figures 145 & 147) would be a relatively simple procedure, the integration of mechanical and control systems with the associated wiring and sensor network will have to be performed by highly trained, responsible individuals. This is an area where portions of the performance goal of simple, low-skill and time-efficient site erection has not been met due to the complexity of inter-

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Figure 138

Figure 139

Figure 140

Figure 141

Figure 142

Figure 143

Figure 144
connected systems. Since the components of the system are prefabricated assemblies, however, the time spent on the site would be minimal. In addition, a few individuals without the use of a crane or scaffolding would, in most cases, be sufficient to erect the small, lightweight component assemblies of the D.B.E. Prefabricating the struts as assemblies including all the mechanical and electrical components would remove a large percentage of specialized electronic work from the building site. These struts, perhaps delivered in assemblies of three or four, would be folded into compact configurations and have plug-in electrical connections at the ends to link adjacent sections. In the same manner, membranes and panel assemblies could potentially be delivered with their associated sensors and wiring. It is also a reasonable assumption that the mechanical systems provided on the frame will be capable of significantly assisting in the erection process. Once the frame is in place the enclosure system would be added to complete the assembly.

4.4 Environmental Performance
Environmental performance is an extremely important section of the performance evaluation and locus for this research. A great deal of testing and evaluation is required to establish credible environmental performance on any project, or building component. This phase involves many different consultants, highly specialized equipment and accurate models and production prototypes. The complexity of testing a mutable surface in changing environmental conditions is even more formidable. Due to time and resource restrictions this section was limited to a simplified study of wind loading and lighting control. Thermal performance, control of natural venti-
lation, indoor air quality and acoustics will have to be studied in detail if this research is continued in the future.

There are several capabilities of the D.B.E. which suggest that occupants would benefit from the dynamic control of environmental parameters accommodated by the system. An interesting byproduct of the mutating surface of the enclosure is the reduction of area inside the envelope. The cross sectional studies (Figure 149) illustrated in section 4.2 demonstrate that the transformations of the twelve-panel arched system into a rectangular configuration reduces the interior area by thirty-percent. A minimization of volume at night in a cold environment could substantially reduce the operating energy required to heat the spaces. At the other end of the climate spectrum, in hot, humid climates the ability of the system to increase the total height of spaces and create openings in various places could generate a stack effect (Figures 153-155) to promote natural ventilation. In addition, this stack effect, or wind-driven ventilation could conceivably be directed and focussed by the enclosure to specific areas of the interior.

4.4.1 Acoustics
Acoustic characteristics of spaces enclosed by the system would also fall under its dynamic control. Three variables which could be affected by the mutations include reverberation time, diffusion and reflectance patterns. Reverberation time \(\text{Rt}^{22}\) is directly proportional to the spatial volume and affects speech intelligibility or the tonal quality of music. In other words, if the volume of a space is reduced, the reverberation time is reduced and it becomes easier to understand speech. The high ceilings and large volumes of concert halls have long reverberation times and, therefore, provide better environments for music. Diffusion and focusing are also affected by the specific geometry of the surfaces surrounding a sound. Since the D.B.E. can change the volume and height of interior spaces, and the shape of the enclosing surface, direct control of these variables is achieved. One aspect of the spaces enclosed by the D.B.E. which
would require some attention is the control of sound transmission between spaces. With the open plan interior configuration necessary to allow the spatial mutations and movable partitions the traditional method of sound proofing by providing spatial isolation is not possible. Alternative forms of control, providing sound absorbing surfaces on movable partitions, or flooring panels may be considered. Considering the substantial number of available sound absorbing products and the potential benefits of an open plan configuration, this consideration need not be considered problematic.

4.4.2 Reduction of Wind Loading
The enclosure surfaces of buildings act essentially as sails when they are oriented perpendicular to the prevalent direction of the wind. While careful siting and minimization of surface area with this disadvantageous orientation are possible, additional structural framing or wind bracing are generally required to resist the force of the wind. Due to the affects of several natural phenomena, the higher the building enclosure, the more extreme the loading on the surface. Traditional static building enclosures resist lateral wind loading through the framing components of the enclosure system and then transfer it into the primary supporting system of the building. The pressure value of this loading may be reduced by altering the shape of the enclosure to minimize surface area that is perpendicular to the prevalent wind direction. This fact has been established through the study of fluid mechanics and put into practice on many buildings. While aspects of this approach have been successful, shapes such as tapered sides or rounded corners have a limited capacity to reduce loading. These shapes are generally quite
subtle and changes in the prevalent wind direction or micro-climate turbulence affects require shifts in form that the static enclosures are not capable of delivering. The D.B.E. system, in contrast, has the ability to actively modify its shape and when equipped with a sensor net on the enclosure surface would additionally have the ability to sense shifts in wind speed and direction and adjust the shape to minimize loading. Since it has a surface independent of any connections to interior partitions or multiple floors the shapes it may generate to reduce wind loading may be less subtle than conventional systems and thus more affective.

Three simple computational fluid dynamics simulations *in Phoenics* were used to evaluate the affects of the shape of the enclosure on loading. (Figure 156) These shapes were derived to study the ability of the system to accommodate the tapered forms generally considered to be aerodynamic and capable of reducing drag or loading. A twelve panel rectilinear configuration was used as a control example of a conventional single story building. While the D.B.E. may provide this shape it is not limited to it, and would not maintain it during heavy wind loading. The second file was a twelve-panel arched configuration and the third file has a wing configuration produced to minimize surface area perpendicular to the prevalent wind direction. All three files had identical environmental parameters and plan configurations. It was interesting to discover that the most influential factor in reducing the maximum pressure value was the reduction of height. This is why the pressure value is lowest on the rectilinear configuration. While it is true that the least aerodynamic configuration had the lowest maximum pressure value, when a cumulative accounting of pressure values along the entire surface area of the façade is computed, the total pressure of the wing configuration is considerably less. Although this proves that changing the shape of the D.B.E. will reduce lateral wind loading, the three-dimensional effects of the wind still remain to be evaluated. The critical aspect of this performance which may be completed in subsequent research is how much the system can reduce dynamic
shape to minimize loading. Since it is a surface independent of any connections to interior partitions or multiple floors the shapes it may generate to reduce wind loading could be less subtle than conventional systems and there more affective.

Three files were produced in Phoenics to evaluate the affects of the shape of the enclosure on loading. The first is a rectilinear configuration produced by the twelve-panel model building. This was used as a control example of a conventional single story building although the shape presented is one that the D.B.E. can accommodate. The second file has the twelve-panel arched configuration and the third file has a wing configuration produced to minimize surface area perpendicular to the prevalent wind direction. The objective of this simulation was to discover what effects the shape changes of simple extruded three-dimensional forms had on the loading of the enclosure. All three files had identical environmental parameters and plan configurations. It was interesting to discover that the most influential factor in reducing the maximum pressure value was the reduction of height. This is why the pressure value is lowest on the rectilinear configuration. While this is true when a cumulative accounting of pressure values along the entire surface area of the façade is computed, the total pressure of the wing configuration is the lowest. Although this proves that changing the shape of the D.B.E. will reduce lateral wind loading the three-dimensional effects of the wind still remain to be evaluated. The critical aspect of this performance which may be completed in subsequent research is how much the system can reduce dynamic loading and to what extent the frame may be minimized as a result.
loading, how these movements would affect occupants and to what extent the frame may be minimized as a result.

### 4.4.3 Lighting

Interior and, to some extent, exterior lighting levels may be effectively controlled by the system. Because the enclosure surface is capable of three-dimensional mutations, it can track the arched path of the sun. This capability could be used to maximize or minimize light penetration or to optimize the angle of solar PV panels on the enclosure surface. The surface could adjust its orientation throughout the day to optimize a desirable shading pattern. Due to the ability of the membrane to open its side walls like an awning, this shading pattern could be extended to exterior areas adjacent to the building. When the side walls are open, light is allowed to enter, but direct penetration of the sun's rays may still be regulated. Total darkness could be achieved in a closed configuration, depending on the selection of end wall materials. Allowing light to enter in this manner could provide an entire wall of windows without the potential security and thermal considerations necessary in a conventional glass wall. One additional advantage that the system may support is the inclusion of lighting fixtures along the lines of struts. Lighting attached in this area could either provide general illumination, especially between the surfaces of a membrane configuration, or controlled task or spot lighting.

A demonstration of this lighting control was accomplished using Lightscape. (Figure 157) Two different configurations, a barrel vault with closed sides, and one with two open sides, were modeled and rendered to illustrate the diversity of lighting levels obtainable.

![Figure 157](image-url)
CONCLUSION

5.1 Summary
This section of the chapter includes a brief discussion of the appropriateness and viability of the topic and a summary of the process of research. Section 5.2 will outline some suggestions for future research.

The work scheduled for this research effort was enormous in scope and continuously posed unusual technical and systemic challenges. The addition of movement to building enclosures fundamentally changes all aspects of the present notion of built space. It presents an opportunity for building design to undergo a revolution which, in some respects, is comparable to the affect that Einstein's theory of relativity had on humankind's notion of the universe.

Dynamic Building Enclosures (Figure 159) relate and respond to site climates and user preferences on an unprecedented level. This represents an incredible range of tangible benefits including increased user comfort, flexibility, response to special programmatic spatial requirements, adaptability to diverse configurations and site contexts and economical energy efficient environmental performance. The geometric adaptability of the system with its incredible range of configurations and diversity of enclosing materials provide the opportunity for wide spread use which would be healthful to inhabitants and contextually beneficial to building sites. There is little doubt that the use of this system would produce a host of psychological and physiological effects. Although some effects may be undesirable, understanding them is important and should not impede additional development. While the findings in this research support a substantial range of benefits achieved by the system, the level of
complexity in further developing it must also be taken into consideration. The fact remains that the United States building industry is already constructing designs for Sport facilities and cultural centers which have simplified dynamic elements that indicate a fertile environment for more expansive development and use.

As indicated in section 3.3 the interdisciplinary team approach was essential in the design process of the Dynamic Building Enclosures system. Since the topic was selected in part to explore an area that required the synthesis of several diverse fields of study, it could not have been accomplished as an individual effort. While the task of managing the team was at times in itself difficult, the group contributions and exchange of information was invaluable and provided the means to achieve a well-balanced design. The team was comprised of faculty members from two departments at MIT, the author, two mechanical engineering undergraduates, a Boston Architectural Center student and a Harvard architectural student. The task of organizing the efforts of the individuals and bringing them together for review meetings proved to be an especially difficult aspect of the work. While many departments at MIT encourage collaboration, the working reality offers many barriers. Faculty time constraints, a tendency towards extreme specialization and the diverse and sometimes conflicting demands of individual departments deny success to all but the most tenacious organizers. The program of development adopted by the D.B.E. team took advantage of some exposure to mechanical, electrical and civil engineering disciplines provided by the architecture department. It must be noted, however that provision of additional resources from material sciences, computer sciences, psychology, and economics, which could become a goal of the Building Technology Program, would also be necessary in any truly synergetic architectural research project.

Drawing, physical modeling, (Figure 160) computer simulations (Figure 161) and meetings with consultants were used concurrently to guide development of the project. Computer simulations
were used to understand stresses in the members and aid in sizing components, evaluate airflow characteristics and study lighting. While they provided a substantial amount of relatively quick, accurate information and guidance, extreme care must be taken to ensure accuracy of the input information. On several occasions, structural simulations and drawings suggested a particular aspect of the design functioned properly only to find that in the model it was problematic. For these reasons, the physical modeling was the most effective measure of performance of the D.B.E. design at this early stage of its development. Models were particularly effective because they could physically test the ability of the system to mutate. The models became a source of information to constantly remind everyone involved that this building enclosure moved and how important that consideration was to the design. These events provide conclusive proof that the D.B.E. challenges many deep rooted, fundamental precepts of building enclosures and the spaces they form.

5.2 Suggestions for future research

The topic of dynamic building enclosures is a rich area of emerging interest. Somewhat simplified built examples of these enclosures have been realized in the recent novel efforts of designers such as Jean Nouvel, Santiago Calatrava, Charles Hoberman and the general acceptance of dynamic roof structures over sporting facilities. Research, with continued demand, will undoubtedly continue. While it is obvious that the technologies to develop these systems either already exist, or are readily obtainable, the current level of sophistication is underdeveloped. In addition, systems in use
generally provide a dynamic response to one task, controlling light penetration, raising, or lowering the roof, etc. A more synergetic and dynamic response to many of the tasks a building enclosure must perform would be a more fruitful area of continued research, especially in the academic environment. The concept of the enclosure, as a regulating transition between the exterior and interior environments, providing supplemental conditioning to the healthful natural environment is a prospect that could simultaneously reduce global pollution, increase human comfort and reduce reliance on non-renewable energy resources.
Endnotes:


3 Lonberg-Holm, K., *Time Zoning as a Preventive of Blighted Areas*, Record and Guide, June 24, 1933, p. 6

4 residential wood platform frame with shingle roofing and wood, vinyl, or aluminum siding, commercial light-gage metal framing with built-up roofing and aluminum and glass curtain wall, or concrete and masonry constructions

5 Wind loading increases relative to the distance from the ground due to the affects of drag by the surface of the ground, plants, etc.

6 Heliotropism is defined as the rotational movement in plants.

7 Haptotropism is defined as the triggered movements in plants in response to contact with another object.


15 No new wiring technology is a special type of cabling which accommodates data signals in the same wire used for electrical power.


Multiframe is a finite-element analysis computer simulation tool for structural engineers

Phoenics is a computational fluid dynamics (CFD) computer simulation analysis tool for mechanical engineers

Lightscape is a radiosity rendering and analysis tool for lighting designers

Two-directional mutability, discussed in section 3.2, is an important program goal that allows complete three-dimensional control of the mutable enclosure plane.

Reverberation time (Rt) is the time it takes a sound to decay sixty decibells
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