THE ADVANCEMENT OF THE APPLICATION OF KINETICS IN LANDSCAPE ARCHITECTURE

by

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(Under the Direction of Marianne Cramer)

ABSTRACT

Opportunities abound for landscape architects to include kinetics in their designs and in doing so mitigating all sorts of social and functional issues. Other professions are increasingly using kinetics to provide functional and aesthetic design and works of art in their fields of endeavor. However, landscape architects lag behind. This thesis offers students, educators, and practicing professionals three things: awareness, knowledge, and design tools. This thesis includes a robust literature review, personal kinetic landscape architecture designs, a catalog of kinetic projects, an evaluation of existing kinetic design tools, and concludes with a proposal for two new tools to aid in understanding the complexities of kinetic design. Through the construction of this introductory research, the contours of this new design realm will be generated, proving that kinetic landscape architecture is an accessible new frontier.

INDEX WORDS: Kinetic Design, Landscape Architecture, Adjustable, Design Tools, Movement, Kinetic(s)

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

Kinetic landscape architecture is a term used in this thesis to describe a human-made exterior environment with an additional ability to continually move and/or adjust within the established site. This motion can range from adjustable seating to a robotic, artificially intelligent surface that transforms shape based on need. The assertions made in this thesis suggest a kinetic landscape has the ability to move for aesthetic, environmental, energy, structural, climate, or user desires. The author further claims a concept that beneficial should be widely introduced to address a variety of global problems. However, landscape architects have only explored the edges of kinetic design. The argument that kinetics belongs in landscape architecture and landscape architects need guidance designing kinetic landscapes is supported by this thesis.

This introduction looks at kinetics as a series of opportunities that kinetics can provide landscape architecture along with an argument for each opportunity.

<u>Opportunity #1: Kinetics can provide a powerful new addition to participatory design.</u>

Participatory design (PD) aims to involve all stakeholders in the process of design, particularly community members that will be affected by the design or become the primary end users. PD is meant to democratize the design process and to empower local residents to influence the redevelopment of their area (Salgado and Galanakis, 2014). It is believed to be essential to a successful environment, especially one paid for with public dollars, comparable to the right to vote for governor or president. Landscape architects take the opinions of the stakeholders and attempt to create a design that reflects the stakeholders' desires.

However, current methods of participatory design are failing (Kaplan and Kaplan 1978). PD has not been able to create an environment which is better than one created with conventional practices, where the architect acts as the sole designer (Francis 1983). Because cities are increasingly diverse, deciding on issues that benefit the common good is no easy task (Salgado and Galanakis, 2014). Landscape architects must design spaces to accommodate a diverse set of stakeholders which creates the risk of design compromise.

The Kaplans (1978) discussed the failures of public design in *Humanscape*. From the perspective of citizens, they list not being asked to participate, or worse, designers pretending to ask, but not listening as the most common complaints. From the designer's perspective, the Kaplans (1978) reported frustration due to lack of attendance and participation, as well as uncertainty in the value of asking untrained designers to contribute. Other failures of PD are the process being detached from the final design project or that it is not actually affecting design decisions (Salgado and Galanakis 2014). It has become a box for city officials or designers to check and stop there. Typically, very little of the affected population is involved in the PD process; it aims to please a large number of people and in the end, completely satisfies no one (Albrecht 1988).

Landscape architecture is generally tasked with catering to an assortment of different people, so the design has to offend no one and comply with society's norms. That may be the reason landscape architecture is often broadly prescribed with little customization (Motloch 2000). Adrian Geuze described pre-programmed space as one-dimensional and demoting to human beings (Jormakka 2002). It strips humans of their individuality, requiring them to accept some preconceived notion of what a designer thinks they want.

These problems open the possibility to introduce kinetics as a supplemental medium for participatory design. The author believes that kinetics can offer a better way to democratize a landscape. It allows multiple points of views to co-exist. Landscape architects can broaden how they think about PD by offering the user the opportunity to radically change their environment to accomplish their own needs at that particular time. Kinetic design permits users to customize a space that does not adequately address their needs (Motloch 2000).

Kinetics is not a substitute; traditional PD is still necessary to determine aspects like location or overall function, but kinetics involves the end user in a new way, an individual and detailed way that is not achievable through traditional methods of involving the public in design decisions. Kinetics allows continual individual customization of an environment for both community members and visitors, all of whom are using a space, not just those who show up for PD meetings. If landscape architects can please users with multi-functional spaces, then spaces do not have to be the result of a compromise.

Humans want to have control of their environment (Whyte 1980). This need is shown with William Whyte's (1979) *The Streetlife Project*, in which Whyte described the simple movement of a plaza chair as a declaration of free will. Kinetics can grant the freedom of public creativity by uniquely allowing people to modify their urban environment as they see fit. It can appeal to a diverse population of people with a broader range of human desires.

Negroponte is the author of the book *Soft Architecture Machines* (1975), a seminal text on responsive architecture. In the book he presents the idea of architecture without the architect, stating that the architect is possibly a detrimental middleman. Negroponte (1975) advocated that a responsive built environment is a basic human right and that we should let the machine, the architect, and the user do what they are each good at. This is a potential benefit that kinetic landscape can offer with the landscape architect designing the system that the machine operates in response to stimuli that is customized to the individual user.

Opportunity #2: Kinetics can match the dynamic qualities of society and the built environment.

It is impossible for a designer to predict every current or future desire a society or individual user requires of a landscape (Motloch 2000). Whyte (1980) says "the complexity of public spaces is such that you cannot expect to do everything right initially." Kinetics could provide the framework that allows further adjustability that designers could not initially predict. It offers the possibility of altering the responsibility of a designer from guessing an end user's needs over time to creating a framework for change, allowing the user to individually decide the appropriate end use. The urban fabric is constantly changing and the speed of those changes makes interpreting and forecasting them difficult (Finizio 2006). A city's built environment is modified daily with new construction and demolition changing its composition regularly.

It is not only the built environment that is changing quickly; the world is now a universally fast-changing society. This thesis argues that with a fast-changing society, fast-changing landscapes are needed to continually meet those demands. We are in an era where the natural world, society, and culture are changing faster than our design ideas. It is time that landscape architecture keeps up with the speed of the world (Cantrell and Holzman 2015). To equalize with a quickly changing society and built environment, kinetics can provide a flexible framework for easy modification.

Opportunity #3: Kinetics can better parallel the dynamic effects of nature.

Currently, landscape architects deal with natural dynamic qualities when planning for the growth of plant material or the impact of rising sea levels. However, the author believes the way landscape architects think of dynamism in relation to landscapes could expand. Existing movement with plants could be increased; plants move in the wind and some can even move in reaction to a stimulus, defined as tropism, but kinetic landscape architecture does not have to stop there. For instance, plant material can move substantial distances across a site as often as needed without a laborious intervention.

Cantrell and Holzman (2015) state that landscapes are constantly changing; however, not all elements of a landscape are intentionally being designed for change. This means the artificial parts of a landscape do not match the dynamism of the natural world. Other elements of a landscape can move and morph in addition to the flora and fauna. Design elements like pathways, structures, retaining walls, and seating, do not have to be static. The artificial should accommodate the dynamism of the natural, and landscape designs can move in parallel with the outdoor environment's natural forces like erosion, sun, wind, and water.

Opportunity #4: Kinetics allows for the economization of space.

Large, dense urban areas are quickly running out of room (Clark 2017). Earth's space is not being used as wisely as it could be and will have to be considered with future growth. Kinetics might be the answer to the increasingly limited green space. Megahed (2017) reveals that multi-functionality is one of the most common reasons for justifying kinetics. Kinetic landscapes are versatile and can use space efficiently by transforming to allow multiple functions to take place. One small park could serve as many functions as several large parks.

Opportunity #5: Kinetics can offer a new possibility for making a landscape novel, challenging, and permitting of choice.

Rachel and Stephen Kaplan are best known for their work with environmental psychology, particularly their book *Humanscape* (1978). *Humanscape* is already familiar to landscape architects but can be interpreted from a kinetic point of view. Their work discusses the relationship between humans and the physical environment. Their research found that humans require the right to choose, even if they ultimately decide not to exercise their right, they still benefit from the knowledge that they had the opportunity to adjust their environment (Kaplan and Kaplan 1978). Additionally, they prefer an option they have chosen for themselves even if the other option would otherwise typically be preferred. These are essential arguments to help validate kinetic landscape architecture. Megahed (2017) lists the ability to control one's environment as a top reason for justifying kinetics. The Kaplans and Megahed insist that kinetics can physiologically benefit humans with the opportunity of choice and adjustability, particularly in an environment like a city where virtually everything is controlled by someone else.

The Kaplans (1978) discuss the 'failure of preference,' a phrase they use to describe environments that fail to provide choice and customization. They further question the costs of adapting to such environments, stating that people might not be aware of how much they adapt to unfavorable environments until they experience one with preference. Potential costs of an environment without preference include irritable and aggressive behavior, less social interaction, and a general sense of uncomfortableness.

Years later in an article on cognitive maps, Stephen Kaplan (2016) lists essential requirements that an environment must support. He says an environment must be able to be understood and have the possibility to be novel, challenging, and permit choice. Some of these traits can be satisfied in a non-kinetic landscape, for example, having three distinct pathway options for a walk across a park. However, a kinetic landscape can expand those requirements to allow more choice or to fit situations in a new way. For example, the landscape can have moving pathways that connect to fifteen different locations around a park, a concept that would infest a park with pathways if it were a static one. Lastly, kinetics creates many novel aesthetic possibilities for landscape architects to add to their toolkit.

Opportunity #6: Kinetics can provide novel forms of complexity and mystery in a landscape.

Complexity was being studied by William Whyte as a component of urban space as early as the 1960s. The Kaplans (1978) discovered that people innately prefer characteristics of complexity and mystery over boring and simple features. These environments ensure that one's focus will not be shared with other content. However, they warn that designers must be careful to balance complexity and mystery with coherence and legibility. Complexity can become a source of fascination because it cannot be understood instantly (Kahn and Hasbach 2012). Humans respond to complexity with intrigue. With added complexity comes the possibility for more functional possibilities. Currently, landscape architects might introduce mystery with a path turning around a corner, and disappearing from sight, drawing people to continue on the path to see what is next. They might make a design complex with a variety of topography changes. With kinetics, designers can offer a new way to provide the complexity and mystery that people desire in their environment.

Opportunity #7: Kinetics is one way of accomplishing flexibility.

Flexible does not necessarily have to involve kinetics, but kinetics can be the solution to the desire for a flexible space. Flexibility is an important, but often low priority factor in landscape architecture. It can be defined as the ability to easily adapt to change. With a flexible and kinetic system landscapes can have drastically longer relevancy to a population. Zuk (1967) declares that there are scarcely any buildings erected today that do not need some version of incorporated flexibility and the same applies to landscape architecture. Lyle (2006) predicts the trend for kinetic structures will be upheld by the "economic pressure to provide greater flexibility of built spaces." This seems to point to the fact that flexibility is an increasingly desirable trait and it is now up to designers to incorporate the approach.

Opportunity #8: Kinetics could draw people to an area.

Simonds (1983, 2013) lists movement as a factor that attracts humans to a landscape and furthermore increases their length of stay. Currently, landscape architects do this with the movement of water, but kinetics could offer an alternative option for movement. Kahn and Hasbach (2012) introduce that biophilic architecture can harness the awe-inspiring qualities of constant change in nature. They state that it is not possible to capture the ever-changing and unpredictable character of nature in static and immobile objects. Kinetics could fill the need to produce similar emotions that people have towards nature – the "wonder, delight, and fascination" that draw people to a site (Kahn and Hasbach 2012).

Conclusion: Kinetic technology will continue to advance with or without landscape architecture; it is up to landscape architects to decide if they want to welcome the opportunities and explore the possibilities. Design flaws and catastrophic failures will be more likely without a knowledge set such as the one provided by this research, and a risk this profession, which is responsible for the health, safety, and welfare of its users, should not take. If landscape architects are ready to take advantage of the opportunities just enumerated, then they will need a foundational base of knowledge. This thesis looks to provide that knowledge by answering the following question: **What can aid in the advancement of the application of kinetics in landscape architecture?**

Purpose

The goal of this thesis is to advance the application of kinetics in landscape architecture. This is accomplished by the following objectives:

1. Establish core literature covering foundational knowledge and the kinetic design process.
2. Create a catalog of kinetic projects and analyze any patterns existing in the data.
3. Examine existing kinetic classification, evaluation, and design process tools.
4. Propose new kinetic design tools to aid in the kinetic design process.

Significance

Although there are references detailing kinetic design for architects and engineers there is not a similar reference for landscape architecture. This thesis introduces and explains kinetics specific to landscape architecture in an effort to fill this gap in the body of knowledge.

Limitations and Delimitations

Since there is a limited number of landscape kinetics in existence to study, this thesis expands the boundaries of kinetic projects to include projects from outside the field of landscape architecture. In this thesis other disciplines provide the base of knowledge to advance the application of kinetics in landscape architecture. This thesis does not claim to include all kinetic projects in existence, but any projects discovered through this research were considered for the catalog and listed in Appendix E.

A delimitation set for this research is targeting more advanced kinetic designs over simple, possibly manual, movements. The choice to focus on the more advanced designs is because this is where information for landscape architects is lacking most. Landscape architecture already has adjustable seating, but it does not yet have artificial intelligence that moves a space for a user. The author has also delimited this study with the objective of aiding in the design of spatial kinetics instead of non-spatial kinetics because of the spatial character of the discipline of landscape architecture.

This thesis will not cover kinetics in the contracts and bidding portion of the design process. This stage mostly remains the same despite the introduction of kinetics and little literature was discovered discussing the topic.

Thesis Structure and Research Methodologies

Each chapter's research strategies are defined in this section along with a summary of the chapter contents. The author chose this specific thesis structure to lead the reader through a procession from an initial understanding of kinetics to the current existence of kinetics in design, and then to the aid in the design of kinetic spaces. Four research strategies were used in the thesis, literature review, descriptive case studies, classification, and projective design.

Chapter Two: Foundational Knowledge

The research strategy for this chapter is literature review, providing the infrastructure to support the remainder of the thesis. This chapter clarifies and compares kinetic landscape architecture to other closely related terms. It reviews the history of kinetics and where it is today. The second half presents the idea of an interdisciplinary approach and classifies information into the relevant disciplines and key figures from which landscape architects should glean kinetic information.

Chapter Three: Personal Design Process

The descriptive case study strategy in Chapter Three gives a personal account of three kinetic landscape architecture projects completed by the author. The projects offer a visual of what kinetic landscape architecture can look like, a glimpse at how the design process went, and where problems occurred. The account shows what design tools would have been helpful during the creation of kinetic projects. The tools are then explicated in Chapters Five through Seven.

Chapter Four: Kinetics in the Landscape Architecture Design Process

Chapter Four's research strategy is a literature review and inserts kinetics into the existing landscape architecture design process to best show what components are completed at each stage. This allows kinetics to easily be incorporated into the design process that landscape architects are already familiar with. The chapter further breaks down the additional knowledge needed to implement kinetic designs into the step by step system.

Chapter Five: Existing Kinetic Design Tools

Chapter Five's research strategy is classification. It presents and classifies existing kinetic design tools shows designers current methods that assist in the creation of kinetic projects. It also allows the analysis of how the tools can be improved and what tools are missing. The chapter further supports the question if there should be a design tool unique to landscape architecture.

Chapter Six: Kinetic Catalog

This chapter's research strategy is classification. The catalog quickly displays sixty-six applicable kinetic projects to landscape architects. It helps create a visual so that designers can understand the possibilities of kinetics and how existing projects work. The catalog allows the analysis of kinetic project locations, when they have predominately been built, prevailing designers, common operation systems, key purposes, frequently used materials, and typical movement types.

Chapter Seven: Proposed Kinetic Design Tools

Chapter Seven's research strategy is projective design. This chapter uses the previous chapters to create a chart showing the degree of kinetic adjustability and plots the catalog projects on the chart. The final product is a design decision chart that walks designers through a series of questions guiding them through the kinetic design process.

Chapter Eight: Conclusion

The final chapter concludes by affirming the answer to the research question, discusses the implications of the research, and indicates a direction for future research opportunities.

References:

Following the literature references are image sources. The image citations in this thesis are not listed with each image and are instead shown in this section.

Appendices:

Appendix A includes definitions essential to understand this thesis. Appendix B is important and discusses the most impactful literature to this thesis; future researchers interested in kinetics should begin with the described articles and books. Appendices C and D are existing kinetic tools. Appendix E is an ongoing list of kinetic projects the author encountered during this research. This list has over two hundred projects to provide additional examples that could not be included in the catalog provided in Chapter Six due to time constraints.

CHAPTER 2

FOUNDATIONAL KNOWLEDGE

This chapter is a literature review of kinetics – its foundational knowledge base and history. This is a synthesis of current and relevant information that will form a baseline of knowledge relating to the application of kinetics to landscape architecture (Swaffield and Deming 2011). Information will be assembled from various disciplines currently working with kinetics and includes a small number of existing kinetic landscapes. Examples of both proposed and built projects will be provided to help visualize the different types of projects.

Kinetics Explained

This section discusses the definition of kinetic landscape architecture and similar terms related to the concept of kinetics. The term kinetics can be problematic because it has many meanings which can be too broad and sometimes ambiguous. Kinetic refers to anything in motion and is interchangeable with the term 'dynamic.' By that logic a tree is kinetic, the earth itself is kinetic, and humans are kinetic. Kinetic architecture and the proposed term kinetic landscape architecture are more definitive than 'kinetic' or 'dynamic.' Kinetic architecture has been defined many ways, but the selected definition for this thesis is Fouad's (2012) who defines it as "buildings or building components that act in response to surrounding changes whether changes are indoor and/or outdoor and whether they are forced by environmental factors and/or human ever-changing demands."

The term ‘kinetics’ comes from the field of physics. It is used to define a branch of mechanics that studies motion and its causes. However, physicists have more recently replaced the term ‘kinetic’ with ‘dynamic.’

The author proposes the definition of kinetic landscape architecture as a human-made exterior environment with an additional ability to continually move and adjust within the established site. ‘Human-made’ is an essential distinction to exclude natural moving components in a landscape like trees. ‘Exterior environment’ is the phrase that distinguishes kinetic landscape architecture from architecture. ‘Additional ability’ refers to the difference between a design that can move or change and traditional design that is static. A kinetic design expresses dynamism and becomes part of the inherent identity of the project. It is the conscious decision to include movement in a design. ‘Continually’ is added to the definition to exclude structures or elements that only move once. ‘Move and adjust’ indicates the kinetic ability of the project. The phrase ‘within the established site’ is included in the definition to exclude mobile or portable elements.

Increasing the confusion about kinetics and what it entails, there is a division between spatial and non-spatial kinetics in architecture and landscape architecture. Spatial kinetics involves changing the dimensions or arrangement of a space. Non-spatial kinetics refers to changing features like color, light, or texture; for example, dynamic graphics on a digital panel covered façade. Non-spatial movement adds many layers of functionality without taking up much space and provides a way to accommodate change where more advanced kinetic elements might not be possible. This division is critical since disciplines such as architecture and landscape architecture are spatial oriented design fields that also control or manipulate non-spatial elements.

This research was unable to unearth any literature using the term 'kinetic landscape architecture.' Starke and Simonds include an entire section on motion and even list movement as a factor humans are attracted to in a landscape (Simonds 1983, Starke and Simonds 2013). However, motion is discussed as a topic of circulation and as a person moving through a landscape, but not the landscape itself moving.

Motloch (2000) discusses 'open-ended design' that allows opportunities for users that designers could never predict, enabling places to be efficient and adjustable to change, nature, culture, space, movement, individual behavior, and group behavior. Motloch never mentions the word kinetics in his discussion about open-ended design but eludes to the benefits that kinetics can accomplish. Open-ended design is a term he uses to describe environments "that can change over time to accommodate evolving internal and external conditions" (Motloch 2000, 256). It is misleading because even though Motloch includes the word 'change,' open-ended designs are inherently static. Open-ended or multipurpose design is not synonymous with kinetics; it does not have to involve movement; it can be an open field that allows a variety of uses.

Similar to the definition of open-design is a flexible space; a space that can be easily modified and allow a variety of uses to take place at a single location. Flexible design includes the ability to easily adapt to change whereas open-ended design implies the site is designed to serve many purposes. The important factor to consider here is that flexibility and open-endedness can be accomplished with kinetics.

Motloch's (2000) writing and a recent article titled "Kinetic City" (Mehrotra and Vera 2018) discuss the need for cities to be incomplete, continually changing spaces. Mehrotra and Vera discuss 'ephemeral landscapes' as a solution to efficiently accommodate large temporary events. Again, ephemeral does not mean kinetic. Ephemeral landscapes are temporary spaces and do not necessarily involve moving parts. The authors ask for urban settings to more flexibly respond to complex events and activities that need additional infrastructure to occur. “Kinetic City” is specifically talking about flexibility resulting from the low cost and temporality of recycled material like scrap metal and spare wood. This is not the kind of flexibility that kinetics can offer; however, the ideas mentioned apply to the broader concept of kinetic landscape architecture. “Kinetic City” states that to be sustainable, cities need to allow for active fluxes in motion rather than be limited by static materials (Mehrotra and Vera 2018). The article goes on to boldly assert that the future of cities depends on their kinetic ability.

Similarly, Cantrell and Holzman’s *Responsive Landscapes* (2015) also mentions landscapes as continually changing entities. Here, the authors are discussing the concept of hybridized landscapes equipped with responsive technologies that react by employing the process of feedback. Responsive structures are those that can respond to social or environmental stimuli, usually with the help of sensors. This is different from kinetics, but many kinetic systems can be enhanced with responsive technologies. Responsive technologies allow added ways to understand, interpret, experience, and interact with the landscape (Cantrell and Holzman 2015). The sensing parameters are unique to each site, but they all produce a dataset that can then be processed and visualized (Cantrell and Holzman 2015). Many responsive technologies are kinetic, but an example of a responsive element that would not be considered kinetic is a thermostat responding to the indoor temperature and adjusting accordingly.

Interactive spaces in the context of this thesis involve human and environment interaction with a feedback loop. With a feedback loop, interactive spaces cannot exist as a one-way interaction. This unique relationship allows a conversation between humans and the environment that is not always possible with traditional design. Many kinetic environments can double as interactive spaces, but not all kinetic elements are interactive, for example, a kinetic sculpture that moves with the addition of wind. It should also be noted that merely including a kinetic sculpture in a landscape does not make a kinetic landscape, this is a kinetic element within a landscape.

Landscapes and architecture that resemble motion are not considered kinetic. For example, the Maritime Youth House by the Bjarke Ingels Group (BIG), has an outdoor surface that appears to be undulating as if it is a wave in motion, but it is a static structure (*Figure 2.1*). The term static is used in this thesis to describe features or structures that are not in motion. BIG's same design concept could become kinetic with technologies discussed in the Kinetic Landscape Architecture subsection of this chapter.

Figure 2.1. Maritime Youth House

There is some contention with claiming mobile components as kinetic; some authors include mobile components as kinetic features and others do not. This thesis takes the standpoint of excluding mobile units from the kinetic classification. A mobile object does not necessarily have any physical kinetic properties, just because something is portable does not mean it is kinetic. *Figure 2.2* shows a mobile landscape that can be moved to different locations, but it does not contain any kinetic elements itself as defined in this thesis.

Figure 2.2. Parkmobiles

Throughout this thesis is the purposeful use of the terms kinetic landscape architecture, kinetic landscape, kinetics, and kinetic design. Kinetic landscape architecture refers to the specific definition explained previously in this section. In this thesis, kinetic landscape architecture is both a physical space and a proposed title for a subset of the profession of landscape architecture. The term kinetic landscape is used interchangeably with the physical space definition of kinetic landscape architecture. Kinetics is a general term used to describe the concept of kinetic movement. Kinetic design is also a broad descriptor; it removes the boundaries of categories like kinetic architecture and kinetic landscape architecture and allows all kinetic projects to be named with one title.

Kinetics Historically

Kinetic designs have now existed for over four millennia. A brief look at ancient examples show designs for necessary functions. For instance, wooden drawbridges (ca. 2000 BCE) were initially used for defense by the Egyptians but became popular in the Middle Ages. During this time, they were built for defense and controlled entry into castles. The Archimedes' screw (ca. 600 BCE) is a device used to pump water by turning a screw-like component inside a pipe. It has been theorized that this device was used to irrigate the infamous Hanging Gardens of Babylon. In ancient Rome, a rotating dining room (ca. 64-68 CE) located in Emperor Nero's palace was most likely built purely for his entertainment. Also discovered in Rome was evidence of a retractable velarium, or awning, on the Colosseum (80 CE) covering the entire spectator section to protect viewers from the elements. Leonardo da Vinci (1452-1519) has a remarkable portfolio of kinetic machines; perpetual motion machines, a scythed chariot, ratchet wheel, swing bridge, and an automatic hammer to name a select few.

Various kinetic inventions are seen sprinkled throughout history and even preliminary conceptual ideas for kinetic architecture. In 1832, Père Prosper Enfantin, a French social reformer, theorized bringing movement to architecture and declared "architecture as a theory of construction is an incomplete art: the notion of mobility, of movement, is lacking in it" (Jormakka 2002, 5). Another avant garde thinker, Antonio Sant'Elia with his Manifesto of Futurist Architecture in 1914, calls for architecture to be "transient and impermanent" (Spiller 2008). However, it was only around 1954 that the term 'kinetic' became accepted as critical terminology (Popper 1968).

Kinetics Now

Because of advances in mechanics, electronics, and robotics, discussions of kinetics increased throughout the twentieth century. Today, kinetics is common in only a few select categories: stadia, bridges, facades (mainly to control the light and heat entering a building), and rotating restaurants. In addition, there are a few manual mechanisms common in homes like Murphy beds, partition walls, crank-operated windows, and pull-down attic stairs. Kinetics has entered several disciplines but has not yet become prevalent except for these particular listed uses.

Stadia: Stadia have integrated kinetics since the Roman Coliseum. They are now one of the most common kinetic applications with well over thirty sports venues having kinetic roofs in the world (Riberich 2009). A major success story for kinetics is that it is now more common to construct a kinetic stadium than one that has no moving parts. Kinetics used to be considered risky with significant budget concerns, schedule delays, leaky facilities, and mechanically unreliable systems, but as more kinetic structures are built the risk has decreased, with most structures having a nearly one hundred percent operational reliability (Riberich 2009). Kinetic stadia have increased owner's revenue and guaranteed attendees that an event will not be canceled in bad weather. Increased revenue in part comes from the multi-functionality of such spaces. For example, the University of Phoenix Stadium with the first retractable live grass playing surface can host football games and then minutes later, slide the field outside and switch over to hosting an event on the trade-show floor. A stadium is not only being used for one sport but for a variety of major sports events, concerts, parades, rallies, and any other large event involving thousands of people. This example shows how kinetics can significantly increase the multi-purpose nature of stadia.

Bridges: Bridges have also incorporated kinetics since ancient times. There are many different types of moving bridges: rotating, tilt, vertical-lift, and bascule will be discussed in this section.

Drawbridges, or bascule bridges are the most common kind of kinetic bridge. They have one or two leaves that lift up with the counterbalance of a weight (*Figure 6.15 and 6.18*). A rarer type of bascule bridge is a folding bridge with three segments like Hörn Bridge in Kiel, Germany (*Figure 2.3a and 2.3b*).

Figure 2.3a and 2.3b. Hörn Bridge

Tilt bridges rotate on fixed endpoints (*Figure 6.11*). Rotating bridges pivot around a point, usually at their center of gravity (*Figure 2.4*). Vertical-lift bridges like Pont Jacques Chaban-Delmas have two towers and the transit lanes rise vertically up the towers to allow boats to pass (*Figure 2.5*). With counterweights these types of kinetic bridges can be used to lift substantial weights, like heavy rail, because the structure is supported on solid piers like a fixed bridge.

Figure 2.4. Okeechobee Waterway, Florida Swing Bridge

Figure 2.5. Pont Jacques Chaban-Delmas, France Vertical-Lift Bridge

Facades: According to Fouad (2012), the most common reason for using kinetics in architecture today is to control the intensity of sunlight. This is frequently done with facades that are controlled via sun-tracking systems that are implemented to reduce heat gain and control when and where light is entering the building. The vertical plane is easier to move and generally allows more creative freedom than moving the entire structure.

Rotating Restaurants: The typical rotating restaurant is usually located on the top floor of a tower with a good view of the city in which it is located in. They usually operate on a large slowly rotating turntable. It should be emphasized that it is typically just the floor plane that is revolving, not the architectural structure. There are currently more than two hundred and fifty rotating restaurants worldwide, and the United States has the most of any country.

Kinetic Landscape Architecture

Landscape architecture has both currently and historically included kinetics in most landscapes. Landscape architects commonly design with naturally kinetic elements like wind and moving water. This is seen with natural circumstances like streams and more artificial situations like a water fountain. This research explores opportunities that could expand the use of kinetics in landscape architecture. Kinetics can provide solutions that current landscapes are struggling to accomplish and meet unmet needs that are not physically possible with static spaces.

Although the use of moving water is common in a landscape, the incorporation of a moving ground plane is extremely rare. The first ground plane kinetic landscapes discovered during this research were both completed in 2000. The first is a rotating courtyard titled *Courtyard in the Wind* designed by Acconci Studio + Wolfgang Hermann Niemeyer after winning a competition for the job (*Figure 2.6a and 2.6b*). Ironically, the landscape architecture firm Wolfgang Hermann Niemeyer did not design the kinetic portion of the site; instead, the rotating landscape was designed by New York-based artist Vito Acconci. Before concentrating on architecture, furniture, and public spaces, Acconci dabbled in writing literary texts, performance art, and sound installations (Acconci and Schütz 2003). Prior to the *Courtyard in the Wind,* he co-designed another kinetic project, *Storefront for Art and Architecture* with Steven Holl (*Figure 6.9*).

Courtyard in the Wind is operated by a turbine placed atop of the nearby building. It captures wind energy that is converted to electricity used to slowly rotate the seventy-two-foot diameter ring. When it is not windy, the ring does not turn. Trees, paving, lighting, and the benches all rotate on the ring. The landscape turns on a track that houses a set of motors and wheels. It only revolves twice per hour but is still noticeable by visitors occupying the landscape. This is a sculptural element that is an artistic and exciting addition to what could have been a very typical plaza design (Acconci and Schütz 2003). It serves an aesthetic purpose of enlivening a space that would have had a typical lawn and sidewalk.

Figures 2.6a and 2.6b. Courtyard in the Wind

Courtyard in the Wind is powered with clean energy – the wind. Now consider the thought of powering a kinetic landscape with the same thing that powers plants – photosynthesis. This process which has a much higher efficiency percentage is not to be confused with solar power (Majidi 2014, Hataway 2013). Using spinach as a test subject, researchers at the University of Georgia have developed a way to interrupt the photosynthesis process to steal the electrons before the plant uses them (Hataway 2013). Plants use photosynthesis to create energy from the sun by taking in carbon dioxide and water to yield electrons that help make sugars for growth and reproduction. Plants are one hundred percent efficient in turning sunlight into energy because they produce an equal number of electrons for every photon of sunlight they capture, on the other hand, photovoltaic solar panels operate at twelve to seventeen percent efficiency (Hataway 2013). For comparison, coal-fired power plants operate at twenty-eight percent efficiency and create problems of mercury and CO_2 emissions (Hataway 2013). Achieving one hundred percent fficiency in energy production would certainly alleviate some of the worries involved with how to power kinetic functions efficiently. However, there are also other ways a landscape can power itself like the inherent movement of natural features such as water and plant material.

The second kinetic landscape designed in 2000 is *Ascot Movable Turf Crossing.* This movable turf tray acts as an alternative to an underpass or overpass at a lower cost (Everett et al. 2006) (*Figure 2.7 and 2.10*). Due to the enclosed shape of a turf racetrack, this is a method to access the center. It was important that the tray fit snuggly so horses could not detect shifting or be injured in any way. For this purpose, its cross-section is in the shape of a wedge, like the keystone of an arch. Specifically, the walls of the pit and the tray are at a twenty-two point five degree angle (Everett et al. 2006). A digital controller activates the tray. Hydraulic actuators raise and lower the tray, and sixteen electric motors move it back and forth on a rail system (*Figure 2.9*).

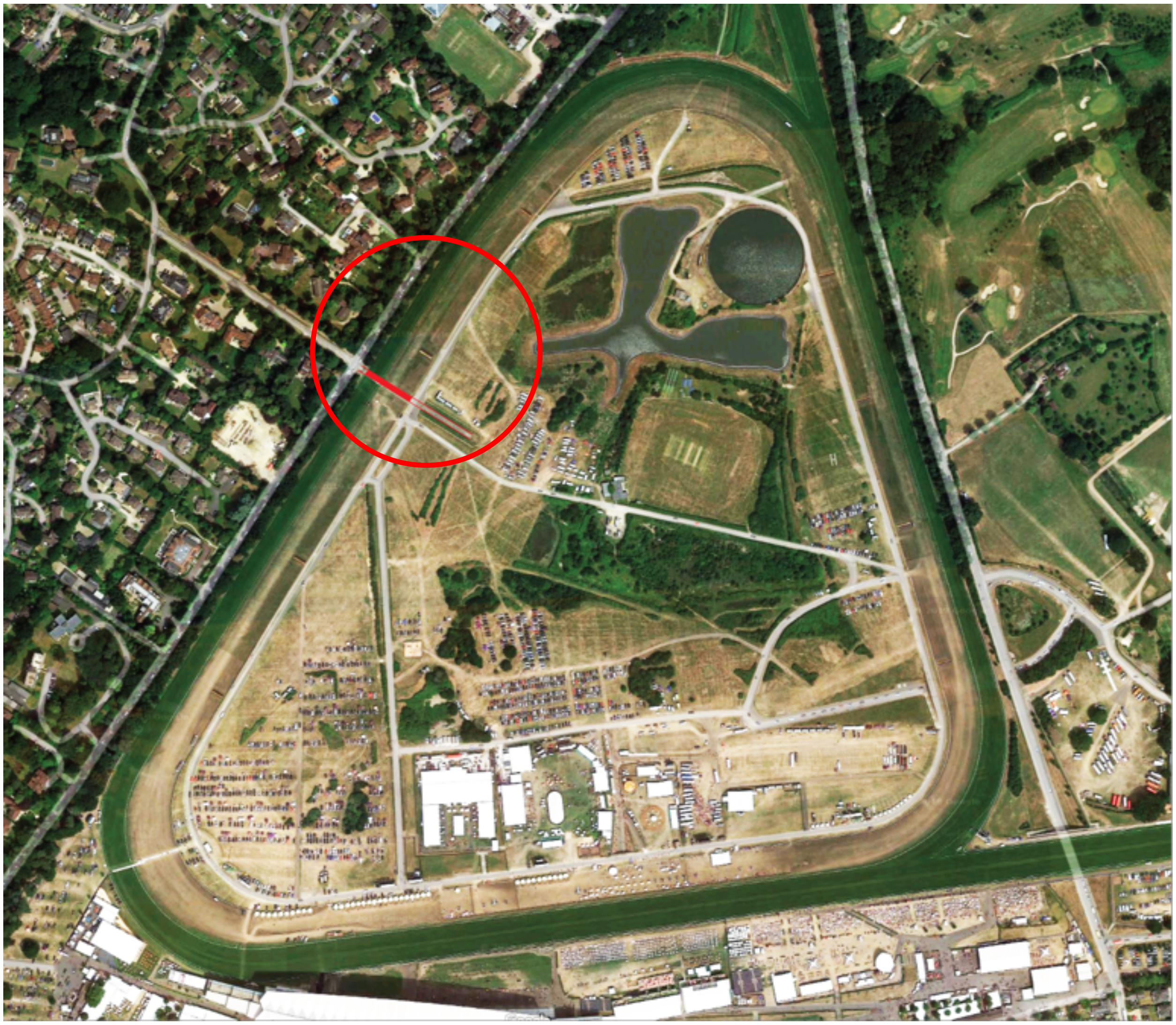


Figure 2.7. Aerial View of Ascot Racecourse with Circled Movable Turf Crossing

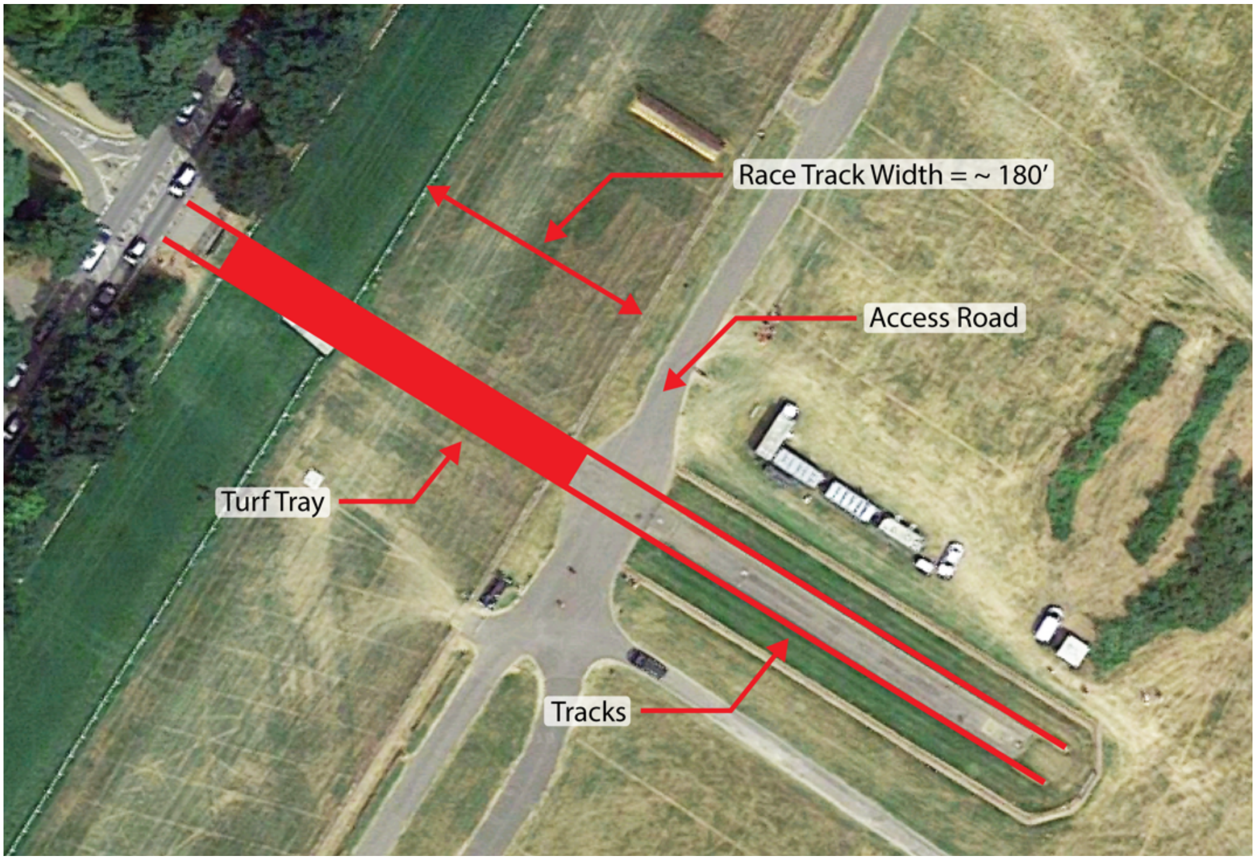


Figure 2.8. Aerial View of Ascot Movable Turf Crossing

Figure 2.9. Ascot Movable Turf Crossing

Figure 2.10. Ascot Movable Turf Crossing Kinetic Mechanism

SCX Special Projects designed and patented the movable turf technology for this project. The technology for the turf tray can be used for any activity surface like a football stadium. Patents for movable turf began with a modular method of moving and replacing the turf before progressing into a more advanced stage involving a track system. Patents for movable turf were first granted in 1978 and in 1998 a patent was published that is similar to the system used for the movable turf at the University of Phoenix Stadium (DiBenedetto 1998) (*Figure 6.62*). It is disputed whether a stadium that has a kinetic system allowing turf to move in and out of the building is kinetic architecture or kinetic landscape architecture. However, the early patents do show that movable plant material was designed prior to the turn of the twenty-first century. It should be noted that SCX referred to the project as ‘kinetic architecture.’ The author views manipulating the ground plane and specifically the topography as a distinct characteristic of kinetic landscape architecture.

Several other kinetic structures have been built that could be considered landscape architecture. For example, Fortress Kufstein Courtyard has an adjustable canopy covering the outdoor courtyard (*Figure 6.53*). A landscape architect was not involved in the design of the kinetic structure, and the project has been claimed as kinetic architecture (Asefi, Valadi, and EbrahimiSalari 2013).

Several concepts and prototypes have been attempted for adjustable topography. They are *Dynamic Terrain* (*Figure 2.11*), *Kinetic Topography* (*Figure 3.15*), and *Feelex* (*Figure 2.12*).

Figure 2.11. Dynamic Terrain

Dynamic Terrain is an art installation by Janis Pönisch (Figure 2.11). Pönisch's words describe the project perfectly, "it is a surface without a fixed form, its form is virtual, and therefore adjustable and erasable" (Glynn 2006). Dynamic Terrain is a rubber membrane with mechanical pistons to produce flexible undulations (Moloney 2011). The spacing of the pistons and the scale of the composition can be modified to fit various needs, for example, an outdoor playground surface. This demonstrates how sculpture can be an excellent testing ground for potential kinetic landscapes; it is typically at a smaller, more manageable scale that offers greater creative freedom.

A design team from the University of Tsukuba's Institute of Engineering Mechanics and Systems created Project Feelex. They did not necessarily have the goal to create kinetic topography, but the invention can be directly applied (*Figure 2.12*). The objectives of the project were to create a surface that users can receive haptic and visual sensations concurrently (Iwata et al. 2001). Feelex 1 consists of a flexible screen, an array of linear actuators, and a projector. The screen is made of a rubber plate and white nylon cloth (Iwata et al. 2001). The project was constrained by the size of the motor that could fit on each actuator, and the team has made several iterations since then to improve the design.

Figure 2.12. Feelex 1

Whereas the ground plane may be its main domain, landscape architecture is not solely limited to its design. *Figure 2.13* shows a movable green wall built for research purposes at the University of Washington. Researchers have studied several aspects of the project including bird counts, insect counts, heat intake, irrigation needs, and the survival of the five hundred plants (Kelley 2012). The green wall is designed on a pulley system so the panels can be pulled to access for research purposes at the nearby balconies. The roof of the structure supplies one hundred percent of the necessary irrigation water.

Figure 2.13. University of Washington Gould Hall Green Wall

The amount of ground plane acreage that landscape architects deal with can be significantly more than architects. This difference will show in the types of kinetic structures being designed by landscape architects. The cost per square foot or per acre will impact the type of kinetic structure designed. Landscape architects must also be mindful of natural ecosystems and create kinetic structures that work with nature and not against it. Landscape architects already design to accommodate the dynamic qualities of the outdoor environment – living plant material, animals, and natural forces like erosion, sun, wind, and water. However, designing a human-made structure that moves with those elements is a more complex task.

Interdisciplinary Approach

The author recognizes that the lack of literature about the application of kinetics in landscape architecture demonstrates the need for an interdisciplinary approach. The subject of movement and kinetics stretch across an extensive set of disciplines, providing an eclectic collection of knowledge and precedent inspiration. Naglaa Megahed (2017, 143) suggests designers "should work in teams in close collaboration with specialists from different fields." Several other disciplines are quite relevant for determining how to design a kinetic landscape. Examples of such fields are architecture, kinetic art, engineering, cybernetics, and a grouping of science and technology fields. These disciplines are demonstrated in the subsequent projects along with their relevancy to kinetic landscape architecture. Key figures in the disciplines are displayed at the beginning of each section. Polymaths like Leonardo Da Vinci can be placed in several disciplines, but here they are placed in the section where they contribute the most relevant information for this thesis. This section begins with kinetic art because of the discipline's early influence on kinetics.

<u>Kinetic Art:</u>

Key Figures: Frank Popper, Alexander Calder, Marcel Duchamp, Pol Bury, Lazlo Mohology-Nagy, Naum Gabo, George Rickey, Nicolas Shöffer, Vladimir Tatlin, and Jean Tinguely

Frank Popper's (1968) *Origins and Development of Kinetic Art* gives a comprehensive summary of all the key figures involved with the birth of kinetic art. Popper demonstrates kinetic art's influence on the genesis of kinetic architecture – an influence that is now being translated to kinetic landscape architecture. Popper (1968) also defines a separation between mechanical movements that are predictable and unpredictable movements of natural forces. This potentially indicates an important benefit of a kinetic environment; unpredictability is a challenge landscape architects fight against in a natural environment and kinetics could combat that.

Alexander Calder might be the most famous artist associated with kinetics. The first mobiles of Calder were powered by electric motors, the rest simply moved with air currents. Without motors the movement is unpredictable. He created suspended mobiles that hung from ceilings and 'free-standing mobiles' fixed to stands (Popper 1968). Contrary to popular belief Calder was not the first to create mobiles; Tatlin, Rodchenko, and Man Ray were all creating mobiles prior to Calder.

Marcel Duchamp was the first to introduce the word 'mobile' to describe Calder's work (Popper 1968). He actually used the term to describe Calder's early work with motors, but the name stuck. Duchamp began as a kinetic pioneer with his ready-mades, which in themselves were an attempt to demystify art. Roue de bicyclette, a bicycle wheel mounted on a stool, opened up wide kinetic possibilities (Popper 1968). However, his first real kinetic piece might be his 1920 sculpture titled Rotative Glass Plaques, which incorporates rotating glass and an electric motor (*Figure 2.14*).

Figure 2.14. Rotative Glass Plaques

In 1920, the term ‘kinetic’ was introduced to the visual arts by Naum Gabo and his brother Antoine Pevsner in their work titled Realistic Manifesto. Denouncing much of conventional art for always being static, the manifesto describes their personal artistic theories. He claimed rhythm to be as important as space, structure, and image (Gabo 1957). Gabo also states “it is obvious now to every one of us that by simple graphic registration of a row of momentarily arrested movement, one cannot re-create movement itself” (Gabo and Pevsner 1967, 151). Gabo also believed that kinetic sculptures were more than three-dimensional; they were four-dimensional, with the added element of time. Yet, with all Gabo’s arguments, he produced very little kinetic art himself. However, Gabo’s *Standing Waves* is typically considered the first kinetic sculpture. Lazlo Moholy-Nagy and Alfred Kemeny also produced a manifesto entitled “Dynamic-Constructive System of Forces.” Moholoy-Nagy believed Gabo was only minorly addressing the opportunities available with kinetics. He and Kemeny explored allowing the spectator a much more active role in the artwork. Moholoy-Nagy's *Light Machine* is described by his wife as half-way between a machine and a sculpture (Popper 1968). His works can be best compared to those of Duchamp's – both worked with machines.

George Rickey is a famous American sculptor and theorist of kinetic art. His work is mostly abstract, kinetic, constructed of steel, and is often compared to Calder's. In his own writing "The Morphology of Movement," (1963) he has images from Duchamp, Gabo, Moholoy-Nagy, and Calder as influential artists. Rickey (1957, 220) said, "if great talents use movement, great art will move." His designs are prefaced by a long process of experimentation before he creates a satisfactory work of art. Rickey's sculptures do not have complex or a wide variety of movement. He claimed that it was possible to classify all types of movement into six or eight categories, mostly based on nautical and aerial navigation (Popper 1968). He is quoted as saying "when you construct an object in movement, you are always surprised by the movement itself: however well worked out the design may be, the movement seems to come from somewhere else" (Popper 1968).

Jean Tinguely began making kinetic art around 1948 with a focus on motorized movement (Popper 1968). Like several other artists mentioned, he too experimented with movement induced by the spectator. His machines grew increasingly complex and even chaotic in their movements. Some were self-destructing and not all of them are still working today. Tinguely always made sure to include an element of surprise, he called this the 'functional use of chance' (Popper 1968). Rickey (1963, 224) says "movement is not, in itself, esoteric; art which moves become accessible." Rickey specifically mentioned Tinguley in this context and hints at accessibility potentially becoming a problem when it takes away from the meaning of the art, especially with artwork of famous artists.

Jean Tinguely produced a large body of kinetic art. A unique series of work he produced were called Métamatics, or machines that produced art works. These pieces questioned what we consider the typical roles of the artist, the artwork, and the viewer. His Métamatics produced thousands of drawings, signaling the commercializing effect these machines could have.

Nicholas Schöffer produced the first cybernetic sculpture in 1956 (Popper 1968). Cybernetics involves the automatic control of any system using technology. It is the scientific study of communication and control in humans, animals, and machines. It is based on systems theory and involves feedback loops. The first cybernetic sculpture was *CYSP 1*. The name derives from the first two letters of cybernetic and spatiodynamic. Schöffer created twenty-six of these cybernetic, spatiodynamic sculptures. He also created *Cybernetic Tower* in Liege, Belgium (*Figure 2.15*). It is over one hundred and seventy feet tall and consists of thirty-seven rotating elements all moving at different speeds. Schöffer explored integrating mobile sculptures into urban and architectural projects. He had hoped, but never accomplished his goal to carry out even larger projects than his towers.

Figure 2.15. Cybernetic Tower

Pol Bury was a Belgian sculptor, greatly influenced by Calder (Popper 1968). He went through several distinct stages in his artistic career. He started with what he called ‘mobile planes’, cut out planes that required a human for movement. This idea progressed to ‘multi-planes’ that included small motors removing the need for the spectator to move them. Bury was in the category of artists that thought the motor should stay hidden; that the artist should conceal himself after the creation is complete (Popper 1968). Next, he explored movement in light, followed by complex constructions of various materials. He ended his career with slow, almost imperceptible movements in his sculptures. Bury has been referred to as the master of slowness and once said “speed limits space; slowness increases it.” Bury is most famous for his moving stainless-steel fountains.

Vladimir Tatlin is considered the father of constructivism (Popper 1968). He was the first to replace the traditional importance on the composition of a work of art with a focus on construction and material properties. His work has been described as sculpting space. He is famous for his counter-reliefs and his work called *Monument for the Third International* (*Figure 2.16*). The counter-reliefs were not kinetic, but they influenced kinetic art because of their dynamic resemblance and the use of the spatial aspects of a room. Work on the monument ended with only a model of the structure, a sculpture in itself, but it would have been the largest and arguably the first modern kinetic piece of architecture. If realized it would have straddled a river and been a one thousand three hundred feet tall structure constructed of iron and glass.

Figure 2.16. Monument for the Third International

Architecture:

Key Figures: William Zuk and Roger Clark, Cedric Price, Chuck Hoberman, Archigram, and Reyner Banham

Architecture might include the most applicable knowledge to landscape architecture because of the comparable design process and close relationship of the two fields. Architecture has now been working with kinetics for many years. Zuk and Clark (1970) suggest that because of architecture's inherent static personality it is more important that architecture embrace kinetics. This thesis argues that it is no more important for architecture to have kinetics than it is for landscape architecture; components of landscape architecture do have dynamic characteristics, but those can be enhanced. It has many components like benches and sidewalks, that are usually only perceived as static.

Only two years after Popper (1968) published *Origins and Development of Kinetic Art*, William Zuk and Roger Clark (1970) produced the first book on kinetic architecture – appropriately titled *Kinetic Architecture*. William Zuk was a professor in charge of structural engineering at the University of Virginia's School of Architecture. Zuk and Clark considered kinetic architecture "a form [that] should react to [a] set of pressures establishing an equilibrium, [and that] it should not be stable with reference to time" (Fouad 2012, 9). The pair had bold insights, claiming static architecture is the freezing of an era, and the solution to the stagnancy, kinetic architecture, strives to be timeless (Zuk and Clark 1970). Zuk and Clark (1970, 4) go further to compare Charles Darwin's idea that "the problem of survival always depends upon the capability of an object to adapt in a changing environment," seeming to say that it is a necessity of architecture to reflect society today, tomorrow, and as far into the future as possible. Zuk and Clark's masterpiece on the subject of kinetics catapulted architecture into the leading discipline of kinetic design.

Around the same time period (1960 to 1975), utopian groups like Superstudio, Archizoom, Gruppo Strum, and Archigram stimulated futuristic architectural thinking. Archigram was a neo-futurist architectural think tank group that existed from 1961 to 1974. The group was based in London and included six regular members: Ron Herron, David Greene, Mike Webb, Peter Cook, Warren Chalk, and Dennis Crompton. The six worked together in their spare time to produce exhibitions, articles, and a magazine to demonstrate their forward-thinking views to the public. Archigram produced hypothetical projects and inventions to steer people away from what they called sterile modernism (Cook 1999).

The three most well-known projects they designed are *Walking City, Plug-In City*, and *Instant City*. Some elements of their futurist designs included pods, inflatables, hovercraft, and walking architecture. The designs vary as there were multiple versions and iterations of each project. *Plug-In City* consists of a structural framework in which living pods could be inserted where needed (*Figure 2.17*). The *Walking City* included giant robot buildings with insect-like legs that could roam the planet. The robots were self-contained living pods that allowed a purely nomadic life or post nuclear war living. The *Instant City* was a mobile traveling exhibition formed of large inflatable balloons intended to float a roof.

The group produced evocative images of hypothetical futuristic projects that aimed to push the boundaries of accepted architecture. Archigram was probably the most influential group of their time and should be considered pioneers in the realm of robotic, mobile, and kinetic architecture.

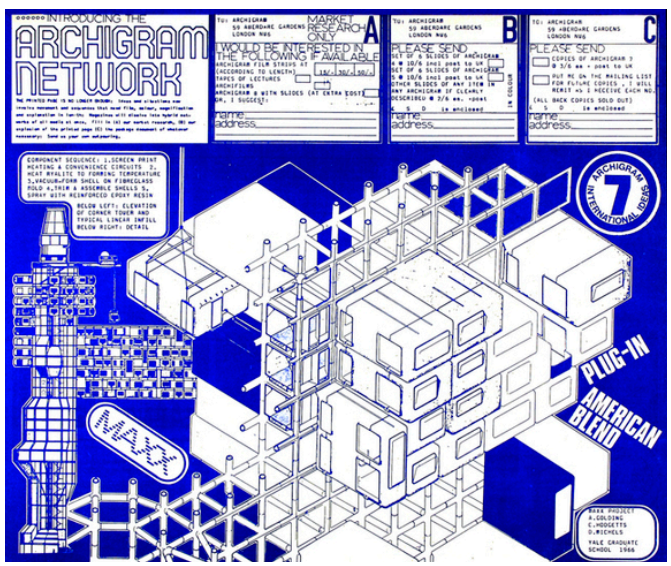


Figure 2.17. Archigram issue 7, page 4 – Plug-In City

Cedric Price was a mostly theoretical British architect, with radical ideas, but few built projects. He was active in the 1960s through the mid-1980s. Price was an early investigator in artificially intelligent architecture, an evolving structure designed with no specific program in mind (Fox and Kemp 2009). Artificial intelligence refers to machines capable of intelligent behavior like humans.

Along with Reyner Banham, Price formulated 'anticipatory architecture,' architecture he believed could give people the freedom to control their environment (Fox and Kemp 2009). This is perhaps an early term for kinetic architecture. It includes flexible and adaptable technologies that respond to changing programmatic and environmental conditions (Perry 2010). Price's *Generator Project*, a commission to design a building for dance, theater, and the visual arts, allowed him to explore kinetic architecture and artificial intelligence. This project was not built, but Price looked at having the computer encourage the visitor to continually refine and improve his or her design (Cline and di Carlo 2002). This computer would also controversially be programmed to make unsolicited alterations if static for too long (Cline and di Carlo 2002). Price was "fascinated by the new technology and believed that it should both serve the public and further human freedom" (Cline and di Carlo 2002). His *Fun Palace* project had moving walkways, walls, floors, and ceilings with an overall moving gantry crane (*Figure 2.18*). The physical volumes of spaces could be changed as often as the use was.

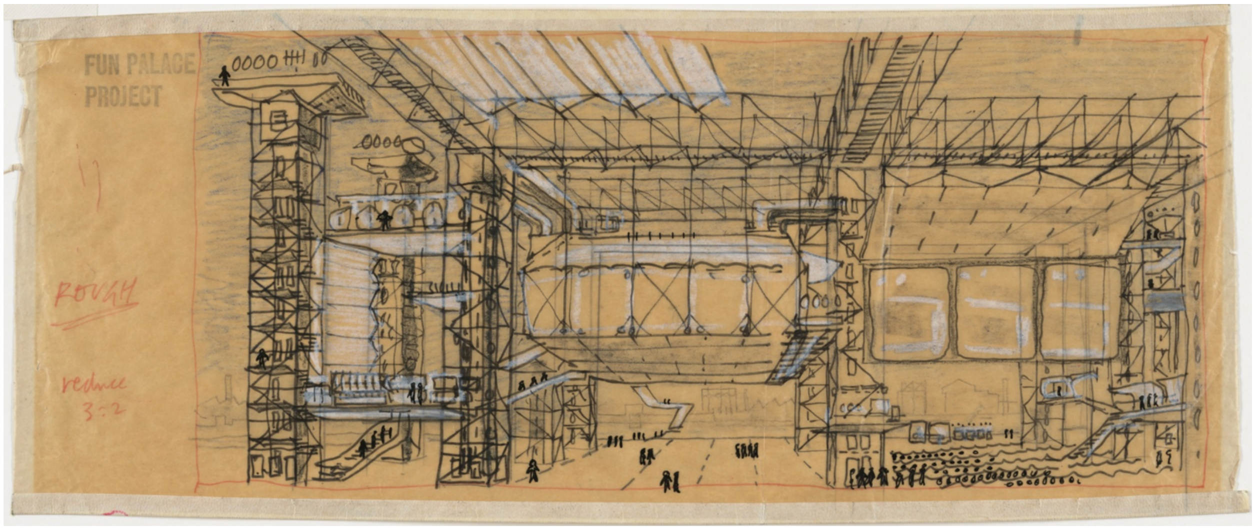


Figure 2.18. Fun Palace

Banham called for a technological extrapolation approach over precedent history, with an inclination towards interdisciplinarity (Perry 2010). Instead of primarily relying on architecture's own immediate history of geometry and form, this approach allows the discovery of new knowledge and expertise (Perry 2010). Price, Banham, Summerson, and other postwar thinkers took interest in temporality and the performative implications that new technology could offer architecture (Perry 2010). They asked for a dynamic relationship between a building and its users that allowed both parties to respond to each other, resulting in non-static buildings that can respond to both programmatic and environmental forces as they change over time (Perry 2010). This desire for responsive and dynamic performance, along with Banham's interdisciplinary push, closely aligns with cybernetic theory; a theory that Cedric Price was the first to adopt into architecture.

More recently, an influential generator of kinetic design is Chuck Hoberman, an inventor, engineer, artist, and architect with a firm in New York called Hoberman Associates. Hoberman's most famous invention is the Hoberman sphere, a frequent find in many toy stores, that uses scissor joints to expand and contract. He uses the same concept as used for the toy to create architectural domes and sculptures (*Figure 2.19*). Hoberman also co-founded Adaptive Building Initiative aimed at designing structures that adjusted to environmental changes. Many of his ideas could possibly be extended into the landscape.

Figure 2.19. Hoberman Domes

<u>Engineering:</u>

Key Figures: Leonardo Da Vinci, Buckminster Fuller, Santiago Calatrava, and Frei Otto

Engineers will play a crucial role in advancing kinetics in landscape architecture by providing the knowledge to construct many of the kinetic designs. Leonardo Da Vinci, known as an artist, inventor, and architect, was one of the greatest geniuses ever to have lived. Born in 1492 and without more formal education than an elementary academy, he began with painting, but quickly moved to a diverse set of interests; inventing, sculpting, architecture, science, music, mathematics, engineering, literature, anatomy, geology, astronomy, botany, writing, history, and cartography (Isaacson 2017).

With his explorations, he expanded the fields of art, both painting and sculpture; geology; aviation; astronomy; geology; astronomy; and cartography. He also proposed an amazing array of new inventions that depended on his grasp of advanced engineering principles. For the purposes of this thesis, DaVinci is grouped in the engineering discipline. Particularly applicable to kinetic landscape architecture are his machines and inventions. Of the hundreds of inventions, many of them were kinetic. Yet, he published little while he was alive and left many ideas unfinished, demonstrating he cared more for designing than completing projects.

The sketchbooks of DaVinci that have been preserved provide insight into his thinking process. Da Vinci designed inventions of all scales, from large flying machines to an automatic hammer. He had several ideas for military devices like a scythed chariot that had four rotating scythes on a revolving gear and a deployable revolving bridge. He had a deep interest in flight and drew designs of several flying machines, an experimental wing, a helicopter, a hang glider, and a parachute. Another category of his designs is perpetual motion machines (*Figure 2.20*). Da Vinci tried to invent a machine that could perpetually stay in motion. After many attempts, he learned it was not possible, but such designs could play a key role in creating efficient kinetic movement with zero net energy consumption. Da Vinci was also an admirer of the theater, and many of the mechanisms he drew in his sketchbooks were likely theatrical machinery with the primary purpose of amusing audiences (Isaacson 2017). He designed machines for changing scenery, creating special effects, and revolving stages (Isaacson 2017).

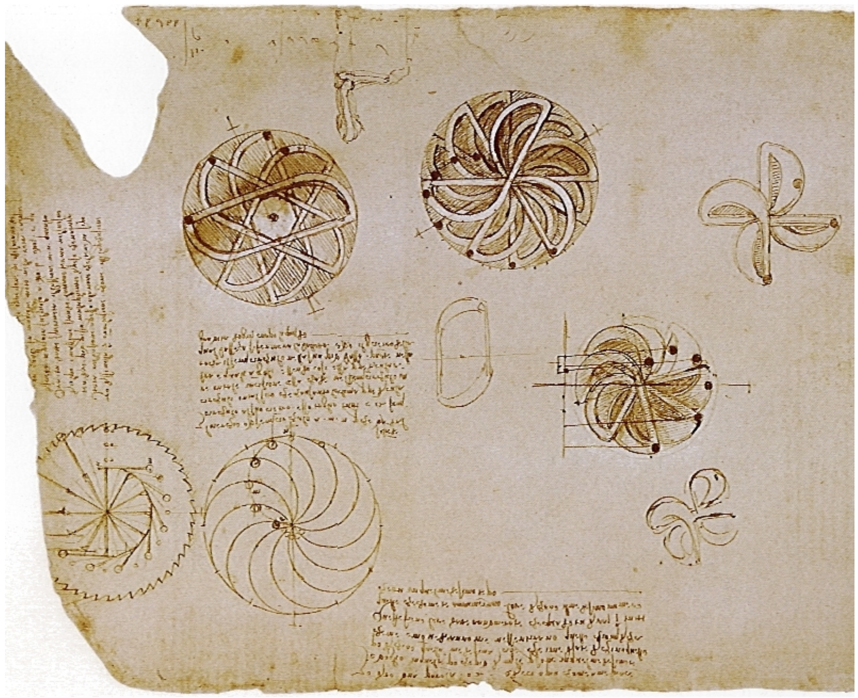


Figure 2.20. Perpetual Motion Machines

Da Vinci was a master of studying motion and would do so in detail by observing the movement of birds and dissecting their bodies to understand the interior structure. Learning about his work provides a solid foundation for those wishing to create kinetic spaces.

The most famous current kinetic architect and engineer is Santiago Calatrava. Calatrava did his first university thesis on the flexibility of three-dimensional structures, involving shifting structures from three-dimensional to two-dimensional and one-dimensional forms. The second thesis was on the foldability of frames (Calatrava 1981). Both academic works were able to jumpstart his career in kinetics.

He has received lots of criticism for the cost, delays, and functional problems associated with his projects. All are accurate critiques, with personal fees over eighty million dollars, delays up to seven years, budgets surpassed by up to two billion dollars, and many projects requiring major repairs or material switches. Yet, Calatrava is responsible for producing break-through kinetic projects and has played a large part in introducing kinetics to the public. Some examples of his kinetic projects include Valencia's City of Arts and Sciences and Opera House, Florida Polytechnic University, and Turning Torso. Turning Torso is the first constructed rotating skyscraper, composed of seven stacked cubes twisting on the mechanical core hosting the elevators and stairs.

Other engineer/architect professionals include Frei Otto and Buckminster Fuller. They might be the considered the most renowned designers of deployable structures – Otto for his tensile and membrane structures and Fuller for reinventing the geodesic dome and his work with structural efficiency (Friedman and Farkas 2011). Deployables are precisely what their name portrays; they are structures that can be transformed from a closed or compact configuration to an expanded form (Hernández Merchan 1987). Deployable items like tents, umbrellas, and even party horns that roll out when blown into, are extremely common. They contract for transportation or storage and expand for use. NASA has hired numerous engineering companies to design deployable structures for potential Mars or deep space habitats. FAST Mast (Folding Articulated Square Truss Mast) was used in the International Space System to deploy solar arrays for energy harvesting (*Figure 2.21*) (Adrover 2015).

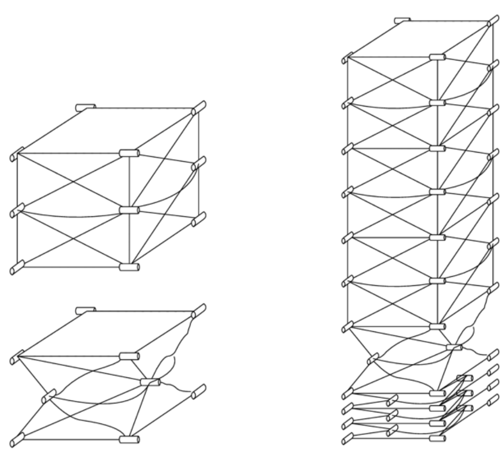


Figure 2.21. FAST Mast

Cybernetics:

Key Figures: Norbert Weiner and Gordon Pask

Norbert Weiner, the father of cybernetics, saw humans as complex systems which could be defined mathematically and mechanistically (Spiller 2008, Pask 1968). Today, there are a variety of definitions for the term Weiner coined as cybernetics, all of which can be hard to decipher. Essentially, it is a broad science, covering many disciplines, examining the design and function of regulatory systems involving feedback loops, information, and goals. The Interactive Architecture Lab (2016) describes a cybernetic space as obtaining the role of 'space manager' and planning the function or form of a space and communicating with the user; with embedded computation as the main system of control – 'the brain'.

With the help of cybernetician Gordon Pask, Cedric Price was able to successfully incorporate the more scientific approach of cybernetics into architecture – 'scientific aesthetic' as Reyner Banham liked to call it (Perry 2010). Cybernetics is relevant to design because architects and landscape architects act as system designers, and even more so if kinetics is involved. Cyberneticians desire architecture and landscape architecture to be living, evolving entities and kinetics can be part of the solution to this type of dynamic system. Furthermore, artificial intelligence will play a key role in cybernetic spaces.

Science and Technology:

Key Figures: Michael Fox, Skylar Tibbits, Nicholas Negroponte, Carlo Ratti, MIT Media Lab, MIT Sensible City Lab, Self-Assembly Lab, and MIT Kinetic Design Group

Cantrell and Holzman (2015) predict that landscape architecture will increasingly blend into the fields of computer science and robotics. This section is grouped as science and technology to cover the interdisciplinary work MIT design labs are working on with robotics and materials science. MIT has a cluster of labs and groups devoted to advancing kinetics using a multi-disciplinary approach. The MIT Media Lab contains more than eighty people, has a fifty million dollar annual budget, and is a conglomeration of research groups focused broadly on designing advanced technology. The lab was born out of MIT's Architecture Machine Group and was co-created in 1985 by Jerome B. Wiesner and Nicholas Negroponte. Some relevant groups within the lab include Tangible Media, Social Machines, City Science, Mediated Matter, and Responsive Environments.

Another research group, MIT Sensible Cities Lab, aims to learn about cities through design and science. A key member of the lab is Carlo Ratti. In addition to being a professor at MIT, helping author over five hundred publications, and being on several lists of the most influential designers and innovators of our time, Ratti founded his own firm – Carlo Ratti Associati (CRA). CRA has projects ranging from kinetic architecture to kinetic furniture. One project that is particularly notable is *Digital Water Pavilion* (*Figure 2.22*). The walls are made of flowing water reconfigurable with computer-controlled water droplets. The water can be formed into writing or patterns and allows access to and from the structure. The idea probably stemmed from a water wall Dennis Frenchman, another key member of the Sensible Cities Lab, worked on with an MIT design team for Zaragoza's *Digital Mile*.

Figure 2.22. Digital Water Pavilion

Zaragoza, Spain's ongoing *Digital Mile* project has many interactive components; one is a digital graffiti wall that creates an open-source landscape by allowing anyone in the world to submit designs to be digitally displayed on the wall. The concept of 'open-source' was first used in computer programming to describe software that any programmer has access to the source code and can modify. The designers at MIT behind the Zaragoza *Digital Mile* introduced the idea of applying it to the built environment (Franchman and Rojas 2006). Designs also show moveable physical elements that provide shade and the previously mentioned interactive water wall that reacts to movement and will not get people wet. This project combines digital and physical placemaking.

The Self-Assembly Lab, started by Skylar Tibbits, researches self-assembly and programmable material technologies. The lab works on projects like Liquid Printing, Active Textile Tailoring, 4D Printing, and a Fluid-Assembly Chair. Tibbits (2017) wrote the book *Active Matter* with the goal of the book and the lab "to program nearly every material to assemble itself and transform in useful ways." Advancements in architecture have always been symbiotic with developments in material science, a discipline focused on the discovery of new materials (Fox and Kemp 2009). Tibbits' (2017) book, discusses kinetic materials like shape memory alloys (SMA), elastic hinges, and hygroscopic materials. Tibbits writes about using elements of the natural world to produce new materials that exhibit properties of growth, repair, mutation, and replication to then be used for kinetic applications.

Michael Fox, another key influence of kinetic design, started the MIT Kinetic Design Group (1998-2001). Fox has a research focus on the intersection of robotics and digital fabrication and has taught the topics of interactive, behavioral, and kinetic architecture as well as interdisciplinary studios on space architecture at several universities (Fox n.d.). Example projects of the Kinetic Design Group include: Responsive Wall, Deployable Teleconference Station, Boeing Business Jet Interior, Servo-Controlled Choreographed Elevator Doors, and Responsive Skylights (Kronenburg, Lim, and Wong 2003). Unfortunately, the group ceased to exist when Fox left to work at roart/KDG, an architecture firm in New York, but due to so many other MIT labs picking up kinetic projects, MIT is still the clear leader in kinetic technology. However, having a lab dedicated solely to kinetic design again would surely be beneficial to advancing kinetics and educating the world on the importance of such technology.

Analysis / Conclusion

<u>Kinetic Introduction:</u> This thesis uses the term kinetic landscape architecture, but this is a placeholder. Only time can tell if the name will hold like the term kinetic architecture. The definition of kinetic has morphed over time and will continue to change. The author believes kinetic designers have the ability to shape the meaning to be what is needed to accurately depict the essence of kinetics.

One element that is perhaps missing from the proposed definition of kinetic landscape architecture is a time limitation. Time and speed play such an essential role in kinetics, yet they were not included in any definition of kinetic architecture found during the process of this research. This may be because it is difficult to objectively attach a minimum speed to the definition. But yet, without a time or speed minimum, the fact that imperceptible kinetics is taking place muddies the definition. How slow does an object need to be to no longer be considered kinetic?

Instead of proposing a speed minimum, the author suggests the consideration of a human perception minimum. This means for something to be considered kinetic, the speed of the movement merely needs to be noticeable by humans. However, again, this is a soft boundary and not a concrete limitation to the kinetic definition. This is why the concept was not included in the final definition. It remains a subjective minimum speed, but perhaps it is still beneficial with the definition being customizable to the individual – if it is kinetic to *you*, it is kinetic. Despite the decision to not include a time limitation in the proposed definition of kinetic landscape architecture, the author believes it to be an important idea for future revisions of the definition.

The definition excludes mobile landscapes, one-time movements, and designs that imitate movement but do not actually move. Even with set definitions, it is not always a binary choice between what is kinetic or not and what is kinetic architecture or kinetic landscape architecture. For example, the author argues that the University of Phoenix's stadium is a combination of both kinetic architecture and kinetic landscape architecture.

Kinetic design exists more as a spectrum. Kinetics can be ephemeral, open-ended, responsive, interactive, mobile, flexible, and artificially intelligent, but all of these listed terms are not necessarily kinetic. These can exist separately, and combinations of every kind exist. The kinetic sculpture *Dune* is responsive, interactive, ephemeral, and kinetic (Figure 6.44). Mobile architecture can be equipped with kinetic features like a wheeled tiny house with a roof that opens, making it both mobile and kinetic. The author believes kinetics should be used in alliance with these other terms to better the use of a kinetic structure. The true value of kinetics is expressed if a space can strive to not only be kinetic, but a flexible and interactive hybrid.

During the process of this research, no literature was found that used the term ‘kinetic landscape architecture,’ and there was minimal literature that discussed the general topic. Without the topic being mentioned in common introductory books on landscape architecture, it could be missing from the curriculum in many landscape architecture schools. This is something worth advocating for in order to advance the profession forward towards a more kinetic built environment.

Historically, kinetics has been incorporated into the built environment since ancient times – drawbridges, the Colosseum’s velarium, and the use of Archimedes’ screw. However, even after four millennia, kinetics is still only popularized in a few select categories: stadia, bridges, facades, art, and rotating restaurants. It will take the dedicated work of kinetic designers to expand the scope past these popularized applications.

It is apparent that landscape architecture is not in that list of popular kinetic structures. There are very few kinetic landscapes in existence today, giving the niche specialty room to grow. In the early stages of kinetic landscape architecture, and where the profession has not yet advanced out of, the projects seem to mostly involve turf; the *Courtyard in the Wind* and the Ascot Movable Turf Crossing are prime examples. This trend of moving turf is likely the beginnings of kinetic landscape architecture because it is easily comprehendible and does not require more advanced mechanisms. The *Courtyard in the Wind* moves more than turf, it moves trees, paving, lighting, and benches, hinting at where kinetics can progress to in a landscape.

All three of these kinetic ground planes move on track systems also indicating the early use of kinetic mechanisms in the landscape. Kinetic architecture started with similar beginnings, so the likely trend is to see kinetic landscape architecture eventually move past track systems to more advanced mechanisms. Track systems can be the solution to many projects; the only concern is if they are chosen because it is the only mechanism designers know how to easily do and not because they are the best solution for the job.

The author predicts kinetic topography will be a major opportunity for which landscape architecture could focus in the future. There are other applications for kinetic landscape architecture, like vertical planes, and roof or canopy covers, but the ground plane is the landscape architect's domain, and the amount of freedom associated with kinetic topography could be a very beneficial tool.

Lastly, a major issue discovered during this research is that none of these kinetic landscape architecture projects were designed by landscape architects even though they clearly involve the landscape. Often the kinetic landscape architecture projects are being referred to as kinetic architecture. This could be because the term kinetic landscape architecture does not exist – signifying the need for the introduction of the term and integration of the theory into landscape architecture educational programs.

Interdisciplinary Approach: A collaboration of disciplines will be essential to successfully advance the application of kinetics in landscape architecture. The disciplines included here are certainly not the only options to look for kinetic expertise. A noted trend is that many of the architects discussed in this section are involved in more disciplines than solely architecture and the same pattern is seen in engineering. This points to the idea that designers educated in multiple disciplines have an easier pathway to kinetics. Clearly, multidisciplinary research labs like those at MIT are doing much of the innovative kinetic mechanism design work, and the author believes this is the best approach to progression. There is certainly room for expansion and creation of additional labs.

Kinetic landscape architecture can point its origins to kinetic sculpture and kinetic architecture. Art movements typically do not begin at the large and permanent scale of landscape architecture with stakeholders involved. They typically follow the trajectory of beginning with art and percolate through architecture before reaching landscape architecture. The field of kinetic art has had more time to develop and the same technology used in kinetic sculptures can be scaled to a landscape's dimensions.

Kinetic art may have established itself first, but architecture might be the most applicable discipline to landscape architecture because of the similar design process and close relationship of the two fields. One reason kinetic design is apparent in architecture and not landscape architecture could simply be because it is easier to move stable, non-living objects. It is reasonable to infer that some popularities in architecture will also play a role in kinetic landscape architecture, for example, reducing the impacts of the sun. A positive result of kinetic architecture being more established than kinetic landscape architecture is the opportunity it provides for landscape architects to learn from architecture's failures and successes. The author believes that kinetic architecture has been successful in moving large elements with impressive engineering. However, most kinetic architecture fails to incorporate the site and the environment. A goal of landscape architects can be to remedy this shortfall.

It is extraordinary to see how kinetic architecture has advanced; now it is time for landscape architects to adapt the knowledge and apply it to the exterior environment. Landscape architecture needs an Archigram to energize and embed kinetic landscape architecture in its discipline and practice. Radical ideas by the landscape architectural versions of Cedric Price, Chuck Hoberman, and Archigram might provide the inspiration to make kinetic landscape architecture concepts a reality. Additionally, Zuk and Clark's *Kinetic Architecture* (1970) is the seminal book on kinetic architecture and continues to influence the field today. Similarly, a seminal book on kinetic landscape architecture could help spring landscape architects into action.

Landscape architecture will progressively become more digital and technological; the author believes it is in the best interests of the profession to embrace the possibilities that such elements provide. Cybernetics as a discipline involves a complex theory on systems, to a designer interested in kinetics cybernetics offers a realm of thought on controlling the kinetic structure from a systems level. This potentially results in an artificially intelligent control system to operate the structure and takes 'architecture without architects' to an entirely new level. Whereas some would consider it ill-placed to consider artificial intelligence this early in the process of introducing the concept of kinetics to landscape architecture, the author believes due to the speed of technology advancement it is a necessity.

Lastly, a warning: if landscape architects do not welcome kinetics, it is likely that another discipline will enlarge their purview to include the landscape anyway. Engineers and architects already incorporate kinetics, and it would be easy for their disciplines to capture the new opportunity that could belong to the field of landscape architecture.

CHAPTER 3

PERSONAL DESIGN PROCESS

The personal pronoun, 'I,' will be used in this chapter as it is a personal account.

The design process portion of this thesis begins with a personal account of three kinetic projects I designed for various studio classes at the University of Georgia. Although some might not consider these standard landscape projects, I argue that they are despite their nontraditional format. The primary purpose of this chapter is to indicate which tools could have aided in the design process. By using the descriptive research strategy, it additionally allows a first-hand report of the thought process behind the kinetic projects, when kinetics entered the design process, and a visual idea of what kinetic landscapes can look like. It should be noted that with all three projects a personal underlying goal was to explore possibilities with kinetics. This intent altered the course of the design and resulted in extreme examples of kinetics. This is critical to understand as designers will go through a different process if kinetics is not a predetermined component.

My process shows one example of an approach to create kinetic projects – the difficult way, without the aid of good design tools or heuristics. Process sketches show some of the iteration that took place. Unfortunately, these were only preserved for project one. After each project is a timeline showing the design process, indicating where kinetics entered the project and where specific design tools would have been helpful. Personal projects are used instead of built projects due to the lack of existing kinetic landscapes. The three projects were chosen because they were my most recent kinetic designs and are clear examples of kinetic landscape architecture.

It should be noted that many of this chapter's proposed technologies currently exist in some form but are combined or expanded to push the limits of these projects. They are various conjectures for what could be. For example, in project two, with the idea for the street being controlled by people's hands, feet, voice, or cellphones, a combined product that performs these functions does not currently exist. However, abductive reasoning is being used to assume that these technologies, that do exist in other forms like voice-activated home automation devices, could be applied to this situation.

Project One: Permeable Edge

Our studio was tasked with creating a masterplan for Fort Valley State University (FVSU), along with a personally selected portion of the plan to design in further detail. Early in the project, for a participatory design component, we traveled to FVSU to meet with students about what they wanted to be included in the masterplan and campus design. The students and faculty asked for outdoor entertainment, event notification, security, technology, and a "wow factor."

Upon visiting the campus of FVSU, one of the first things noticed was the non-locatable entrances and the border wall surrounding the campus. The wall was mostly large, brick columns spaced fifteen feet apart with wrought iron fencing in-between. It spanned almost thirteen thousand and five hundred feet to surround the spatially fragmented campus with some parts being chain-link fence or other fencing forms. However, when conversing with the students, no one said they hated the wall; in fact, they said they liked it. Quite quickly it came forward that the wall provided a sense of security even when data showed the area was relatively safe. I realized they also liked it because it made them feel special; they got the opportunity to go to college, and they wanted to be distinguished from the rest of the community. They did not seem to mind the annoyance of waiting in line to go through the checkpoint to get the campus every day.

Yet, the school administrators, the community, and we as designers were advocating for a more open campus. FVSU is a land grant university, but if it is walled off, it is hard to serve the dual purpose of giving back to the community and educating the public. As a student having attended non-gated universities, I wanted the FVSU students to know what that felt like. It did not seem like the wall was necessary, but we could not ignore the students' desires to keep it. Could there be a comprise, a way to keep the wall, but still make it more inviting and accessible? This was the point when the idea of kinetics entered the design process – during the problem investigation.

A permeable edge seemed like a possibility, one that is easily passed through at many locations (*Figure 3.1*). It allows for the feeling of an open campus without taking away a sense of protection. To accomplish the goal of many entrances without the addition of gate attendants or clunky security measures, the idea of a kinetic wall was generated. *Figure 3.1* shows a small rendering of one of the kinetic panels in action and diagrammatical details are shown in *Figure 3.2*. *Figure 3.3* shows a collage of process sketches created to figure out the design of the kinetic wall.

The metal kinetic panels move on underground track systems much like a garage door system. I imagined a torsion spring, belt, electric motor, and tracks pulling the panels underground and maybe the panels could be sectioned with hinges to reduce the depth underground. Also, like a garage door system, the kinetic panels would have sensors to stop the panels from potentially moving up as someone is crossing over. This mechanism was something that I was familiar with and felt like I could apply to the project, but it was never designed in detail.

None of the panels are physically touching; there is a five-inch gap between them to allow space for the track mechanism to operate. The panels have a top cap to create a smooth ground surface to walk over when in the down position, this along with scrubbers at the base of the panels prevent debris from getting in the track system. To open and close a kinetic panel it requires a handprint or a visitor access card, but this can be placed anywhere on the panel to start the movement.

Most of the panels surrounding the campus would be kinetic and a few would be non-moving digital panels. The digital panels would display information on both the interior and exterior sides of the wall. These provide images and information that can be changed and updated daily. They were designed to be interactive and serve educational purposes like outdoor classrooms as whiteboard space or screens for lectures, but the panels also provide entertainment in the form of digital games, movie screenings, or music players. *Figure 3.1* is a shot of the wall at the main entrance to the university where visitor information would need to be displayed like interactive campus maps, event calendars, live chat with campus welcome guides, student award displays, etc. This permeable edge is an all-in-one resolution to their aspirations, further providing a competitive “edge” over alternative universities.

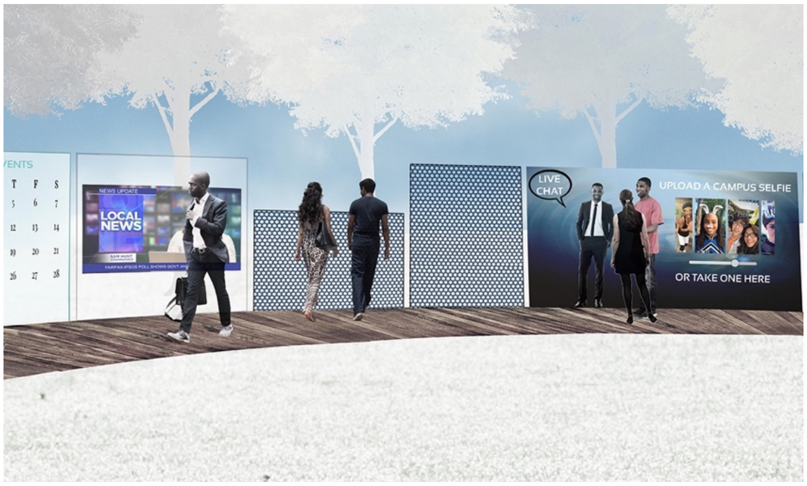


Figure 3.1. Permeable Edge Rendering

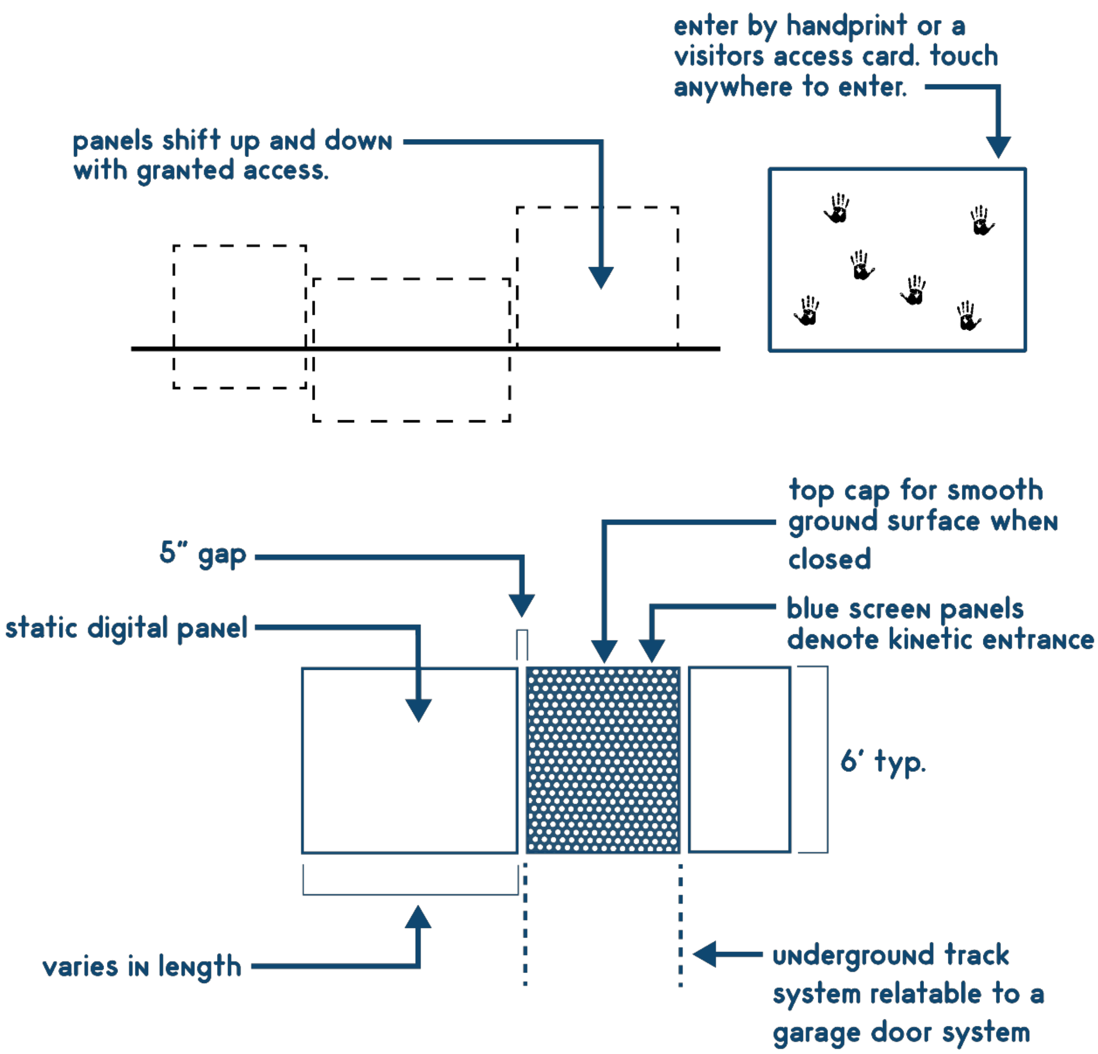


Figure 3.2. Permeable Edge Details

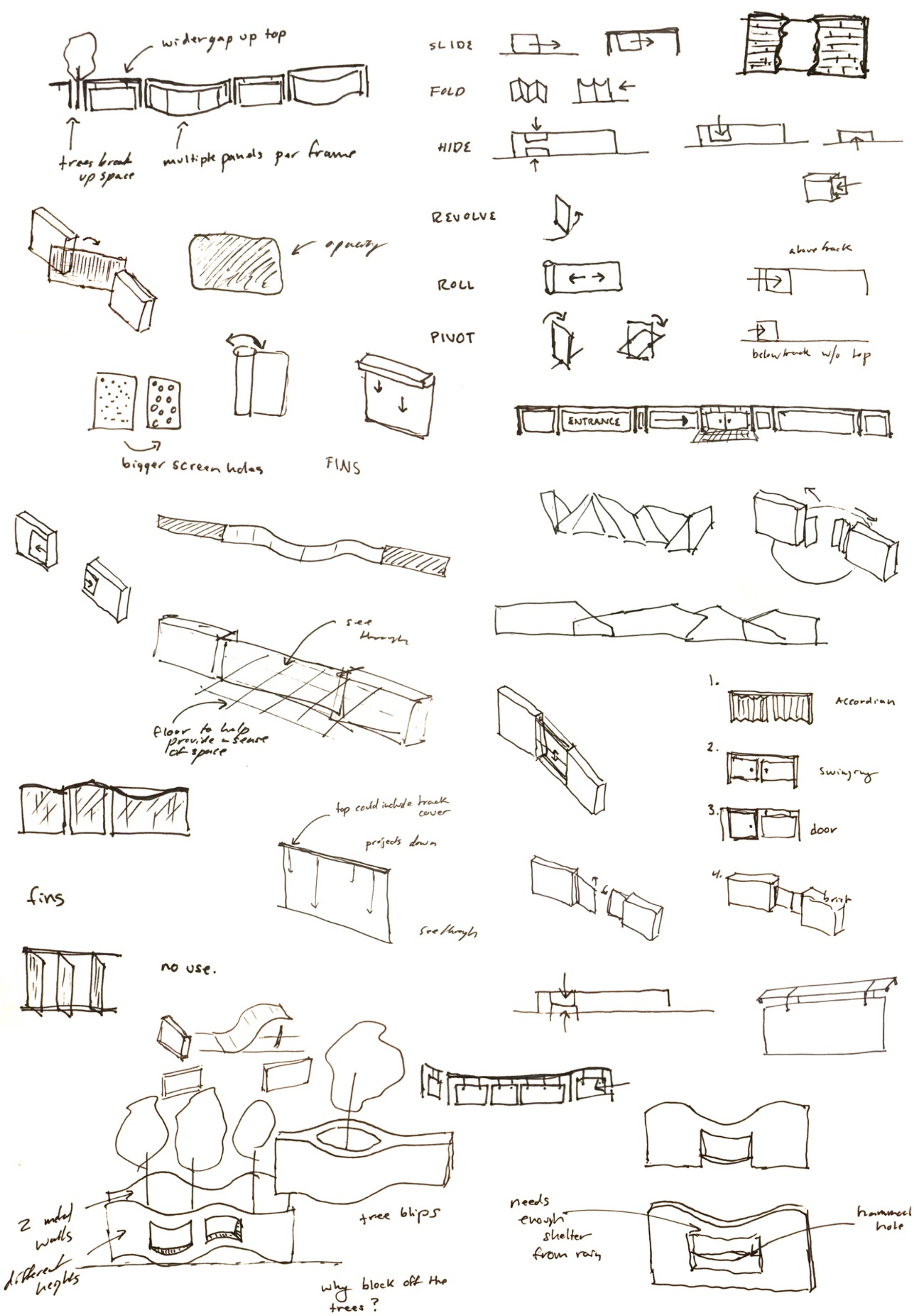


Figure 3.3. Process Sketches

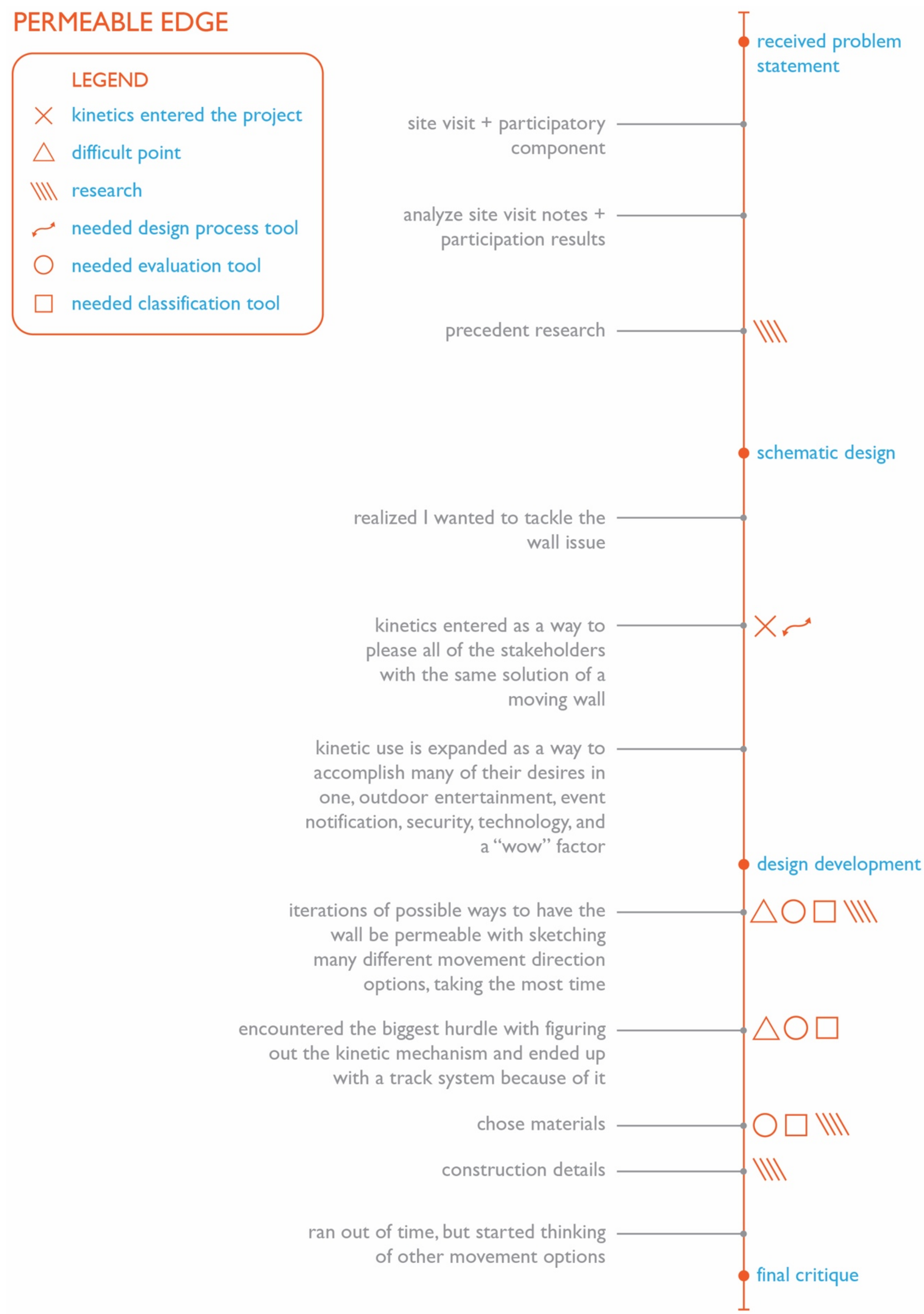


Figure 3.4. Design Process Diagram

Project Two: Open-Source Landscape

Our studio class was given three weeks to quickly make a proposal to redesign Atlanta's Ted Turner Drive as a resilient corridor. Little detail was provided on the parameters of what a resilient corridor meant to the client. I chose to take resilience in the direction of a flexible space that allows for a society's transition into technologically advanced built environments. A space that is flexible is resilient in that it can adjust to different stresses and complications. A flexible space can allow for technology that can be continually updated as society's need change. It future proofs the street to be easily compatible with autonomous vehicles and other unforeseen cutting-edge technologies that have yet to be invented. There are several ways to accomplish flexibility, and three ideas developed throughout this project: digital street panels, movable trees, and a flexible subsurface structure.

The inspiration for this concept came during precedent research. I stumbled upon an image of a crosswalk that was projected onto the asphalt instead of painted. That seemed like a brilliant idea and I began to question why a traditional streetscape is the way it is.

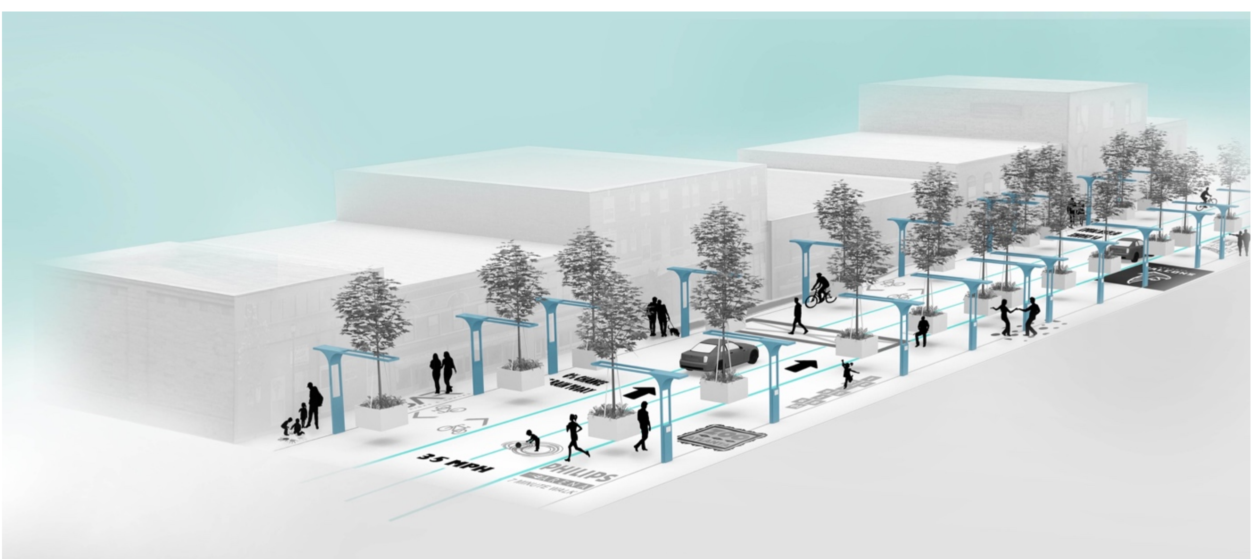


Figure 3.5. Open-Source Streetscape

To have a completely flexible street, I felt a digital street would allow the most amount of adjustability. A digital street would allow continual live updates on lane configurations and street uses. It enables the street to easily be multi-functional. The current method of adjusting a street includes blocking off lanes with cones, but that is a temporary fix. The lines are still painted on the asphalt and it does not come close to the possibilities of a digital surface.

A digital street in this context will allow the adjustability of every graphic we see on today's average street: car lanes, crosswalks, stop signs, traffic lights, pedestrian zones, bus stops, parking spots, bike lanes, etc. All of that becomes digital with the installation of interlocking digital panels that span the entire width and length of the street (*Figure 3.5*). Digitized streets allow the street to be a test space for new configurations. For example, introducing a pause lane where drivers can pull off for cellphone use or dropping people off. The space can flash red when the car has been in the lane for too long, indicating the car should get back on the road.

The panels can only be unlocked by the city for safety reasons and to prevent theft. The panels should be multi-functional, offering features like slip resistance, waterproofing, data collection, energy harvesting, and snow melting for northern applications. As data collectors, they can compile data like popular spots to gather and the number of travelers using each lane. As energy harvesters, they can have piezoelectric technology that converts the pressure of car and human impact to energy to help power the digital panels. It should be noted that one collective panel does not yet exist to do all of these things, but these technologies exist separately so it is plausible in the future.

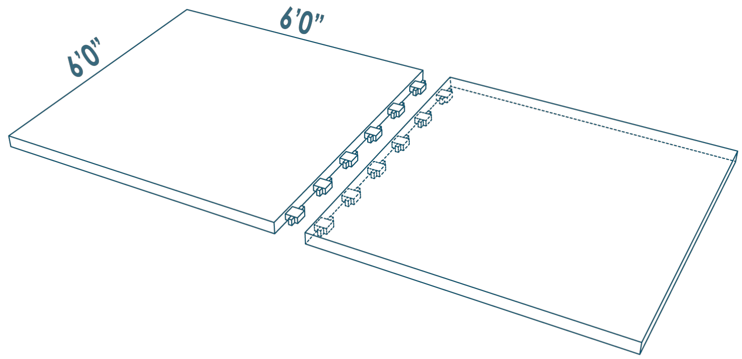


Figure 3.6. Interlocking Digital Panel Mechanism

The proposed design calls for a street with an open-source feature. Open-source in this context refers to the ability to have the public contribute to the material being displayed on the digital panels. It allows public participation in the design and function of their street. If people can individually decide how to use the street, it will increase the use of the space and their level of interest in the well-being of the street – their sense of ownership. Different levels of control should be implemented. The city would be the sole operator of the panels being used as a travel corridor, the public can control some panels, and others can be rented for commercial use (*Figure 3.6*). The city would have control over all the panels and would oversee lane changes, street signage, and space configurations that should not be left to the public to decide.

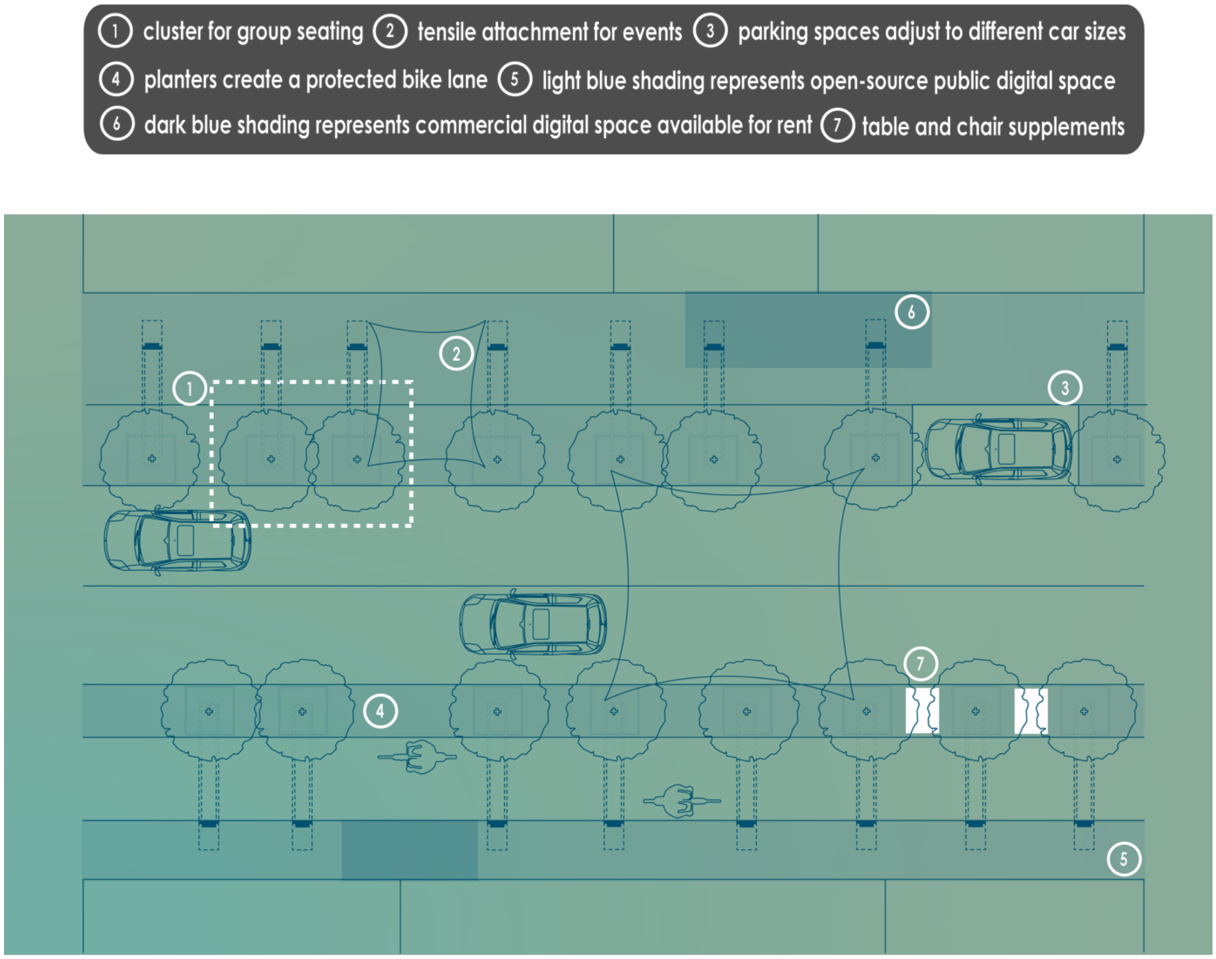


Figure 3.7. Plan Applications

With the introduction of a digital street comes the addition of an entirely new set of street signage. To allow for a completely adjustable space, no typical post signage or traffic lights can exist. It may seem like a hard goal to accomplish, but that is only because we do not currently have digital streets. I wanted to test if everything could be done on the ground plane without cluttering the streetscape. The proposed digital and interactive display graphics and descriptions are shown in *Figure 3.7* and can be seen implemented in the main rendering, *Figure 3.5*. The public aspect of the street can be controlled with people's hands, feet, voice, or cellphones.

A digital street can be safer than a traditionally constructed street with indicator warnings and sensors. Warning circles can instantly indicate when someone has entered the traffic lanes without a crosswalk. Safety warnings about incidents or accidents in the area as well as the street conditions can be displayed.

Digitized lanes give complete control over the street functions, for example having an extra lane for morning commuters and switching the direction in the evening. Crosswalks do not have to be statically placed and can instead appear with the gestural swipe of a foot wherever someone needs to cross. An outline flashes for thirty seconds before the user can cross to allow for others to join the crosswalk and to give a warning to drivers. Bus stops are also ephemeral and can appear where needed and be altered easily. Transit options and schedules can be digitally displayed too. Parking indicators give cars directions to available spaces that adjust in size to the needed space for that individual car, thereby greatly reducing wasted street space and travel time. Rideshare stopping spots can temporarily appear to reduce pick up time, confusion, and safety hazards. Individualized directional travel pathways can appear on the surface to lead people to recommended or desired locations.

Lastly, the panels can offer social and entertainment value for solidarity or group interaction. An infinite amount off interactive street games like hopscotch, Dance Dance Revolution, coloring, and digital ice hockey, can draw people to the street and keep their attention. Event notifications can recommend activities going on in the area. Public bulletin board space allows for additional digital public messages.

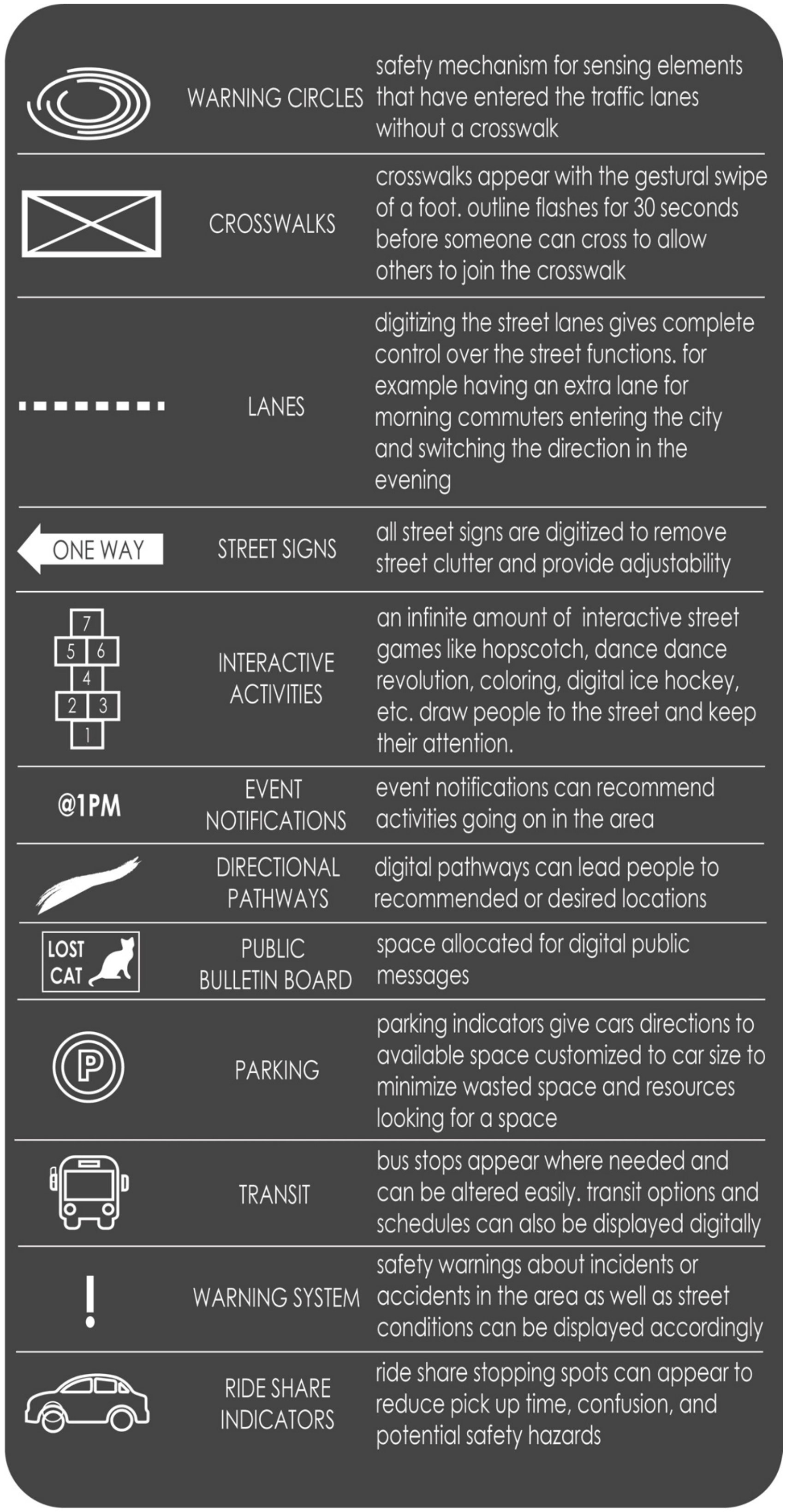


Figure 3.8. Digital Display Graphics

The most challenging part of designing an adjustable street was figuring out a way to move everything: the trees, lights, trash bins, and benches. It took many iterations to get to the final design. To reduce the amount of street furniture necessary, one structure was designed to combine all of the street furniture uses into one element. I have called it a tree armature – an innovation used to hold and move the trees (*Figure 3.10*). The armature operates on track system held beneath the street allowing the trees to move side to side (*Figure 3.9*). The armature itself contains another track system to move the trees forward and backward. The armature, or tree crane, allows the trees to act as buffers for pedestrian and cyclists even when the size and configurations of those spaces change.

A decision was made to have the armature hold the trees off the ground so that the digital panels would not be damaged from shifting trees back and forth on them. The armature contains several adjustable features like seating that can slide out from the bottom of the planter. The trash receptacles are smart to indicate when they are full and expand outwards to accommodate additional trash. It also holds two sets of lights, one facing the center of the street and the other facing the buildings.

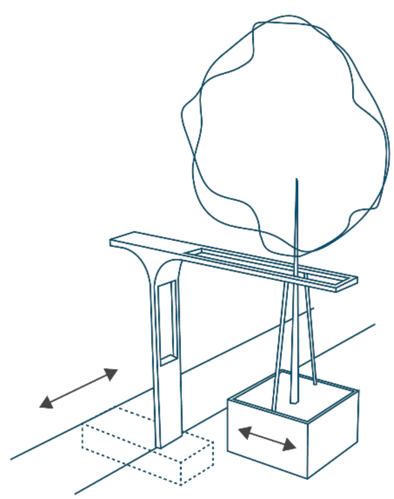


Figure 3.9. Movable Directions of Tree Armature

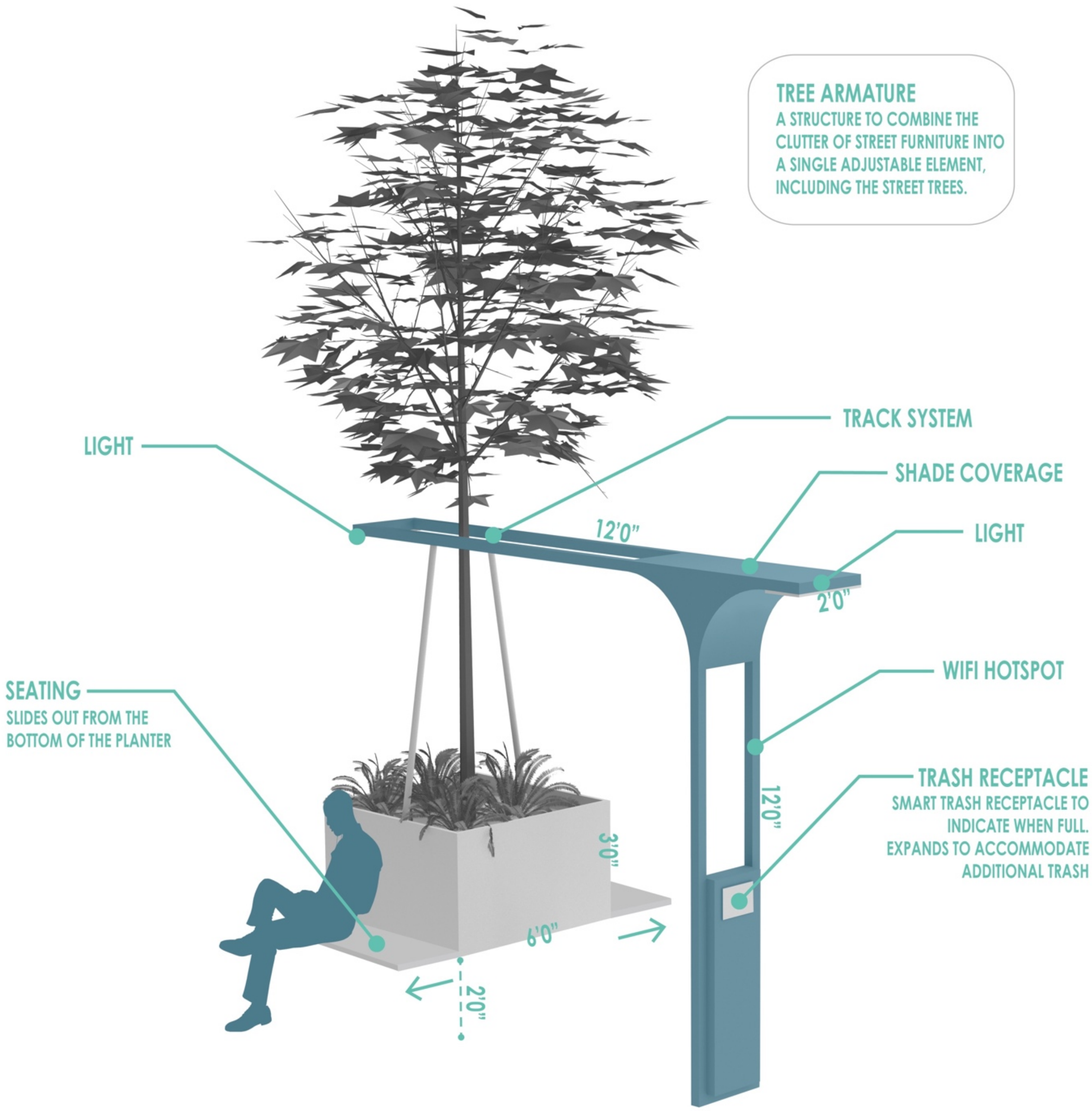


Figure 3.10. Tree Armature

Ted Turner Drive is currently dressed in the typical materials of asphalt and concrete, which are not at all flexible. The project called for a complete redesign of the conventional street structure. I started from scratch without using asphalt, concrete, or any standard paving materials. The interlocking digital panels allow for easy access to the below structure. Beneath the street is the support structure for the street and accessible pipes and wires. The track system for the trees is also housed under the street with heavy bases to help counterbalance the weight of the trees.

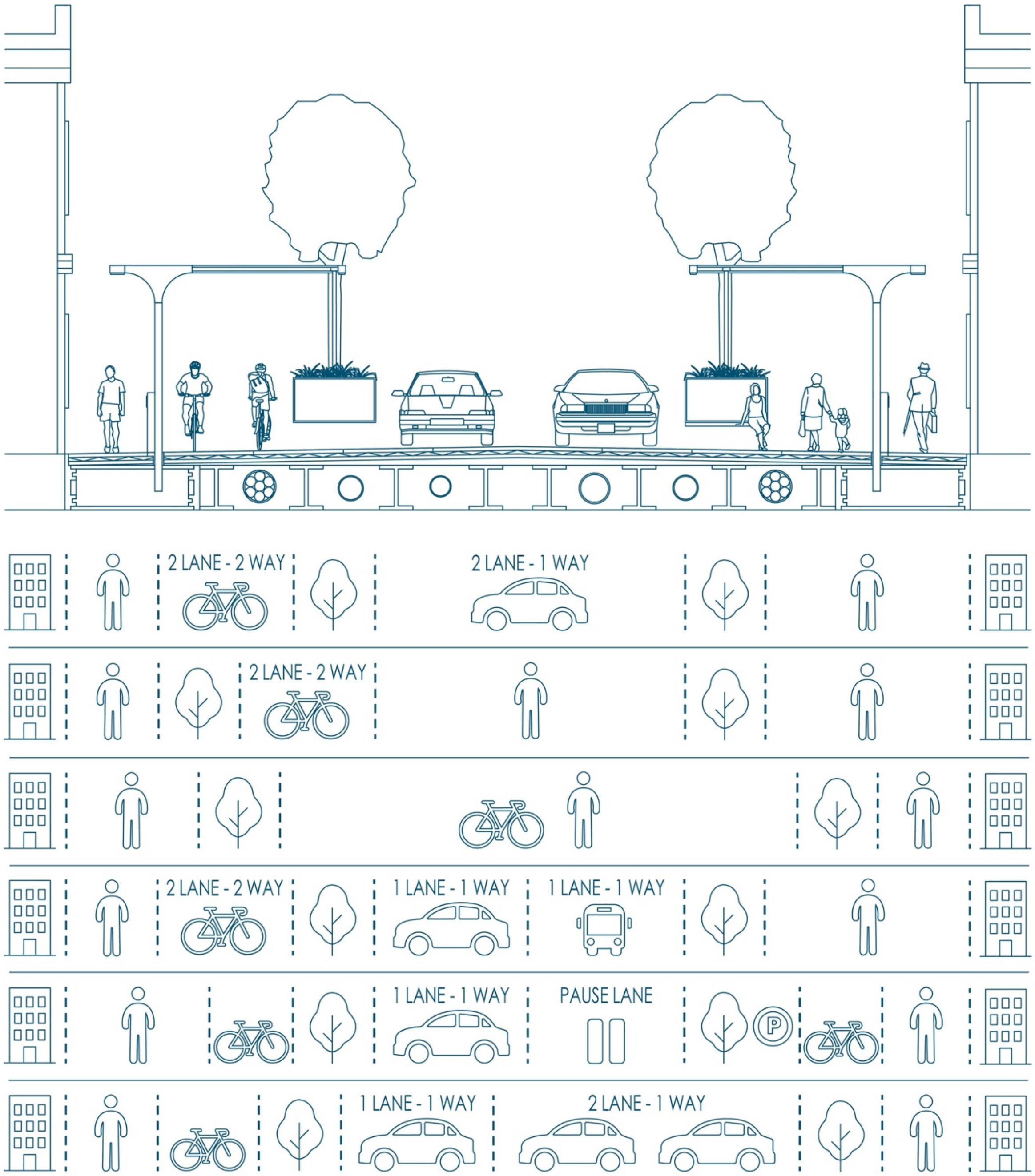


Figure 3.11. Street Section and Lane Configurations

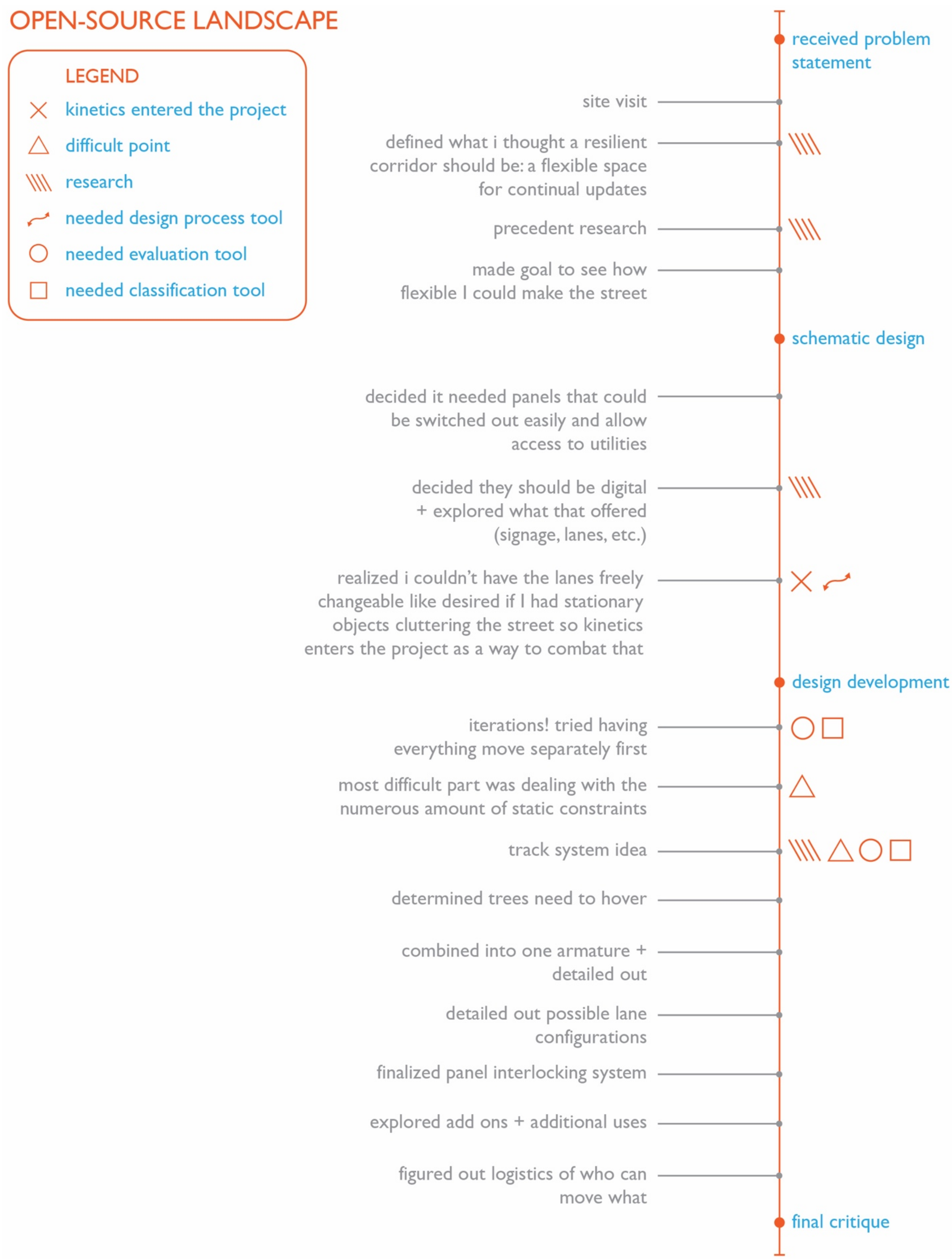


Figure 3.12. Design Process Diagram

Project Three: Innovation District

Our studio was assigned a site and told to design a masterplan for the area to show future development. Implementation years were never mentioned, so I chose to design for a more distant future. I was interested in the area becoming an innovation district to set an example for the rest of the city. The idea for a singular surface formed directly from researching what existing innovation districts looked like. I was completely astonished to find that in the current time, they typically look no different than the rest of the city. It has become a label that cities apply to an area without doing much to truly innovate the environment.

I wanted to question even the most standard aspects of a city and, as a continuation of the previous project, start from scratch. A truly innovative district innovates not just individual elements but design at a system level, a system that could work as one unit. Without the constrictions of existing infrastructure, it gave me the freedom to test out some ideas that might otherwise not be possible (*Figure 3.13*). I approached the project assuming anything could be possible and did not constrain myself by imitating precedent research.

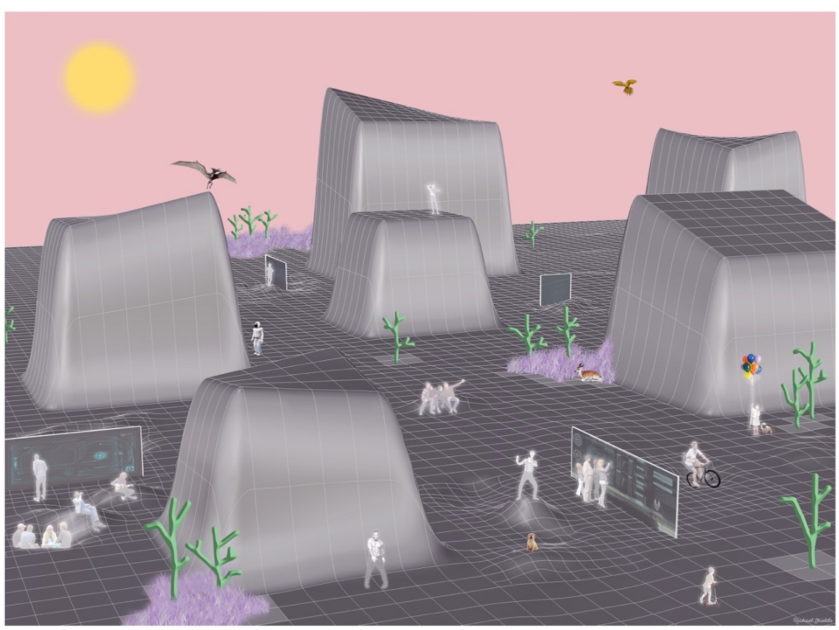


Figure 3.13. Innovation District Rendering

The entire area is blanketed in one continuous surface that can be pushed and pulled for different uses. Structures can form from the surface, be built on the surface, or be surrounded by the surface. The surface is adjustable and kinetic to provide enjoyable interaction with the built environment, but also to help future-proof the infrastructure of the area. It becomes this alternative space unbound by the typical city restrictions where freedom to design and adjust the built environment is a basic right of any user.

I approached the project by first researching what an innovation district should include. I compiled eight principles that an innovation district is comprised of and figured out how to make each one possible in this project. The innovation district should (1) occupy a location with a sustaining population, (2) be minimally restrictive, (3) be adjustable, (4) include technology, (5) be green, (6) have mixed-uses, (7) be people friendly, and (8) have connective circulation.

For the purposes of this thesis, I will only be discussing the kinetic portion of this project. Having a flexible and adjustable structure allows an infinite number of configurations and the possibility for things to be continuously updated. Without this principle, an innovation district becomes a static element in time much like Disney's Epcot. Epcot was supposed to be an experimental community of the future, but it has not progressed since its inception so it is more so displaying the past now. *Figure 3.15* shows how the flexible structure operates. The kinetic mechanism is a robotic telescoping structure with a pivot head that allows custom heights and angles. Layered on top of the telescoping structure are flex panels that hold the form of the designed topography. Lastly, there is a malleable membrane that creates a smooth surface to travel across. I did not know if the mechanism would function well at such a large scale, but my goal for the project was to be purely explorational, and to worry about construction later.

At the heart of an innovation district is the technology involved with every element of the design. *Figures 3.13 and 3.15* show digital programming walls that allow the public to adjust the topography in kinetic zones. On the panel, they can select from pre-existing configurations like a bench and modify it or create a new topography configuration (*Figure 3.14*). The kinetic zones encourage social interactions and public creativity. With customizable designs, street furniture can be more ergonomic to the individual.

Sadly, I ran out of time before I could complete a personal goal of the project. As discussed, I approached the project from a systems level and I wanted to figure out how to not only have the landscape kinetic, but the architecture as well. This would form one cohesive, kinetic built environment. The architecture is included in the rendering (*Figure 3.13*), but I never figured out how it would actually work.

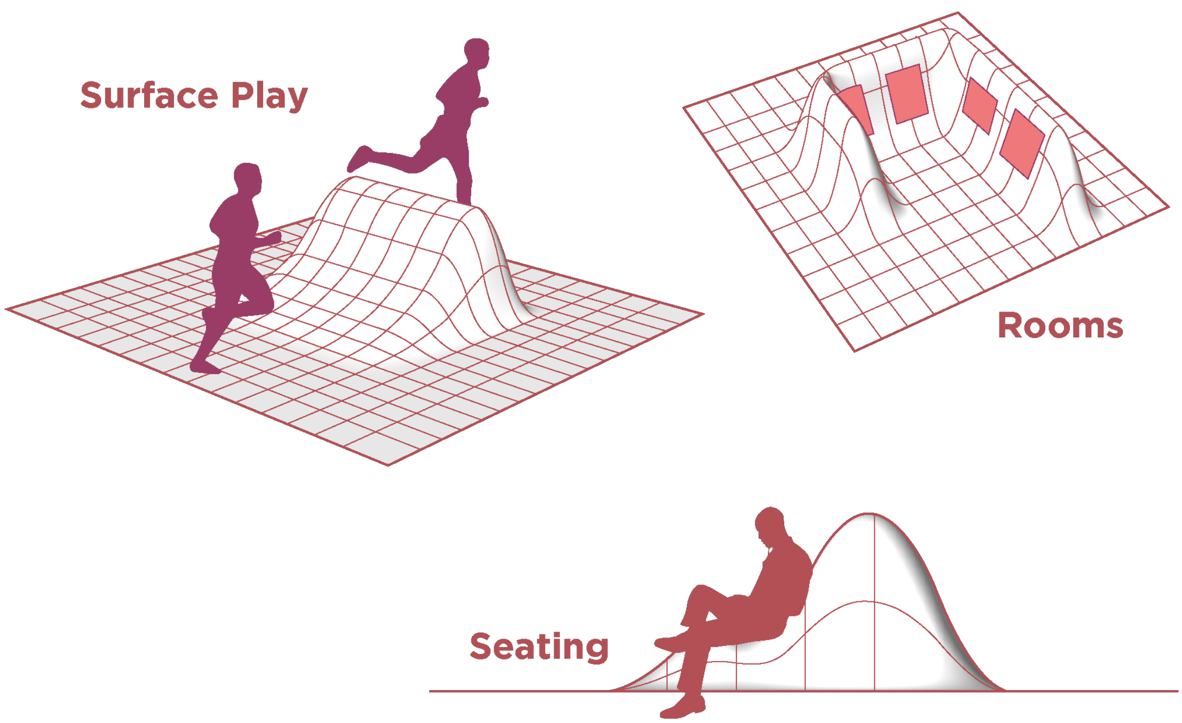


Figure 3.14. Kinetic Topography

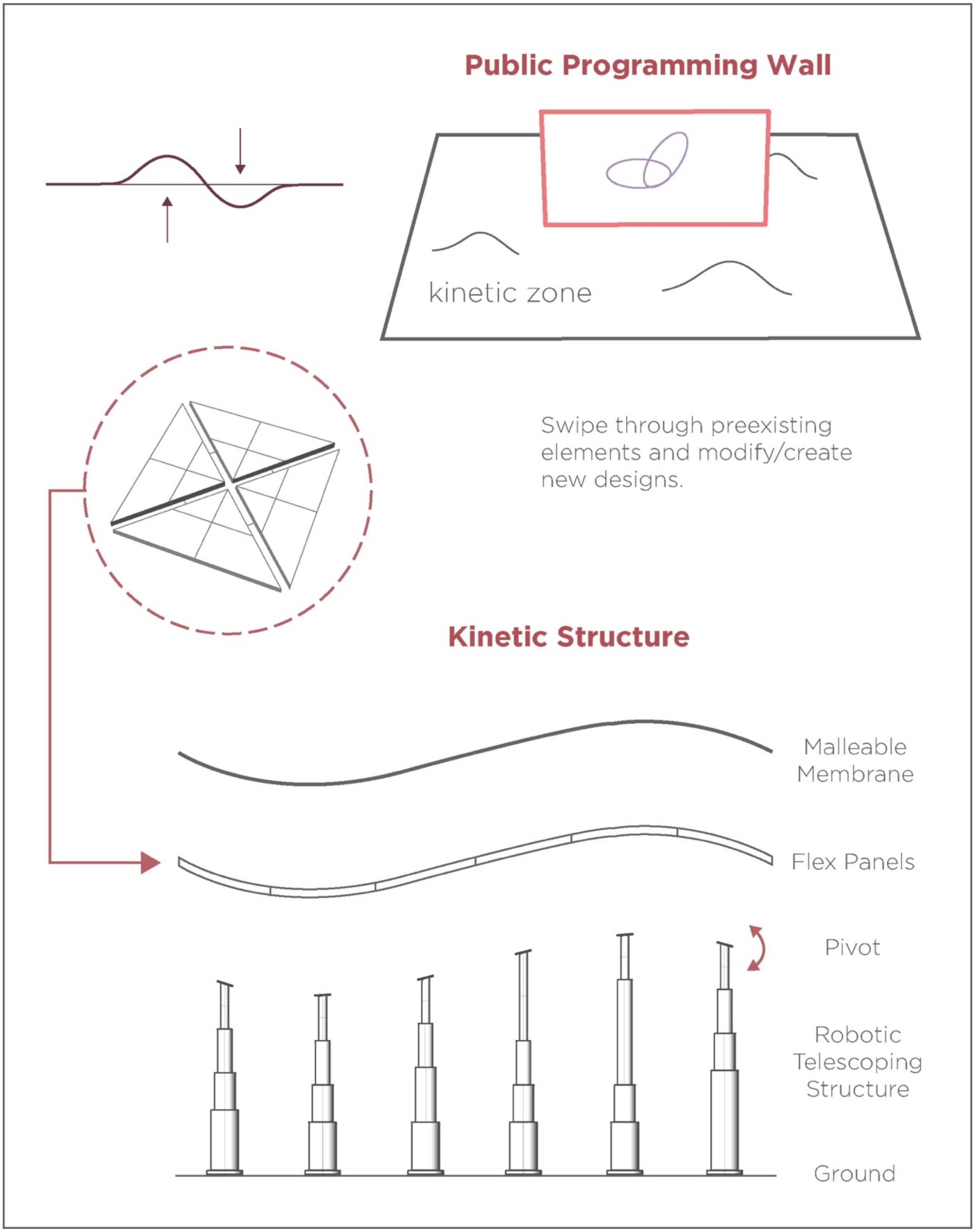


Figure 3.15. Kinetic Mechanism

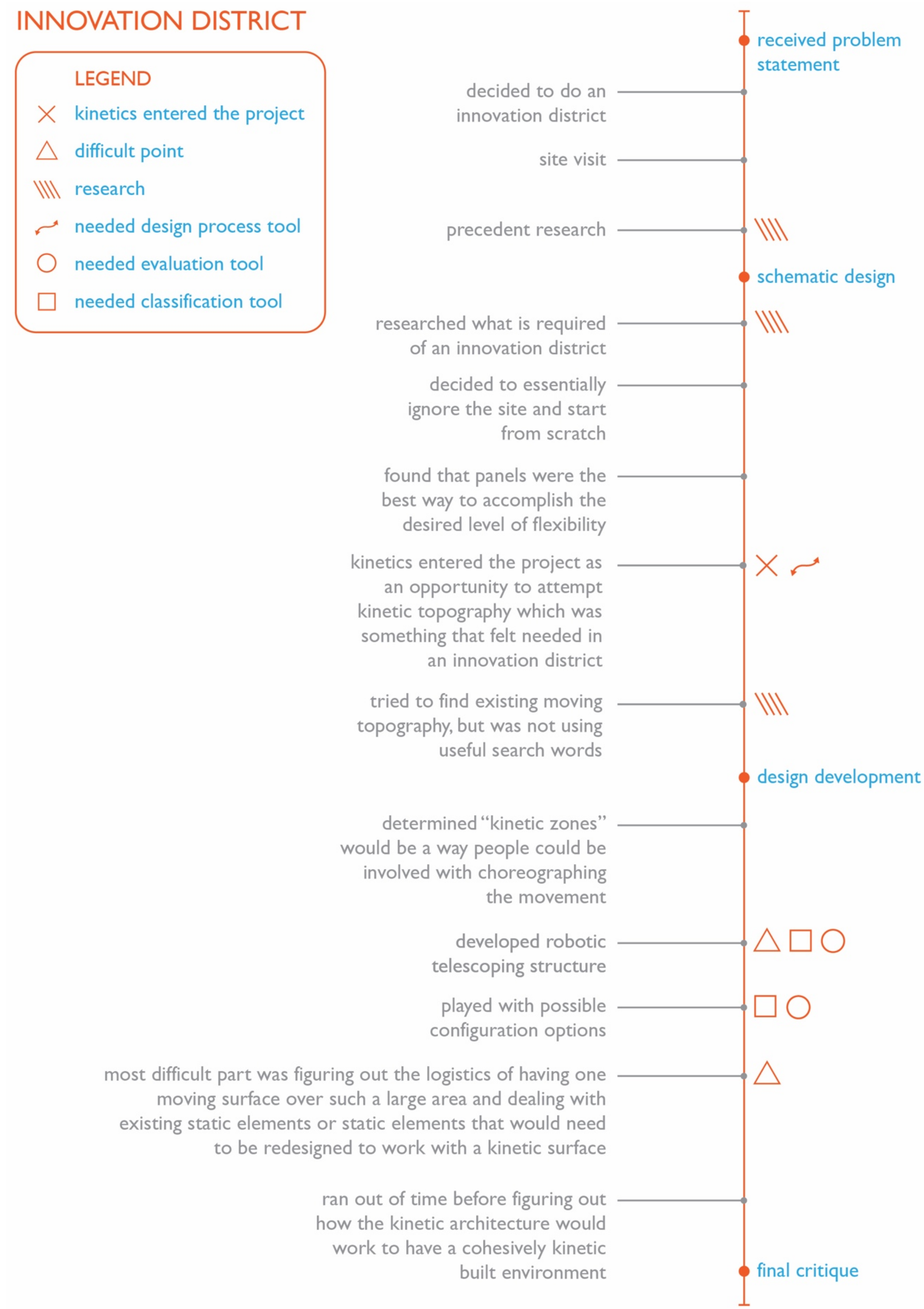


Figure 3.16. Design Process Diagram

Analysis / Conclusion

Kinetics entered the first project to include the permeable wall as a way to mediate two distinct points of view about a design. The project included a form of participatory design which resulted in both the students and faculty getting what they wanted for the campus. Kinetics not only allows multi-functionality but in this case, it allows multiple points of view to coexist.

Permeable Edge was one of my first kinetic designs, and it was created with minimal prior research on kinetics. I went back and forth on how the panels should move, making it the most time-consuming portion of the project. I kept thinking of different ways they could move, sliding, folding, or rotating. Had I been aware of movement diagrams or mechanism drawings like those shown in Move: Architecture in Motion - Dynamic Components and Elements (Schumacher, Vogt, and Schaeffer 2010) it would have made the process go more smoothly, and I would have been more confident in my choice of movement type and mechanism (*Figures 4.2 and 5.6*). Without having the knowledge of the many kinetic mechanism options, I chose a track system because it was something that I could easily visualize and understand. Again, for the second project, the *Open-Source Landscape*, the design included a track system for the same reasons. If I had known of a good classification system that had listed possible mechanisms, materials, or control systems maybe the wall could have moved on ball joints, hinges, or be made of a tensile membrane. For precedent research, a catalog of existing kinetic projects would have been helpful to show a range of possible ideas so that I would not have had to start from "scratch."

For the *Open-Source Landscape*, kinetics entered the project in the schematic design phase because I could not have the street lanes freely configurable without moving all the stationary street objects. I was happy to have the freedom to explore what a futuristic and kinetic street could become. I did not have the goal of a kinetic space, but the goal of a flexible space; kinetics allowed me to accomplish that. The project tested three methods of flexibility: digital street panels, movable trees, and a flexible subsurface structure. I wanted to see how flexible the space could become. I did not reach one hundred percent flexibility, but it allowed me to contemplate how that could become a reality.

The key point of this project was testing how to move the weight of plant material. This is only one potential solution, but it inspired other ideas during the process that could be tested out for others. For example, instead of hanging the trees from a crane-like mechanism, perhaps they could be moved on a 'walking' scissor lift mechanism that could raise and lower the planter and move position. I realized how constrained moving plant material is by having to contain the roots in a planter. So, my next area of interest would be to incorporate the ideas of hydroponics, aeroponics, aquaponics, and dryponics to overcome that constraint.

For the first time in any of my design projects, I encountered the problem of operational responsibility of the street. Boundaries became blurred with the introduction of kinetics. It is a public amenity so people deserve the right to control some of the movement but I contemplated the impact to public safety? There is, of course, no existing standards or regulations but three groups of involved people would need their roles of control in the streetscape redefined.

I decided the public did not need to move the trees but they could operate the digital panels without any harm. The city needed to have sole control over the reconfigurable lanes and street signs due to the public safety concern. I also knew it was inevitable the street design would include some commercially available space for purchase. There would need to be some regulation to prevent the street surface from becoming distracting to drivers. This is an early indication of the ethical questions to consider when integrating kinetics into landscape architecture.

Project three, *Innovation District*, includes a robotic telescoping mechanism with the primary goal of testing out the concept of kinetic topography. Kinetics entered this project in the schematic design phase after researching what an innovation district should include. I felt kinetic topography was something that should be explored for a futuristic innovation district. It is not an easy feat to accomplish and the logistical planning took a large portion of the allotted time. I did not know of any existing kinetic topography projects, but I was positive something like that had to exist. I attempted to find images, but a quick Google search of keywords like *moving topography* or *kinetic ground* did not produce the desired results. Eventually, I figured out how to make my own kinetic mechanism to do the job, but a tested mechanism might have legitimized the project.

Undoubtedly dealing with engineering, the kinetic mechanism is where landscape architects will experience the most significant learning curve. Moving plant material is difficult but moving the entire ground plane seems to be even more ambitious and problematic. Again, this is only one method of artificially creating moving topography, but it is an important step towards making it a reality. I went through several iterations to get to the proposed mechanism, like a computerized mesh. While it is a possible method, it seemed like a cop out to say the topography would just be computerized and not design the mechanism further. I did not find out until after the completion of the project that there were several existing concepts like *Dynamic Terrain* by Janis Pönisch; the difficulty lies in economically scaling existing prototypes to a landscape size (*Figure 2.11*).

The innovation district I designed was an example of an extreme situation, experimenting with the idea of an entire district being one kinetic entity. It demonstrates the next step after advancing kinetic landscape architecture as the concept of an entire kinetic built environment, blending where architecture and landscape architecture start and stop.

The design process diagrams helped to compare the projects and they clearly indicate points along the design timeline where landscape architects should be alert. However, it is clear that the goal of including kinetics in each project before starting the process greatly influenced the timeline.

The process diagrams show that aid was desperately needed when dealing with movement and mechanism options. Furthermore, a significant finding was that with the streetscape and the innovation district one of the primary challenges was dealing with existing static components. Granted these are extreme kinetic examples, but kinetic projects will need to work with static elements and an existing site. With the streetscape, static elements had to be redesigned to be incorporated into the kinetic system. The site was almost completely ignored with these two projects because of the goal to test kinetics to the extreme, but it would have been even more difficult if I tried to work with the site conditions.

All three projects had a shortened design process and I felt like I was quickly fumbling my way through the kinetic design. I did not know the ideal sequencing for the design process. The guesswork involved in the process demonstrates the need for a thorough design process guide that is imbedded within the landscape architecture design process so that implementation can be streamlined. I felt like I was going to miss important details and I also had uncertainty towards the functionality of the proposed mechanisms. The uncertainties indicate the need for the incorporation of collaborators such as kinetic architects, mechanical engineers, structural engineers, or civil engineers.

Personally, the most important takeaway was that all landscape architects should have a base level of awareness of kinetics in order to decide if they would like to include it in a potential design. Without being at least minimally aware, landscape architects will be very hesitant to specify kinetic mechanisms.

CHAPTER 4

KINETICS IN THE LANDSCAPE ARCHITECTURE DESIGN PROCESS

This portion of the thesis inserts kinetics into the landscape architecture design process to best show what components are completed at each stage. This offers a new contribution to the body of knowledge to aid in expanding the understanding kinetic landscape architecture that the discipline previously lacked. This method allows kinetics to easily be incorporated into a design process that landscape architects are already familiar with. A literature review is used to present the base level of knowledge a landscape architect should have at each stage of the design. This chapter aligns with the Design Decision Chart in Chapter Seven and they should be used together. The literature review is organized according to a design process based on the design stages presented by Kevin Lynch and Gary Hack (1984):

1. Defining the Problem
2. Analysis of Site and User
3. Schematic Design
4. Design Development
5. Contracts and Bidding
6. Construction
7. Occupation and Management

This thesis will not cover kinetics in the contracts and bidding stage. This stage remains mostly the same despite the introduction of kinetics. In this chapter, kinetics will be inserted into an existing landscape architecture stage process to allow landscape architects to seamlessly embed kinetics into their daily design work. Kinetics is ideally introduced into a project during the problem finding and problem definition phase of the project. However, a majority of the kinetic investigation takes place in the design development phase. For this reason, the design development section is further subdivided into the following categories: movement, materials, operation, and prototyping.

There are several kinetic trends landscape architects should be aware of that are relevant to this chapter. James Alison (2019), a mechanical engineer, describes several trends he personally sees taking place in the realm of movable structures:

- Movable structures continue to become more computerized, whereas mechanical mechanisms have received only minor updates over the years.
- Structures are getting bigger and heavier.
- Steel is by far the most common material for movable structures and that does not seem to be changing anytime soon
- Aesthetics have become more of a major concern, a trend our field will benefit from.
- Structures are heading away from looking movable and instead are looking more static.
- Drive systems are becoming simpler and more powerful.
- There is more of a desire to monitor structures for maintenance and prevention of error. This saves owners from having to shut down the entire system. They can receive warnings to anticipate failures prior to a potentially harmful incident.

Defining the Problem and Schematic Design

Before implementing kinetics in a project, the first step is understanding the project's design problem and deciding if kinetics is the correct approach to a solution. Kinetics can be the solution to many problems, but it might not be right for every project. Does kinetics fit within the budget as well as its continued maintenance? If there is a tight budget it does not mean kinetics cannot be included, the moving elements might just need to be less elaborate or human powered. Is there a time constraint on the project? Again, that does not necessarily mean kinetics cannot be included, the designer will just need to be strategic. Is there someone with kinetic knowledge or can someone be acquired for more complex problems?

There may not be any indication from the client or user to include kinetics in the project so it might be up to the designer to advocate for the option of kinetics. During this early phase of the project kinetics may not be recognized as a solution, but it may surface as a way to solve a specific problem encountered in design development. The schematic design phase is when many kinetic design tools start to offer guidance, see Chapters Five through Seven for details.

Design generation in the schematic design phase includes developing an idea and choosing how a space will function (Megahed 2017). This is where a designer should begin to figure out what is being moved in the project. A design can have a function-based purpose, an aesthetic purpose, or most likely both. The initial investigation of form and structure would be considered part of the schematic design phase, just as in static landscape architecture.

Design Development

There are countless choices that designers will need to make when designing a kinetic project and most of them will take place in this step. Some kinetic systems will be quite complex and can get very technical. The understanding of how kinetic projects work and the physics involved is one of the most substantial deterrents of designers. It is a topic of debate to what level landscape architects must know the technical aspects of kinetic systems, but this thesis takes the position that landscape architects should be aware of kinetic technology and its possibilities to be able to involve them in their designs. Collaborating with a team of mechanical, structural, and civil engineers can solve the remaining uncertainty towards kinetic knowledge. However, Lyle warns that even with the addition of engineers, they often have little experience with movable structures (Lyle 2006). He suggests that an engineer should be brought in early for some preliminary advice, but that designers should be careful to not have them heavily involved until a schematic design is fully developed or else the kinetic creativity can be obstructed (Lyle 2006).

<u>Movement:</u>

The Ways and the Means: When concerning kinetic mechanisms, the phrase 'the ways and the means' is used by several kinetic architectural writings to describe the primary function of a kinetic system (Fox and Kemp 2009, Megahed 2017, Moloney 2011). 'Ways of movement' is the kinetic action and includes verbs, or the 'what,' such as folding, sliding, shrinking, transforming, and expanding. 'Means of movement' consists of adjectives, or the 'how.' The author splits the 'means of movement' into three categories: passive, active, or human power. Passive refers to environmental actors causing the movement; for example, the wind moving a Ned Kahn façade (*Figure 6.4*). Active refers to movement by means like pneumatic, electrical, magnetic, or chemical.

Kinetics does not necessarily require advanced technology, it can involve simple machines or be human powered. Human power is an interesting addition to a project because of the empowering experience it can give a user. Low-tech solutions like wheels and simple track systems, with elements that are movable by the average human strength, can be easy ways to add kinetics to the site. The American Association of State Highway and Transportation Officials (AASHTO) standards list thirty to forty pounds as the maximum for manual operation. This maximum can still move large structures with friction management and simple machines (Alison 2019). If the weight needs to be moved by humans there are several ways to make this possible: (1) using a lightweight object or material, (2) simple machines, or (3) mechanical assistance. The mechanical assistance then makes the project not completely human powered, but it could still have similar benefits.

Movement Direction: Mechanical movement is divided into two basic types: rotation and translation (or a combination of the two) with six degrees of freedom (*Figure 4.1*) (Schumacher, Vogt, and Schaeffer 2010). One degree of freedom looks like a standard door opening and closing on a hinge; it can only move in those single directions. Two degrees of freedom looks like a window that has the option to slide open and rotate outwards. Whereas a jet has six degrees on freedom allowing rotation and translation in all directions. Translational movement is accomplished more easily than rotational movement.

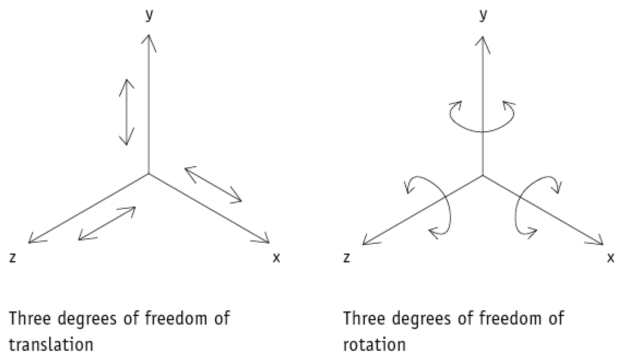


Figure 4.1. Degrees of Freedom

Mechanism: There are hundreds of types of possible kinetic structures. The best way to learn about them is in Chapter Six's catalog, but a particular category that should be mentioned is deployables. Deployables allow structures to be assembled quickly, require a minimal amount of construction equipment or knowledge, and are necessary for limited space situations (Hernández Merchan 1987). Deployables are relevant to kinetic landscape architecture because they can aid in transforming spaces and create multi-functional spaces. Consider the idea of picnic tables folding into the ground for the space to be used for a game of catch. Another idea is deployable ramps extending out of a curb for equal access. Five types are covered here: inflatable or pneumatics structures (*Figure 6.2*), telescopic structures (*Figure 3.15*), scissor-hinged structures (*Figure 6.60*), folded structures (*Figure 6.52*), and umbrella structures (*Figure 6.51*), all of which can be explained with common everyday objects. It should be noted that these five types of structures can be deployable, but they are not always. For example, a structure can fold and not deploy into an expanded form (*Figure 6.57*).

Pneumatic structures, like a balloon, consist of a membrane supported by the pressure of different gases, liquids, or foams (Hernández Merchan 1987). Pneumatics can cover large spans and be more cost-effective than traditional building materials. The technology has been used to create dams, greenhouses, bridges, shelters, and experimental housing. Telescoping structures work like collapsible radio antennas. Scissor-hinge mechanisms look and work like scissor lifts and are sometimes referred to as pantographs. Folded structures can be collapsed and expanded like an accordion (Hernández Merchan 1987). And umbrella structures typically have a sliding mechanism on a central support that allows them to act like umbrellas. They can be used as a complete roof or shelter structures.

Track systems are an easy way for designers to implement movement because they are straight forward for designers and construction workers to understand and can be readily purchased. *Figure 4.2* shows a few possible configurations. Many existing kinetic projects use a track system as their method of movement; examples include *Courtyard in the Wind, EWE Arena, The Shed, Spielbudenplatz, and the University of Phoenix Stadium*. Track systems allow heavy weight, like that involved with soil and trees, to be moved easily. They also offer a fail-safe; if the control system fails, the element on the track can be towed safely. Bogies are also commonly used with track systems; a good example is the wheel configuration under a train car. Bogies are modular subassemblies of wheels and axles that secondarily help support the weight of the structure it is moving. It is a compact unit that houses everything needed along with the wheels like the suspension system and brake equipment.

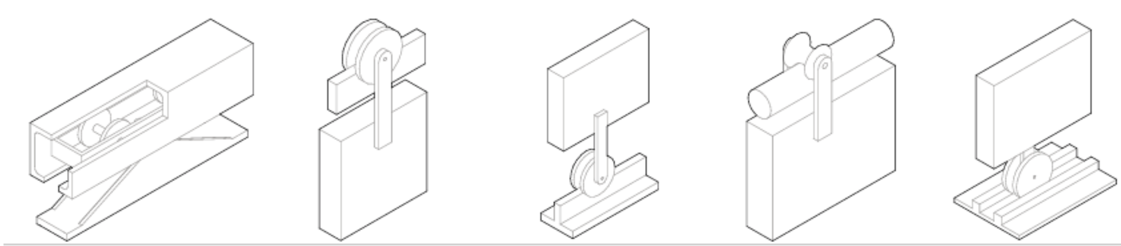


Figure 4.2. Track System Options

Movement mechanisms require elements like joints and bearings. Joints are critical points in moving structures, they are the spots where forces converge, and their ability to resist and transmit forces will determine the structural soundness of the construction. Ball or roller bearings are rolling elements placed between two bearing rings called races and are used to reduce friction where two elements touch (Schumacher, Vogt, and Schaeffer 2010) (*Figure 4.3 and 4.4*). Hinges are separated into two categories based on whether they contain a pin or not. Complex hinges combine the principles of several basic hinges to create two to five degrees of freedom, or a sequence of hinges can perform the same hinging movement (Schumacher, Vogt, and Schaeffer 2010) (*Figure 4.5*). Movement mechanisms and connections that allow movement usually require some form of a lubricating agent to separate contact surfaces from each other; however, using lubricant-free materials that have a low coefficient of friction, like Polytetrafluoroethylene (PTFE), is an alternative (Schumacher, Vogt, and Schaeffer 2010).

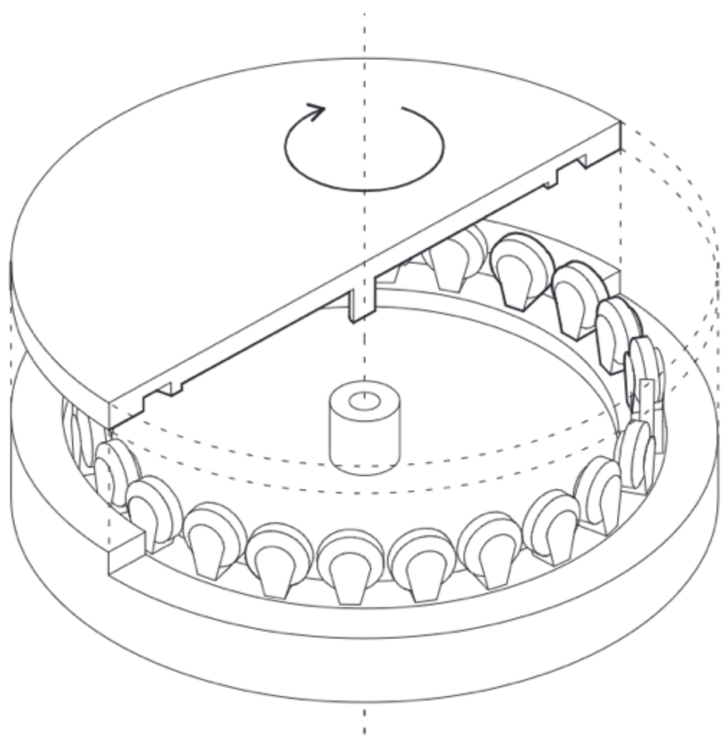


Figure 4.3. Turntable with Fixed Rollers

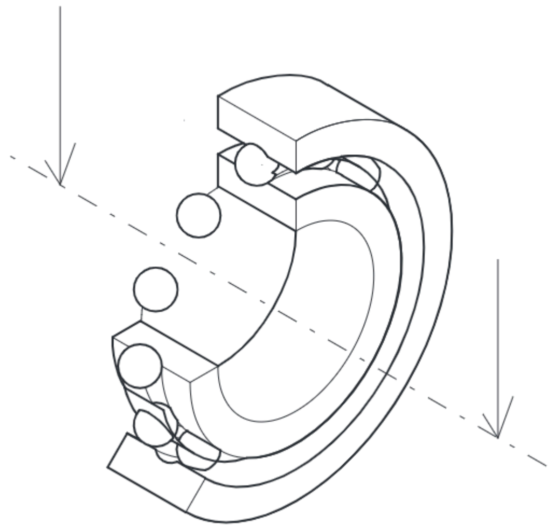


Figure 4.4. Radial Ball Bearing

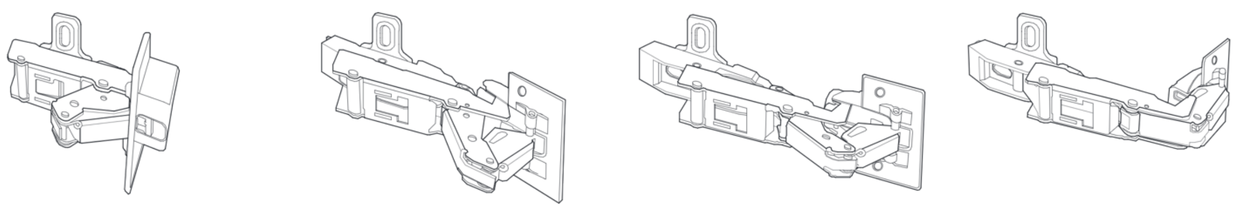


Figure 4.5. Complex Hinge

Materials: There are copious amounts of materials that can be used with kinetic systems and more are constantly being discovered. Asefi (2009) lists four selection criteria to be considered when choosing the materials of a kinetic structure: environmental aspects and safety issues, mechanical and structural properties, foldability and durability, and aesthetic issues and light transmission. It is clear that the most important material aspect to consider is that it needs to withstand wear and tear during the movement process (Megahed 2017).

Technology can be present throughout all of the landscape architecture design steps. In the material design phase "all the information for assembly, all the information for interaction, and all the information for decision-making can be embedded in the materials themselves," in materials referred to as programmable materials (Kolarevic and Parlac 2015, 147). Intelligent or smart materials are general terms for materials that have one or more properties that can be altered (Fox and Kemp 2009). Of great promise is how smart materials can be used as sensors, detectors, transducers, and actuators (Fox and Kemp 2009). Smart materials can be divided into two classes. Type one materials undergo a change in response to external stimuli (chemical, electrical, magnetic, mechanical, thermal) (Fox and Kemp 2009). Type two materials transform energy from one form to another (photovoltaic, thermoelectric, piezoelectric) (Fox and Kemp 2009). The following paragraphs offer some examples.

Photochromatic materials (type 1) are those that change color when exposed to light; this material could be applicable to a non-spatial kinetic design. Consider photochromatic glass that shades a building just by the glass changing color. Shape memory alloys (SMA) (type 1) exhibit the ability to deform from one shape to another and then return to their original shape, a trait that will be extremely valuable to kinetics. Picture self-repairing or self-deconstructing structures. SMAs are kinetic without additional mechanisms and can therefore be cost-effective, energy saving, and space saving. A hygroscopic material (type 1) absorbs moisture from the air. This can allow for humidity responsive design. Responsive materials that react to weather changes could act as kinetic shade or shelter elements in a landscape. In the landscape all of the environmental factors become possible options for modification.

Piezoelectric materials (type 2) have the ability to produce an electric charge in response to applied pressure. The word piezo actually means pressure. An example of a piezoelectric material is the airbag sensor in a car. The material senses the force of an impact on the car and sends an electric charge to deploy the airbag. Imagine powering a streetscape from the pressure of cars driving through or powering lights from users walking through a landscape.

Smart materials offer an infinite amount of potential, but non-smart materials should not be forgotten. Some non-smart, flexible materials are shown in *Figure 4.6* that are malleable in their inherent properties like rubber, or due to the joining method like ring mesh. Non-smart materials can be classified as 'high-performance' materials if they are static, but offer optimized properties like extremely high strength or particular reflective properties (Addington and Schodek 2012).

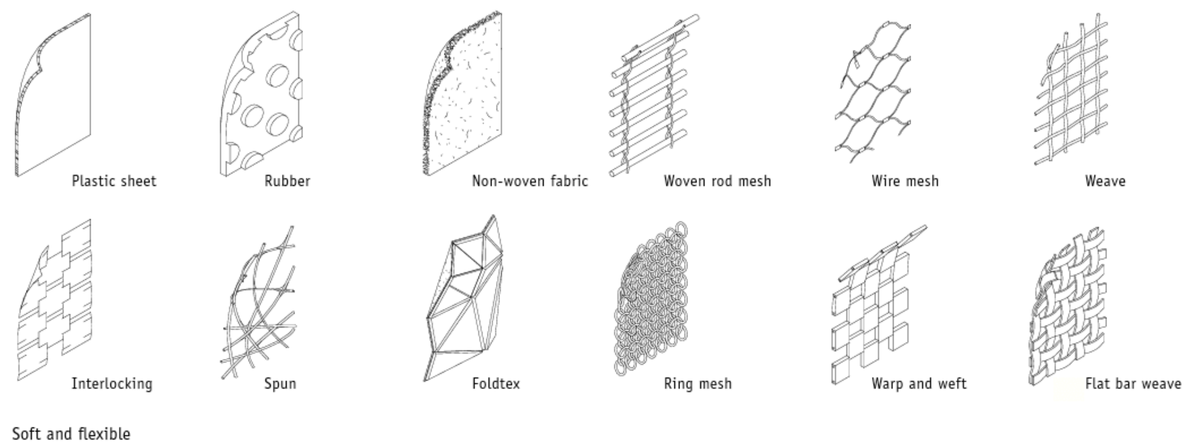


Figure 4.6. Flexible Materials

ETFE (ethylene tetrafluoroethylene) is a thin, flexible, plastic foil similar to PTFE (Teflon), that is currently popular in the field of kinetics. Both ETFE and PTFE, a very close relative, are classified as textiles. ETFE has a higher tensile strength and is more commonly used in architecture, but PTFE has a higher heat resistance, so it is being used in more industrial applications. ETFE is one percent the weight of glass and can be used as an alternative to glazing or act comparably to a tensile membrane due to its flexibility. It is transparent, tear resistant, has a long life, and does not deteriorate with UV light. The lightweight and flexible qualities would allow for a kinetic system with less structure to support the weight. It can be applied as single or multiple layers, but a more effective use is as inflatable cushions. Several layers of ETFE are combined with a pocket of air held between them. Constant air pressure is needed in the pockets, but this requires minimal energy as they do not need air flow, just maintained pressure. The pneumatic panels offer better insulation values than triple glazing, increased flexibility, and a major reduction in dead loads and large structural supports. A famous project incorporating ETFE is the swimming center for the Beijing Olympics, also known as the *Watercube*, with a façade of inflatable cushions that are made to look like bubbles. The *Media-TIC Building* in Barcelona takes ETFE one step further and has a monitoring system that moderates the daylight and heat gain of the building by inflating or deflating different pieces of the façade.

Operation: Operation involves the control mechanisms involved in the movement process, the associated technology, and choreographing the movement of the kinetic design.

Control: There are six types of controlled movement, developed by the Kinetic Design Group; internal control, direct control, indirect control, responsive indirect control, ubiquitous responsive indirect control, and heuristic responsive indirect control (Fox and Yeh 1999). Internal control systems possess the potential for mechanical movement in a structural sense, but do not have a direct control mechanism, like a Hoberman sphere or a collapsible truss (Fox and Yeh 1999). Direct control systems have movement operated by an energy source like a human or a motor. Indirect control systems are computer controlled via sensor feedback. This is a "singular self-controlled response to a singular stimulus" or comparable to only having an on and off switch (Fox and Yeh 1999, 6). Responsive indirect control systems are similar; however, with their sensor input, they can make an optimized decision with potentially hundreds of options compared to only having the binary option (*Figure 4.7*). Ubiquitous responsive indirect control is a system with many autonomous sensors and actuators acting as a network (Fox and Yeh 1999). Lastly, at the level of heuristic responsive indirect control, the system has a learning capacity – artificial intelligence.

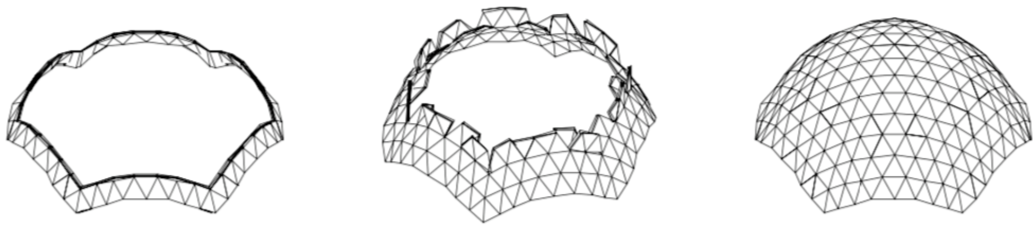


Figure 4.7. Responsive In-Direct Control Tents

Actuators: There are three main types of actuators: electric, hydraulic, and pneumatic. An actuator's purpose is to move something linearly or rotationally. Loads (wind, ice, live loads, etc.) and site conditions govern the choice in the drive system. An electric actuator is the most common and commonly uses a motor and screw to move a piston rotationally, or linearly like shown in *Figure 4.8*. This method of movement is cheap, precise, and can be automated (with the addition of a programmable logic controller (PLC)) whereas, a mechanical actuator cannot. PLCs are the computerized brains used for automation in industrial purposes like manufacturing and robotics. They allow a more precise control of the electric motor, for example gently setting a load down by slowing the movement when the element gets near the closing position.

Hydraulic and pneumatic actuators are pressure related. Hydraulic actuators work by controlling the movement of a fluid, typically oil. Basic hydraulic systems have a control valve, pump, reservoir, hoses, and a cylinder and piston (*Figure 4.9*). These systems have high power density, meaning they have a high power output to size ratio. They are very strong and direct, but do not have smooth movements and are known to leak. However, it is possible to harness smooth movement with a more elaborate system, a good example is the Cirque du Soleil stage in Las

Vegas, Nevada (Alison 2019). Pneumatic actuators move air instead of a liquid. They are similar to a hydraulic system, but instead of a reservoir they are open to the atmosphere and need an air compressor instead of a pump. Pneumatic systems are strong but precise control is a difficult task. Hydraulic and pneumatic systems are noisy due to the pumps, but a possible solution to the noise is moving the pump to an isolated location.

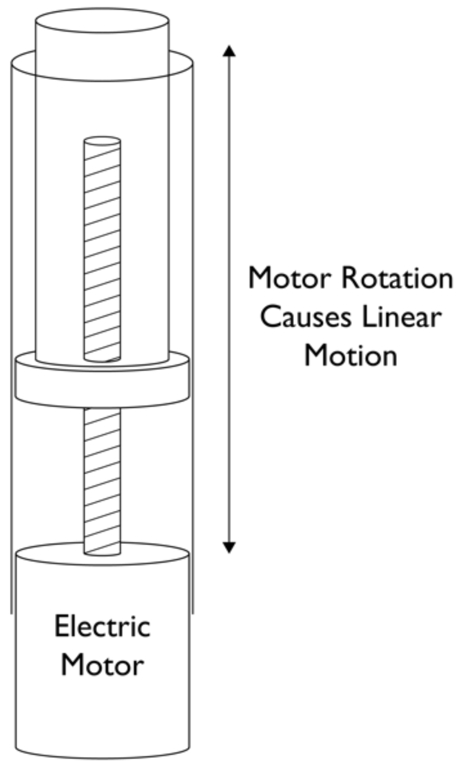


Figure 4.8. Simplified Electric Actuator

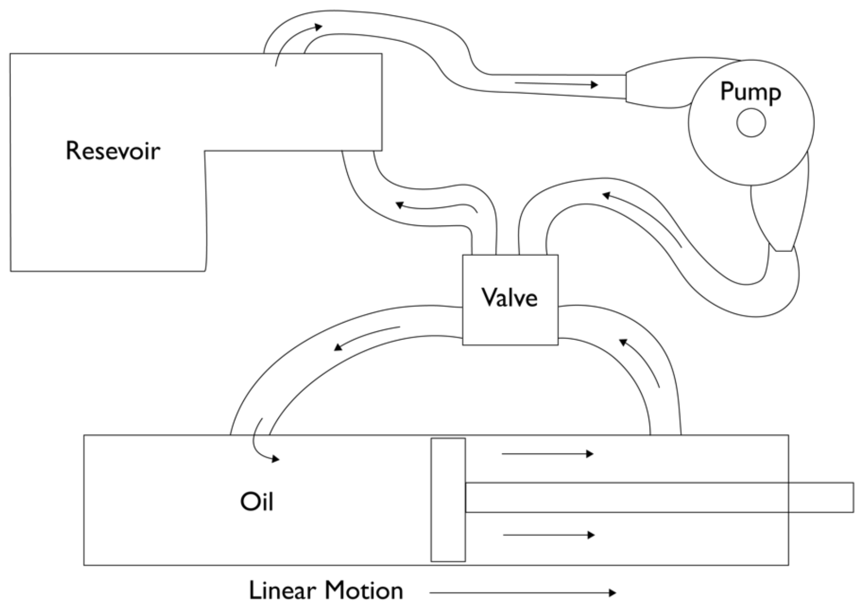


Figure 4.9. Simplified Hydraulic Actuator

Auxiliary Power, Brakes, and Lock: Auxiliary power is important as a fail-safe if the main power source cuts out. In some cases, this is a hand crank to return the structure to a safe configuration. It could also be a simple backup generator that the mechanism switches to if necessary. Having this backup power option in the design is referred to as redundancy. If it the movement is purely aesthetic or the function is not required, then there does not necessarily need to be a backup power source; it can move again when the power connection has returned.

As it is hard to stop heavy moving objects, brakes and locks are needed to accomplish this. Friction can be a good thing when moving large pieces for quick braking. Brakes can break many drive systems when attempting to stop heavy structures quickly (Alison 2019). Brakes should be applied gradually, allowing for a proper deceleration so as not to incur forces that have not been provided for. Locks restrain the structure in rest when it is needed in a static position. This could be for maintenance or the mechanism could be choreographed to start and stop frequently and when it is stopped it needs to be stable. Locks override the drive system and could be a simple bar or pin between a moving and fixed element. A mechanism will have to be included to the move the pin.

Technology: With technology comes the responsibility to design a space that can easily be updated and evolve as new technology comes along (Fox and Kemp 2009, Kolarevic and Parlac 2015). In the information technology (IT) industry, technology is referred to as ‘legacy’ if the object or software has become obsolete. This does not mean just because something is old it does not function well; this refers to situations where the technology is no longer accessible, being made, or no longer effectively does the job it was intended to do. For example, floppy disks are not only out of production, but computers that read them are no longer being made.

Siu and Wong (2015) discuss flexibility as the capability to adapt to unforeseen change. A flexible space that contains the ability to quickly substitute products and elements of the design for newer technology will increase the longevity of its relevance. The importance of flexibility cannot be stressed enough. The cost and material savings can be staggering without the need to destroy a structure or element in order to implement a renovation. Flexibility also allows the much-desired aspect of always having the latest technology, known as perceived obsolescence. Siu and Wong (2015) suggest reconfiguration and modularization as design tactics for achieving flexibility to adapt to change. The author suggests kinetics as a method for achieving reconfiguration and flexibility in a landscape.

Within the area of technology, a niche area of robotics is called soft robotics. A soft robot is capable of completing a diverse set of tasks and overcoming obstacles in a variety of environmental conditions, which is a crucial component of kinetic landscape architecture. Whereas traditional robots tend to be rigid in form, soft robots are made of materials like fluids, gels, soft polymers, and silicone. Carmel Majidi (2014), a member of Carnegie Mellon's Soft Materials Lab, uses the example of an octopus squeezing through a tight opening as a prime example of a soft robot. Soft robotic technology could be necessary to perform tasks involving organic materials like trees that will grow in a landscape.

To be considered a robot, three things are required: sensors, intelligence, and actuators (Kries 2017). Sensors detect or measure physical or chemical characteristics in their environment and send a signal to the actuator. Sensors can be contact-based like wind or pressure or non-contact based like infrared or sonar (Fox and Kemp 2009). In architecture security and safety sensor examples include motion and human presence, fire and smoke detection, access, photo optics, acceleration, shock and vibration (Sherbini and Krawczyk 2004). Weather and space quality sensors include temperature, humidity, light, air contents, and chemical measurement (Sherbini and Krawczyk 2004). System monitoring sensors would be to monitor a heating, ventilation, and air conditioning (HVAC) system or structural system monitoring (Sherbini and Krawczyk 2004). Intelligence is software capable of making sense of and using the data collected from the sensor (Kries 2017). Finally, control mechanisms, or the actuator, receives a signal and is then responsible for triggering the change.

Microcontrollers are associated with sensors and other hardware components used to construct or prototype kinetic technologies. Arduino microcontrollers are a common example of a do-it-yourself prototyping technology. They are similar to computers and contain a processor, memory, and input/output functions (Fox and Kemp 2009). The difference is that microcontrollers perform an individual function and computers implement thousands. They are also small and inexpensive. Microcontrollers play a significant role in kinetics and can be found in most projects containing a digital component; they act as the link between the digital world and the physical world (Bullivant 2006). Landscape architects have already used microcontrollers and sensors to reveal ongoing processes in a landscape like micro-topographic changes, thermal energy transfers, and species behavior (University of Tennessee College of Architecture and Design 2017).

Artificial intelligence (AI) is a method for solving problems and is operated by a computer. AI must "think logically, use knowledge, plan, learn, process language, and perceive the world" (Kries 2017, 300). Desirable traits of AI include learning, self-correction, emotion, speech recognition, reasoning, and problem-solving. In spatial terms, an intelligent environment (IE) could gather data from the participants and adjust to best fit their needs. IEs could assist users in accomplishing specific tasks or possibly suggests new ways to interact with space or other users. Or consider the possibility of an IE monitoring itself similarly to a human body to adjust based on regulatory parameters.

Creating AI to mimic total brain function is currently impossible; we do not know precisely how human intelligence works. The Turing test is a benchmark for determining if intelligence is indistinguishable from human intelligence. However, trying to copy human intelligence may be an incorrect approach because that assumes human intelligence is the highest form of intelligence. Cantrell and Holzman (2015) ask if there could be a form of the Turing test for ecological systems. This points to a farther future, but one where there is a need to distinguish artificial from natural environments.

John Frazer worked with Cedric Price to study change in natural systems. When discussing the meshing of architecture and nature Frazer (1995, 16) states, "natural ecosystems have complex biological structures: they recycle their materials, permit change and adaptation, and make efficient use of ambient energy." This seems to point to the idea that adaptive architecture should act like natural ecosystems, a concept that would be equally important to kinetic landscape architecture. This potentially indicates a complex form of biomimicry where nature is the inspiration for a completely artificial ecosystem.

To preserve natural aesthetics, landscape architects might be intrigued by the concept of naturalized technology, also known as pervasive or ubiquitous computing. Naturalized technology is the concept of tech being everywhere and ideally indistinguishable from nature (Kries 2017). Cantrell and Holzman (2015, XVII) predict an emerging world "where matter at all scales is programmable, parametric, networked, and laden with artificial intelligence." And "an emerging paradigm shift – where biology, intelligent machines, and systems will begin to productively co-exist and co-evolve." Such technology could take kinetics further than we can currently even fathom.

However, there is controversy involved with being able to distinguish an artificial ecosystem from a real ecosystem. A potential dilemma landscape architects will have to face is the ethics behind an artificial ecosystem. This is similar to the popular ethical discussion of humans becoming indistinguishable from artificial intelligence. Is this something landscape architects should be advocating for? To what level is technology interspersed in the environment acceptable? Both are questions out of the scope of this thesis but something landscape architects should consider. However, it should be noted there is the possibility that artificial or kinetic environments can still provide similar health benefits that real environments do. Experiments demonstrate that virtual reality landscapes have the same positive effects as a real-life spaces (Kahn and Hasbach 2012).

Natural movement and change in ecosystems and landscapes can serve as inspiration for the design of kinetic systems. Role models taken from nature, which have developed over many years, might offer the best foundation to build from (Gruber 2011). Cantrell and Holzman (2015) ask an important question, “ecosystems are constantly in flux, so why are our [designed] landscapes not representing that?” What is preventing landscape architects from further emulating the dynamic traits of an ecosystem in landscape designs? The human-made components of our landscapes could be as active as the natural elements.

Choreographing: There are two types of movement that can be designed: digital and analog. Digital movement is only concerned with the start and end position. However, analog movement focuses on designing the movement itself. Analog movement involves designing the transition, and with continual movement, it does not place concern on the start and end position. Digital movement might be chosen (1) out of ease, (2) if that kinetic element is an insignificant or hidden portion of the project, (3) if the mechanism is complex and the start and stop positions are already a major endeavor, (4) there is limited availability of kinetic mechanisms that allow for analog design, or (5) if the designer does not have the knowledge to design analog movement. Schumacher, Vogt, and Schaeffer (2010) state there currently is not much analog movement in architecture, but this would undoubtedly be a vital component of a good kinetic designer’s job – to choreograph the movement of a kinetic environment. The choreographing can be preprogrammed depending on the situation, but another possibility is allowing the user to choreograph the movement themselves. They can play with the system and see what movement patterns and speeds they prefer.

Speed is the time required for a movement to take place and is vital to the perception of movement. Without speed, there is no movement (Schumacher, Vogt, and Schaeffer 2010). Large masses are more difficult to provoke into motion and stop once the motion has begun, but the material selection can significantly affect this. Mass will play an important role in kinetic landscape architecture. It is very likely that most kinetic projects that are large enough for spatial configuration will be very heavy and slow. It also takes more energy to increase the speed of movement. Consider how will the weight of trees be moved, or if a human-powered kinetic system is desired what materials or methods of movement can alleviate the burden of weight so even a child can customize the landscape?

Time closely aligns with the concept of mass and speed. Time is a vital component of kinetics. Time is factored into the speed of the movement, the pauses between movement, the length of time it takes to move the structure, and the amount of repetition. Currently, landscape architects already deal with time when planning for the growth of plant material or the impact of sea level rise. However, the way landscape architects think of time in relation to landscapes needs to expand. Choreographing moving elements requires thinking about time in a whole new way. David Leatherbarrow is quoted as saying “we need to make space for time” (Kolarevic and Parlac 2015).

The future requires landscapes to be designed as a dynamic and temporal experience (Cantrell and Holzman 2015, Motloch 2000). A dynamic and temporal experience entails a space that can adjust over time – a kinetic landscape. Temporal networks are specifically the structuring of places over time (Motloch 2000, Rapoport 1977). Motloch goes further to state that the temporal network must include open-endedness to allow user modification. However, Motloch (2000) describes temporal networks as a phenomenon difficult to predict by users and designers. This thesis argues that it does not have to be unpredictable with kinetics.

Aristotle’s (350 BCE) Physics contains eight books and discusses in depth his theories on time and motion. He lists place, void, and time as necessary conditions of motion and specifically, time as the measure of motion and rest. Time is a vital element in the process of transformation. When designing kinetic spaces, it is not an option to design time; it is a requirement. Sackl (2014) says, "whenever we create something without taking the effects of time into consideration, we are simply leaving the outcome up to chance."

Well-designed time is the difference between not perceiving movement and becoming sick from too much of it. A stimulating thought by George Rickey (1963, 220) is "use time like a spectrum of colors and space like an open ocean." Adding another dimension to the design process can greatly increase the complexity of a project, but it is worthwhile if it is also increasing the usability and longevity of a space. Designers can both design time and the effects of time.

Our expectations bias anything that we experience; the perception of time is no different (Sackl 2014). Designers can design time, but also the perception of time, just like they design the perception of space. Time perception is an entire area of study within psychology. Philipp Sackl (2014), a lead designer of Firefox at Mozilla, lists three factors that influence our perception of time: "the kind of motion that occurs, our preconceptions of how long a process should take, and the emotional state we are in during that process." One important factor to note is that everyone perceives time differently; time perception is subjective. One's perception of time can vary significantly with age and emotional state. If kids between five and ten experience time at a base level, ten to twenty year-olds experience it twice as fast, twenty to forty year-olds experience it four times as fast, and forty to eighty year-olds experience it up to eight times as fast (Adler 1999). Also, consider anxiety and fear make a period of time appear longer than it actually was (Sackl 2014).

Landscape architects are already aware of time perception; for example, walking on a hot downtown sidewalk with uninteresting surroundings feels like it takes longer to get from point A to B than if that same walk has interesting views and tree coverage. However, with kinetics, designing time perception is an entirely new level of complexity for designers to have to learn. Rickey (1963) states that when measuring time, the interval becomes critical and assumes many forms. How many times does the landscape start or stop moving and for how long? For example, Courtyard in the Wind (*Figure* 2.6a and 2.6b) moves at a speed of two cm/sec, or two revolutions per hour. An interval of time with more divisions feels longer than one with fewer breaks and time that is irregularly divided appears shorter than evenly divided intervals.

<u>Prototyping:</u> Prior to construction, it may be necessary to build a prototype to test the proposed kinetic design. Landscape architects do not typically use the term prototyping, but they are prototyping when building models, whether they are cardboard or with augmented reality (AR) software. Augmented and virtual reality (VR) will allow the level of visualization that kinetics may need for the physics of a design to be well understood prior to construction. AR or VR can be used to sell the kinetic concept to the client. With complex kinetic designs, it is hard for not only clients, but designers and construction workers to envision movement from a set of construction documents. AR or VR could be used to experience the movement and allow for trouble-free implementation. However, with kinetics, a more advanced level of prototyping beyond AR or VR, referred to as a 'working prototype,' may be required. A working prototype showcases all or most of the functionality of the final production. It can be produced out of cheaper materials or scaled down if necessary, but it will need to ensure the kinetic elements move properly in the final construction.

Construction, Occupation, and Management

This section combines the last two steps of the staged process model to cover construction, maintenance, kinetic failures, cost, and post-occupancy evaluation. Asefi's (2010) evaluation criteria for types of kinetic structures shown in Chapter Five provide lifecycle, construction, maintenance, and cost information that will be valuable to designers learning about this step (*Figures 5.2 and 5.3*).

Construction Information: Two groups have been created to aid in sharing knowledge and experience of kinetic structures. ARROW (Association for Retractable Roof Operators Worldwide) was a US-based group of owners and operators of retractable roof structures but has ceased to exist. Another trade organization based in the US is the Heavy Movable Structures Inc. (HMS), a non-profit providing kinetic information to bridge owners, government agencies, designers, contractors, and anyone else involved in heavy movable structures (Lyle 2006). HMS offers a valuable resource of information but is primarily concerned with large kinetic engineering projects and not necessarily kinetic architecture or landscape architecture. Each kinetic structure is very unique, which has prevented the concern of intellectual property with public heavy movable structures (Alison 2019). The creation of an atmosphere with a free interchange of information is a great asset to everyone involved, especially designers.

There is not a standard set of kinetic design guidelines for kinetic architecture or landscape architecture. Engineers designing kinetic architecture have looked to AASHTO (American Association of State Highway and Transportation Officials) for standards on movable structures in relation to highway construction and AREMA (American Railway Engineering and

Maintenance-of-Way Association) for standards on movable structures in relation to railroad construction (Alison 2019).

Safety is a *major* concern with moving objects, especially for an occupied space like a landscape. However, there is a significant lack of literature discussing the topic. The addition of barriers, sensors, and cameras can help with prevention, but as a warning, designers and engineers will likely spend a significant amount of time working on making the design safe.

<u>Maintenance:</u> A management plan followed by maintenance training will be essential components to ensuring the success of the project. Determining if the client is capable of sustaining the required maintenance is part of deciding if kinetics is appropriate for a project. Maintenance is improving with monitoring systems, but often they still require very primitive maintenance techniques such as using a grease gun. It is known that due to repeated movement, kinetic landscape architecture risks rapid depreciation and will require additional maintenance and repair to ensure the kinetic elements continue working as intended (Megahed 2017, Werner 2013, Lyle 2006). Durability is highly dependent on weather resistance and the points of connection like joints (Schumacher, Vogt, and Schaeffer 2010). Lyle (2006) notes that all kinetic structures must offer repeated reliable and safe operation without major supervision and maintenance. Yet, as kinetic designs increase in complexity, they become harder to routinely check for structural complications, and a specialist might need to be hired (Lyle 2006).

The lifecycle of kinetic structures ranges greatly with use and design. For example, some bridges are moved only a few times per year. A seventy five-year life is a currently desirable number when engineers are designing kinetic bridges, but some are rebuilt on a ten to fifteen year cycle (Alison 2019). There are plenty of one hundred-year old bridges that still move, some parts will last that long, but designers need to be aware that they will rust and break, requiring grease and updates (Alison 2019). For significant structures, regular inspections will be essential for safety and to maintain the integrity of the structure.

Kinetic Failures: It is important to review kinetic failures and the possible reasons that could affect future kinetic designs. Olympics Montreal Stadium, Miller Park, and BC Place Stadium are all examples of kinetic structures that had major complications. Asefi (2010) lists various dilemmas that have resulted in failed kinetic structures: clients not adhering to the service plan, insufficient team collaboration, not correctly accounting for loads, poor material choice, and poor waterproofing systems. In landscape, similar problems may be exacerbated.

The Olympics Montreal Stadium incorporated the first modern retractable membrane roof. However, it was not completed in time for the 1976 Olympic Games because the supplier could not supply the membrane on schedule (Asefi 2010). It was later completed in 1987. However, two years after the installment, the membrane tore and a few years after that, in 1991, it was severely damaged by high winds. Later, in 1996 scaffolding erecting for a routine maintenance check tore the membrane again. In 1997 the tensile membrane was replaced with a static cover, but it too has had problems.

The stadium had endless problems and several reasonings were discovered. First, the Polyvinyl chloride (PVC) - Aramid fabric was a poor choice because it is rigid and brittle requiring the seams to be perfect to prevent leaks. The membrane tore several times and small tears were also discovered in the seams. Second, the Montreal weather conditions of extreme snow loads were inadequately calculated for in the cable strength. Third, the design team did not work together with the engineers from the beginning through to maintenance checks.

<u>Cost:</u> Additionally, a major issue with kinetic spaces is their steep costs (Takeuchi 2012). Usman Haque reveals that complexity logistics and costs can prevent designs from being realized unless an investor or sponsor is involved (Bullivant 2006). However, Megahed (2017) alternatively points out that kinetics could lead to cost savings with function sharing or energy efficiency and kinetic stadiums have proven to offer increased revenue (Riberich 2009). The benefits and costs involved will have to be weighed carefully for each project.

<u>Post-Occupancy Evaluation:</u> Finally, due to the novelty of kinetic spaces, post-occupancy evaluation (POE) will be key to the future of kinetic landscape architecture. POE allows users of kinetic spaces to answer important questions that designers cannot comprehend alone. It can answer questions like what are the adverse effects of kinetics on humans? Or how much change is too much change for humans? Or what are the unforeseen benefits or problems of kinetics?

Analysis / Conclusion

This chapter was organized according to a typical landscape architecture stage process allowing kinetic knowledge to be displayed in the appropriate steps for ease of integration into the profession. Kinetics can be introduced at many stages of the design process and by different stakeholders or professionals. Specifically, this chapter was divided into three sections: (1) defining the problem and schematic design, (2) design development, and (3) construction, occupation, and management.

The trends provided by James Alison are powerful in that they give a real sense of the current state of the production of kinetic structures. Particularly noteworthy is the trend towards more concern for aesthetics. This indicates that projects previously monopolized by other disciplines could include landscape architects for a more aesthetically pleasing design. For example, moving bridges that also include landscape features.

Defining the Problem and Schematic Design: If the budget and time allowance creates the opportunity for more advanced kinetics that is great, but there is almost no excuse not to include kinetics. There are options available to meet a variety of needs: the movement can be simple and human powered, only requiring the will of the designer to implement the design.

Movement: This chapter's movement section is the heart of kinetics, and the ways and the means are fundamental to a quick two-part classification of kinetic options. If designers take away one thing, it is to choose the verb and the adjective for the mechanism's movement and the most prominent questions are attended to.

The degrees of freedom are an integral part of this thesis, and it is imperative that designers understand how the six possible degrees work (Figure 4.1). To best design movement, designers need to think in the realm of the six degrees. The diagrams created by Schumacher, Vogt, and Schaeffer (2010) offer a concrete visualization of all movement and become essential categorizing and comparing projects in Chapter Seven.

The most substantial learning curve appears with the movement and operation sections of design development as they are not discussed with typical landscape architecture and can blend into the role of a mechanical engineer. An organization like HMS should be created to unite kinetic architecture and kinetic landscape architecture for an exchange of information. Having an organization and the associated conferences can also help increase the awareness of kinetics.

Alternatively, HMS is currently trade-organization focused, but it could expand to include a student outreach program.

Materials: The author believes smart materials and specifically shape memory alloys show extreme potential and predicts further integration of such materials will be seen in both architecture and landscape architecture. The construction of innovative designs is always possible, but this section is unique in that the discovery and availability of materials are out of the scope of landscape architecture. Landscape architects already experience this conundrum with typical landscape architecture materials, but to increase the application of kinetics, companies will need to be aware of the need for kinetic landscape architecture materials and technology.

Operation: The six types of controlled movement developed by the Kinetic Design Group offer a lot of potential for categorizing kinetic systems (Fox and Yeh 1999). However, with so few existing projects in the three most advanced types of controlled movement, it did not make much sense.

The technology section is packed with inspiring possibilities, particularly by Cantrell and Holzman (2015). Yet, the current state of the landscape architecture profession does not seem very receptive to technology. The author believes that landscape architects may resist advanced technology because of the struggle with trying to be ecologically conscious and blending with a natural aesthetic. The opinion that technology introduces unnatural materials and artificial environments opposes those intentions. However, it is possible to have both by using natural materials, simple mechanisms, and discreet design, all of which are currently being done in landscape architecture.

As the technology of robots and artificial intelligence continues to advance, it is best to be aware of the opportunities such technology can provide for a kinetic design within a landscape. Kinetics is the perfect application for AI; it takes what AI is good at and applies it to a spatial setting – an intelligent environment. This kind of artificial intelligence could potentially not only emulate human intelligence but the intelligence of nature.

It is already important for landscape architects to stay up to date with the latest products, but it is even more vital with quickly advancing technology like kinetics. The design itself must include 'changeover flexibility' allow for the kinetic space to be easily updated.

A significant idea presented in the operation phase is choreographing movement. The author had not learned of the concept of choreographing kinetics when designing the projects in Chapter Three and it would likely have led to better designs. Particularly powerful is the concept of the user choreographing their own movement, and this ties directly into research from Whyte (1979) and the Kaplans (1978), but their research will need to be replicated to consider more technologically advanced environments.

Time and time perception are essential to choreographing and do not have to be an uncontrollable phenomenon to the designer or the user. Time is the fourth dimension, and kinetic designers will need to think in that realm, taking into consideration how designs change over time. Landscape architects are already doing this, differing only now at an accelerated temporal scale.

Construction and Maintenance: There is an absence of design standards for kinetic architecture and kinetic landscape architecture. Engineers must borrow crane or highway safety standards which are not always similar to a landscape. With safety being such a major concern, this could be a necessary future advancement.

There are many unknowns with kinetics, for example, the longevity and durability with unprecedented mechanisms. Maintenance training can be forgotten about with typical landscape architecture, but with kinetics incorporated it is important for clients to understand that the structures require continued maintenance in addition to the plant material. The implementation of post-occupancy evaluation as more projects are built will create an opportunity to eliminate the guesswork currently required by designers.

CHAPTER 5

EXISTING KINETIC DESIGN TOOLS

There are several existing tools created by various authors to help reduce the complexity of kinetic design. This chapter categorizes and analyzes existing methods and points to improvements to create new or improved tools. Specifically, this chapter is investigating whether there should be design tools unique landscape architecture.

There are three types of tools that were identified in the process of the research: design process, evaluation, and classification. Within the three typologies, the author chose nine tools discovered during the process of this research to analyze based on their (1) applicability to landscape architecture, (2) usefulness based on the needs identified in Chapter Three, and (3) if the tool was understandable or if the designer(s) explained the tool enough to analyze it. The process of finding the existing kinetic design tools lead directly to a list of tools that have not been created. The three categories were created by the author after the nine tools were collected. So far, all tools that were encountered during this research fit within the three categories, but they are open for revision.

The tools were evaluated in the following ways: (1) explicating the positives and negatives associated with each method, (2) their applicability to landscape architecture, (3) their ability to be used immediately or their need for modification, and (4) how useful they would be to a designer. The author was then able to identify a series of desirable traits that would be relevant in creating a new tool and determine if there should be a unique tool to landscape architecture. Lastly, as there are multiple options for tools that can be created, the analysis indicates the type of tools that should be made first; these are then later presented in Chapter Seven.

Design Process

Design process tools are used to guide the designer through the entire process of a design project that contains a kinetic component. A designer would begin using the tool at the conception of the kinetic idea and reference it at each step of the design process.

Naglaa Megahed (2017) created a set of kinetic design strategies based on a comparative analysis of existing frameworks and case studies (Alkhayyat 2013, Fouad 2012, Asefi 2009, Asefi and Foruzandeh 2011, Knippers et al. 2012) (*Figure 5.1*). These strategies show her proposed kinetic design process from design generation to management. Megahed invites researchers to debate her framework and improve upon it in future studies.

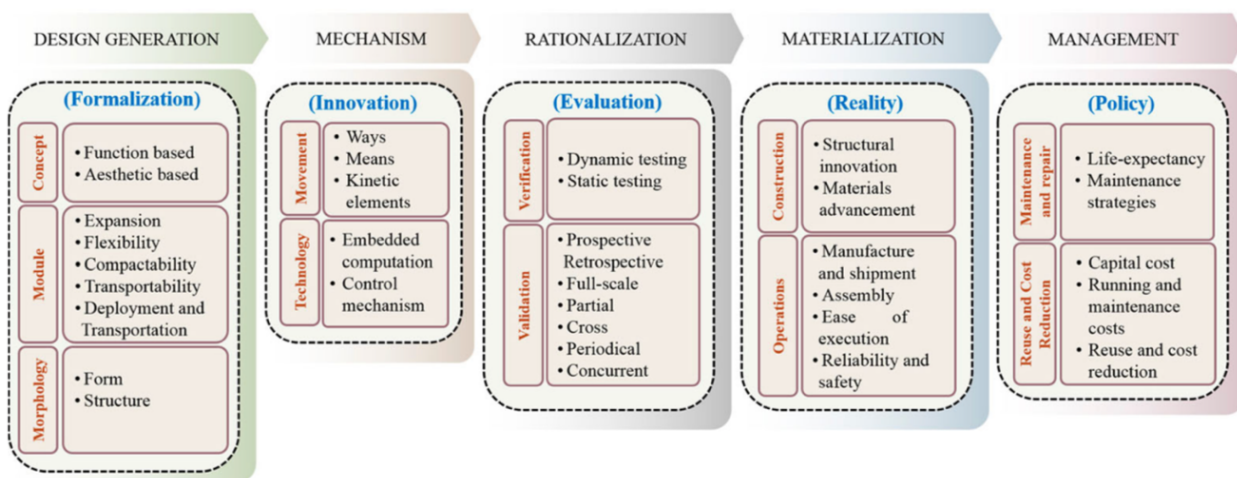


Figure 5.1. Megahed's Design Strategies in Kinetic Architecture

Design generation begins with differentiating between a functional or aesthetic purpose which is a good way to start a kinetic project. This decision greatly affects the concept sketches that are also formed in this sub-step. The next section, ‘module,’ seems mislabeled and poorly defined. The author believes the bullet points are correct in that this is the appropriate time to decide how the kinetic structure should perform and what it can do, however, Megahed (2017, 141) has called it module because she believes this is when “modular components [are] to be sketched, modeled, and fabricated.” Yet, not all kinetic designs can or should be modular so it should not necessarily part of the design process. The design generation stage ends with giving the kinetic concept a form and structure, thus completing the schematic design phase.

Step two is Mechanism; it is unclear why this step is subtitled ‘Innovation’ when all stages should include some level of innovation. Most importantly, this tool includes a distinction between the ways and the means which seem to be the most fundamental kinetic classifier.

Step three is Rationalization with the subtitle Evaluation. Again, this is a confusing choice of titles as they do not seem to fit the described characteristics of the step. Verification refers to “verifying documents, designs, codes, and programs” (Megahed 2017). Validation refers to prototyping. This step is not well explained, and it is unclear what all the bullet points mean. Megahed uses several pages to explain her kinetic strategies tool yet that was not enough for a reader to completely understand what is happening in each step.

Step four and five are reasonably straight forward, but in the construction step she uses the term ‘structural innovation’. It is unclear what she means by this term and why it is happening in stage four. Megahed does not fully discuss these final two steps, but it should be noted that there is a general lack of literature available discussing kinetic construction, operations, maintenance, and cost.

Megahed's strategies are made for kinetic architecture and are mostly applicable to landscape architecture. However, it is abstracted and separated from the staged process model professional architects or landscape architects typically use. A better approach might include most of these steps but integrated into landscape architecture's existing design process. These strategies are the only tool of its kind located during the process of this research and despite the imperfections, has greatly influenced the design process portion of this thesis.

Evaluation

An evaluation tool enters the design process in the schematic design phase for inspiration but is used in the design development phase for more specific details. It can be used to compare the details of individual projects or categories of projects and appraise their benefits and disadvantages.

Asefi (2009) created a table of evaluation criteria for kinetic projects (*Figure 5.2 and 5.3*). Instead of evaluating individual projects he has used it to evaluate kinetic typologies. It is meant to help choose the best general type of kinetic solution that can then later be narrowed down to a specific mechanism. He proceeded to use the evaluation method to analyze tensile member structures, tensegrity structures, pantograph structures, reciprocal frame structures, and spatial frame structures.

Main evaluation criteria for transformable architectural structures

Design	
Expansion and flexibility	The ability of the structure to be used for multi-purpose applications and expansion by the assembly of several individual modules.
Compactability and transportability	The degree of compactness in fully folded configuration. The ability to be applied to portable architecture.
Structural stability and deformability	The stability of the structure before, during and after transformation. The ability of the structure to respond to changing loads.
Architectural obstruction	The affect of transformation on the function of the architecture.
operating system	The complexity of the operating systems and their effects on the architectural design arrangement.
Construction and operation	
Reliability and safety	The complexity and safety of the construction process and the safety of the structure in severe environmental condition and during transformation.
Auxiliary equipment	The equipment required for operation and stability of the structure and construction

Figure 5.2. Asefi's Evaluation Criteria

	equipment.
Manufacture and shipment	The difficulty of manufacture of structural and architectural components and shipment.
Maintenance and costs	
Life-expectancy	The expected life-time of the structure.
Maintenance management strategies	The complexity of the maintenance issues and the strategies for replacement of the components and responsive maintenance in unexpected conditions.
Capital cost	Cost of design, site preparation, manufacture and construction.
Running and maintenance costs	Costs of cleaning and regular maintenance and responsive maintenance.
Application	
Possible applications (small-scale, Medium-scale and large-scale	The possibility of the application of the structure for permanent and temporary usages - as a whole building or transformable section attached to static architecture

Figure 5.3. Asefi's Evaluation Criteria Continued

Asefi's method of providing an evaluation of general categories of kinetic structures is a good approach to quickly help designers reduce the number of options they face when beginning the design process. A collection of his tables for all identified types of kinetic structures would be a great resource for kinetic designers. Whereas creating criteria for every individual type of kinetic mechanism is a daunting and nearly impossible task, establishing criteria for general categories is possible. These tables are directly applicable to landscape architecture and provide a sense of reality in terms of construction and maintenance that is missing from other kinetic design tools. See Appendix D for an example of Asefi's criteria applied to tensile member structures.

Classification

Classification tools can be used to see the many possible options a project has with kinetics. A classification tool enters the design process in the schematic design phase for inspiration but is used in the design development phase for more specific details.

Several authors have attempted classification systems for kinetic approaches; Popper (1968), Fox and Yeh (1999), Parkes (2009), Asefi (2010), Schumacher, Vogt, and Schaeffer (2010), Ramzy and Fayed (2011), and two by Megahed (2017). They are reviewed in the subsequent paragraphs. There are many ways to categorize kinetic projects, however there currently is not a method specific to landscape architecture. Landscape architecture projects will be different due to the dynamic quality of the natural environment, the scale of such projects, and their purpose. This thesis aims to analyze current classification systems and potentially create one unique to landscape architecture.

Frank Popper produced the first kinetic categorization system, influencing key literature, projects, and refined classification systems to this day. He listed twenty-seven elements found within kinetic art and grouped them into five categories: intellect, environment, sensibility, action, and transcendence (Popper 1968). Popper's system is a bit abstracted from landscape architecture with terms like sexuality and hypnosis, but it still has some relevant elements found in kinetic art like 'Identification with Nature' and 'Life and Vitalism' (*Appendix C*). 'Life and Vitalism' is an element in art that identifies with life, like the organic growth of a city.

Megahed's two classification systems are the most recent attempts to classify kinetic approaches (*Figure 5.4 and 5.5*). The most admirable trait of his conceptual framework (*Figure 5.4)* is the division of spatial and non-spatial designs. Non-spatial kinetics refers to changing features like color, light, or texture versus spatial kinetics that can involve changing the dimensions or arrangement of a space. This separation is essential because it is fundamental for disciplines like architecture and landscape architecture that design spaces. The typical 'ways and means' is used to describe how mechanisms move and adequately does the job for both the spatial and non-spatial categories. Another positive of this system is separating function and aesthetic based purposes, displaying the benefits of the design and would be good information for designers to know. The terms 'structural innovation' and 'materials advancement' seem like odd choices and could be improved upon for easier understanding. Lastly, including the entire section on *static approach* does not appear to be very relevant to what a kinetic classification system is aiming to do. It is hard to find anything in that category that would be beneficial to include in a classification system for kinetic landscape architecture.

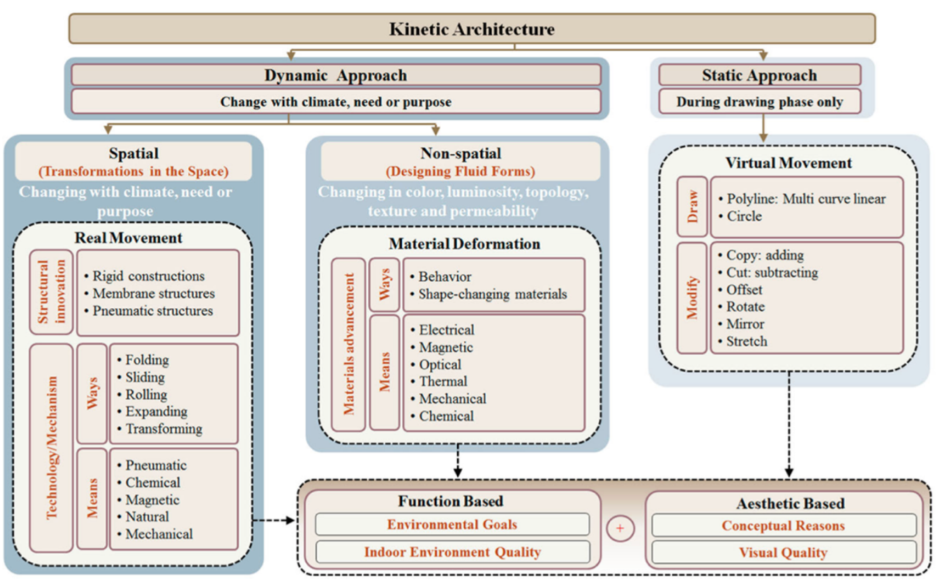


Figure 5.4. Megahed's Conceptual Framework for Kinetic Classification

Megahed (2017) and Schumacher, Vogt, and Schaeffer's (2010) classification diagrams and various other versions can be found in most literature on kinetics (*Figures 5.5, 5.6, and 5.7*). These figures display some of the many movement options available to designers. They clearly and easily depict types of movement and start to show the many options that can be combined, altered, and tested for different applications. The three tools not only display movement diagrams but categorize them. This is the purpose of a classification system. The movement diagrams are very useful for any designer interested in kinetics as they lay out the basic methods of movement without the need for much prior knowledge. These existing diagrams apply to both architecture and landscape architecture, so there does not need to be a unique system for landscape architecture. Megahed's classification of geometric transitions tool was the most influential in the process of this research.

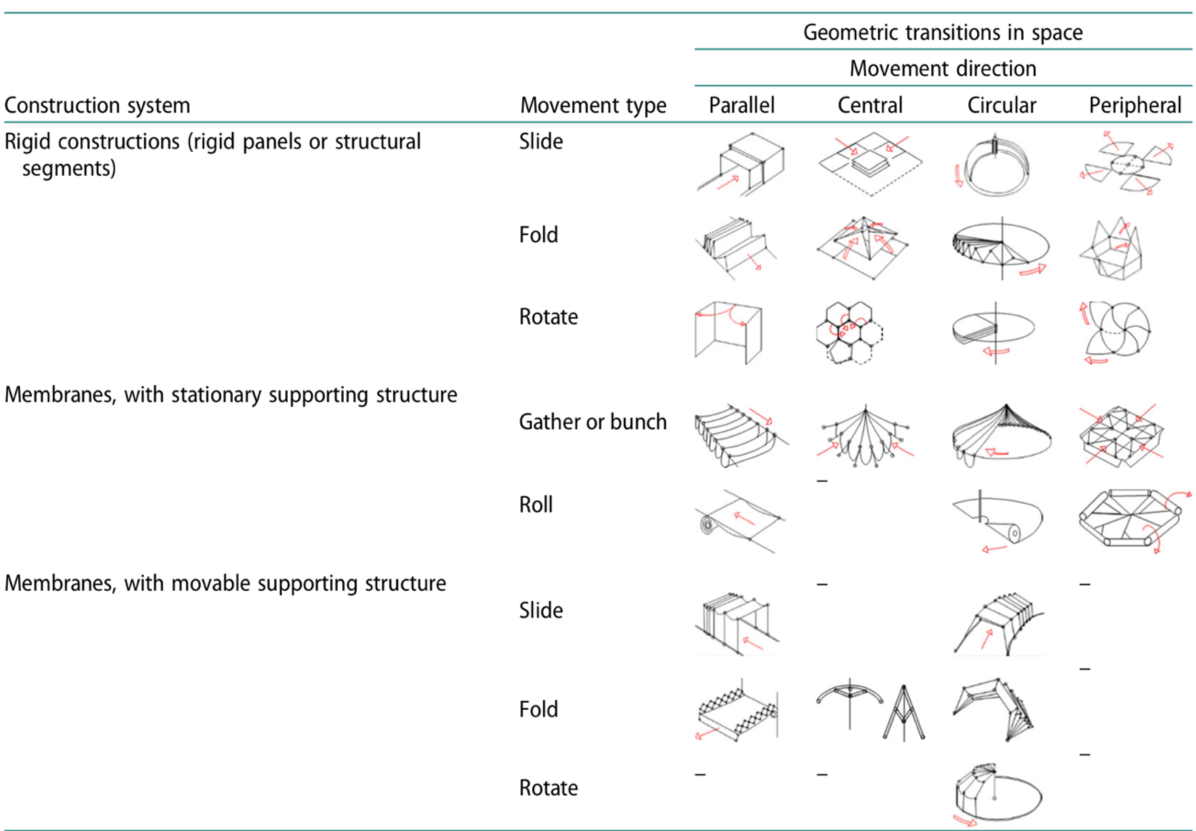


Figure 5.5. Megahed's Classification with Geometric Transitions in Space

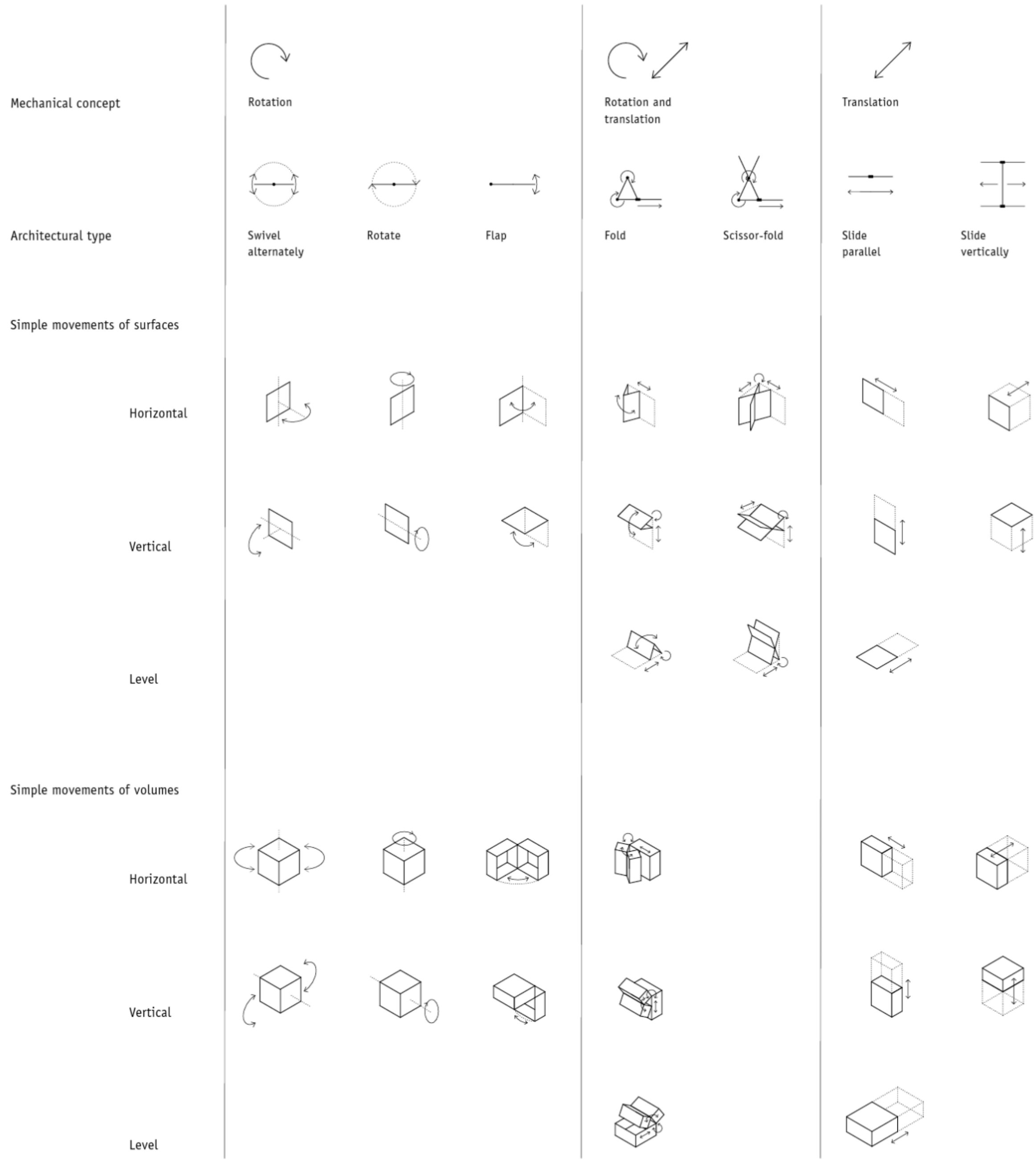


Figure 5.6. Schumacher, Vogt, and Schaeffer’s Movement of Rigid Building Elements

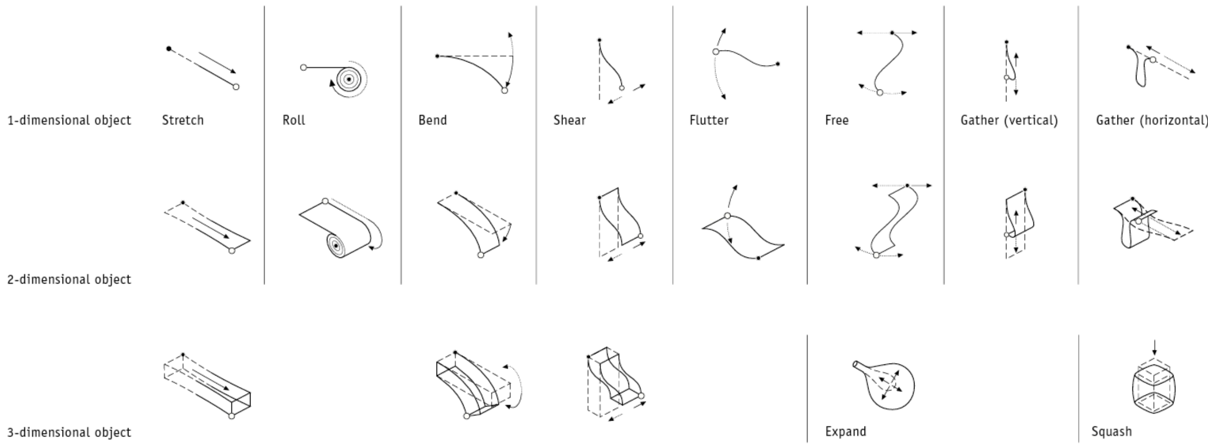


Figure 5.7. Schumacher, Vogt, and Schaeffer's Movements of Deformable Building Elements

The Kinetic Design Group crafted a kinetic categorization focusing on the bigger picture, with the three basic typologies being dynamic, deployable, and embedded systems (*Figure 5.8*). Founders Michael Fox and Bryant Yeh introduced them in 1999 and Fox continues to discuss them with Miles Kemp in their book *Interactive Architecture* (Fox and Kemp 2009, Fox and Yeh 1999). The authors describe an embedded system as that which controls the building as a whole in response to internal and external stimuli. They provide the example of a building adapting to a seismic incident, stating that static buildings have to be over-engineered whereas with Buckminster Fuller's concept of 'emphemeralization,' or doing more with less, initiating an active control system can strip excess structure from the building (Fox and Kemp 2009, 47). As discussed previously, deployable systems allow for mobility using deconstruction and reconstruction capabilities. And dynamic structures, the most common of the three, are typically smaller systems within the building but are not necessarily integral components like movable partitions and kinetic furniture (Fox and Kemp 2009). They further break down the dynamic category into mobile, transformable, and incremental systems. Mobile components include pieces that can be moved throughout the building, transformable components take on different spatial configurations, and incremental components can be added to or subtracted from like modular units (Fox and Kemp 2009).

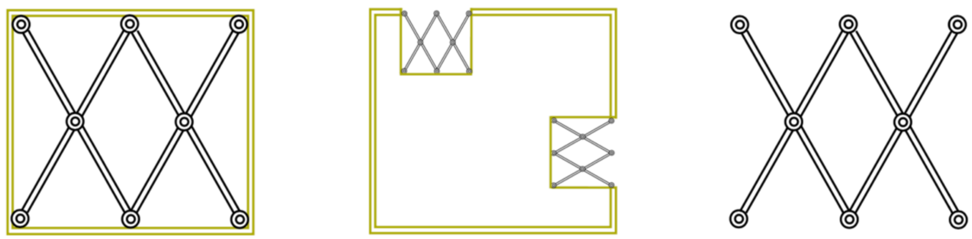


Figure 5.8. Kinetic Design Group's Kinetic Architecture Typologies. From left: embedded, dynamic, deployable

The Kinetic Design Group's categories are good for the first level of separating kinetic projects. They are easy to remember and have quality representational graphics to accompany the terms. However, the system is far too simple to be very useful to designers.

Amanda Parkes created this two-part system as part of her Massachusetts Institute of Technology (MIT) dissertation on kinetics (*Figures 5.9 and 5.10*). Parkes (2009) gives definitions of each element which is a necessary characteristic of a good classification system:

- Material: physical qualities of the matter in which the motion is embedded, affecting the perceived nature of the motion
- Mechanical: physical and spatial design of how the motion is created, based on the view of the user and observer of the system
- Behavioral: temporal control structure of the motion
- Amorphous: entirely malleable
- Layered: a mixture of rigid and flexible materials

- Skeletal: structure of rigid interior with a malleable exterior
- Rigid: a solid structural material
- Rotational: motion moving around a central axis
- Linear: motion expanding outwards along a straight path
- Radial: motion expanding outward and inwards from a central point of a circular form
- Speed: basic velocity control
- Acceleration: increase or decrease in velocity can be cumulative with sequenced playback
- Direction: basic directional control
- Twitter: addition of 'noise' into the motion playback, adding a randomized variability to playback
- Delay: creates an intentional pause in playback
- Pattern: allowing a motion composition to be sequenced

Figure 5.10 is an expansion on the mechanical row from *Figure 5.9* showing different possibilities of accomplishing the same type of movement and degrees of complexity, both would be major benefits to designers when looking at options for a design problem. Parkes' system (2009) has legible symbols to graphically represent each of the components and looks to be easily expandable as additional elements need to be added to the system. Parkes' system is comparable to Megahed's (2017) and Schumacher, Vogt, and Schaeffer's (2010) as it includes movement diagrams.

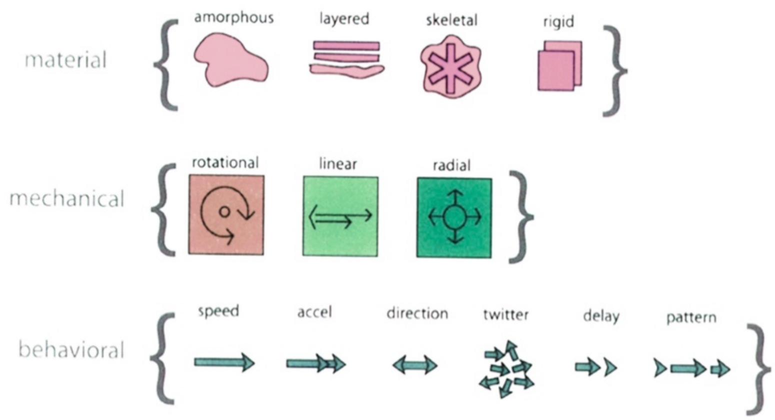


Figure 5.9. Parkes' Motion Design Parameters

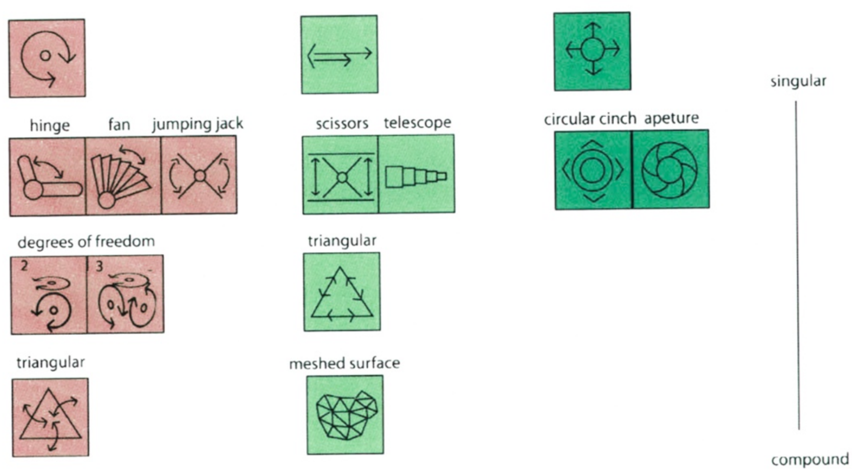


Figure 5.10. Parkes' Families of Mechanical Elements

Ramzy and Fayed have also created a kinetic classification system and show it being tested in (*Figure 5.11*). Ramzy and Fayed (2011) use the term 'kineticism' to describe the amount of movement that is possible with each system; for example, a kinetic system can have partial motion, inclusive motion, or motion that depends on small movable units. 'Control technique' has six control options developed by researchers of the Kinetic Design Group; internal control, direct control, indirect control, responsive indirect control, ubiquitous responsive indirect control, and heuristic responsive indirect control (Fox and Yeh 1999). These six types of controlled movement are described in detail in the Design Process – Mechanism – Movement section. 'System configuration' incorporates the Kinetic Design Group's classification system (*Figure 5.8*). 'Control limit' refers to "the degree of environmental changes offered by the system, and how much difference does it make in regard of human comfort and interaction with the building context" (Ramzy and Fayed 2011, 176).

Kinetic system	Kineticism	Control technique	System configuration	Control limit	Cost
Skin units systems	Limited	Direct or Responsive	Embedded	Minor	Small
Retractable elements	Medium	Internal or Direct	Embedded	Medium	Medium
Revolving buildings	Major	Direct or Responsive	Dynamic	Significant	Big
Biomechanical systems	Variable	Responsive Indirect	Dynamic or Embedded	Variable	Huge

Figure 5.11. Ramzy and Fayed's Kinetic Classification

Ramzy and Fayed's system offers some great promise with their 'kineticism' feature, the attribute and would be an excellent addition to any kinetic classification system. And 'control limit' brings a more intimate and human-centric focus to the system missing from other methods. Lastly, the cost is a topic pertinent to designers and clients and could have a significant influence on the type of kinetic system selected. Classifying cost is less important at this stage of advancing kinetics in landscape architecture without many built examples to form a cost estimate from, but it may be important in the future.

Analysis / Conclusion

The three types of kinetic design tools identified during this research are design process, evaluation, and classification tools. The purpose of the tools is to make designing kinetics easier for architects and landscape architects.

The design strategies presented by Megahed are flawed but offer a good summary of her idea of the kinetic design process. In Chapter Four this process has been expanded and embedded within a general staged process model used by landscape architects. Asefi's tables for evaluation criteria are ready to be used as is and hold valuable information for the five categories of kinetic structures that he analyzed. More tables should be created for additional categories like pneumatic structures or track system structures.

After reviewing the several very different classification systems, it is possible to identify a set of desirable traits that could be important in an improved classification system. These include:

- A 'kineticism' rating
- A human component
- Graphic representation of elements
- Definitions to accompany each component
- A classification system that is not finite and is easily added to as new technology comes along
- Differentiation between spatial and non-spatial kinetics
- Categories of material, means, ways, control system, instigator, purpose, cost, and application

The best existing methods are those that include movement diagrams: Parkes' (2009), Megahed's (2017) and Schumacher, Vogt, and Schaeffer's (2010). And more than one classification system can be used, as it would be difficult to create one to classify everything. Parkes' tool will need to be expanded in order to offer full value. In its current state, it demonstrates the methodology, but only has a few possible mechanisms displayed. Graphical representation seems to be the best method of displaying a classification tool because it adds a layer of knowledge by visually showing the mechanism versus just using the word. Megahed's and Schumacher, Vogt, and Schaeffer's movement diagram tools are ready to be used now, but additional methods of movement can always be added to them.

Ramzy and Fayed's (2011) is more comparable to a catalog like that shown in Chapter Six. It does allow grouping under the displayed terms, like classifying the cost into a small, medium, big, or huge category, but does not contain hierarchy to the level that Parkes' does with the scale from singular to compound features.

However, nothing about this analysis is unique to landscape architecture. The above traits would be part of a general kinetic classification system applicable to architecture and landscape architecture. Through the process of this research, it was realized that it is too early in the establishment of kinetic landscape architecture to create a system unique to landscape architecture. There are not enough built projects to form a consensus on traits unique to landscape architecture. In this situation, until there is more data available, landscape architects should use a general kinetic classification system. The same applies to the evaluation criteria and design strategies. Even in the creation of more projects in the future, it may be realized that there does not need to be unique design strategies, evaluation criteria, or classification systems.

It is difficult to recommend a singular classification system that landscape architects should use because they are not all classifying the same elements. Instead, they have been presented here so that designers can choose which best fits their individual needs. To create a better generalized classification tool, several of the tools could be combined using the list of desirable traits. However, based on the desires indicated in Chapter Three and the discoveries with this chapter, the author believes there is less of a priority to create a classification tool.

Instead, an improved design process tool that is more detailed than Megahed's (2017) and is tailored to the landscape architecture design process should be created first to show designers a precise approach to conquering the overwhelming kinetic design process. Additionally, another type of evaluation tool is needed to evaluate and compare individual kinetic projects, not just types of kinetic structures. These tools were not encountered during this research process, so two proposed tools are presented in Chapter Seven that meet these criteria.

CHAPTER 6

KINETIC CATALOG

Landscape architects interested in kinetics need an understanding of existing kinetic projects to kickstart their own design process, a catalog is the quickest way for designers to get a glimpse of what kinetics can be and learn many of the kinetic mechanisms currently used. This research did not encounter any existing kinetic catalog for any discipline. The catalog is used as part of precedent research. Someone might not understand what kinetics is, but after viewing a catalog of projects, they would have a more coherent idea of what kinetics entails. The catalog provides a quick synopsis of the projects and is not meant to show in-depth case study knowledge, but instead is meant to be a point of departure for designers to then investigate projects further.

The catalog is a classification tool and belongs in that category of design tools mentioned in Chapter Five. It is a collection of kinetic projects organized into seven categories of application. This is only a selection of existing projects, and all the projects listed in Appendix E (currently two hundred and eighteen projects) should be incorporated into the catalog and kept up to date as new projects come along. The categories are vertical plane, ground plane, roof/canopy, sculpture, object, furniture, and architecture/structure. The application categories were created after an initial gathering of more than one hundred kinetic projects. They are organized by the application because that is most likely the first known characteristic following the decision to make a kinetic project. It is also the most convenient way for designers to look at existing projects for inspiration. Each category provides a selection of ten projects with the exception of the ground plane category.

This thesis does not claim to include all kinetic projects in existence, but any projects discovered through this research were considered for the catalog and listed in Appendix E. Projects were chosen for the catalog based on the following criteria: (1) availability of project information, (2) applicability to landscape architecture, (3) originality, and (4) the best representation of their type of kinetic mechanism. The projects that were selected impact the analysis of the catalog and it should be recognized that different projects might yield different results. The projects were chosen to give a broad idea of kinetic possibilities and similar projects are not shown. Due to time restrictions, the catalog is limited to a total of seventy projects or ten projects per category. The restriction also allows designers to review a quick synopsis of some of the most relevant projects by category without having to sort through a large number of entries.

The columns of information listed in the catalog were chosen for designers to be able to (1) research the project further, (2) simply understand the kinetic mechanism, and (3) to visualize the project. Creating a case study catalog of kinetic projects will allow for comparative analysis as well as the study of patterns in the location, designers, application, materials, purposes, types of movement, and the operating system.

The catalog serves as a tool itself but also aids in the creation of more kinetic design tools. A catalog was critically necessary to create the Degree of Adjustability Chart and Kinetic Design Decision Chart shown in Chapter Seven. Moreover, the catalog would be imperative to develop a new or improved classification system. It also dictated much of the literature review. As projects were entered into the catalog, their materials, operation mechanisms, and methods of movement all led to further literature and a better idea of the topics that needed to be discussed.

VERTICAL PLANE

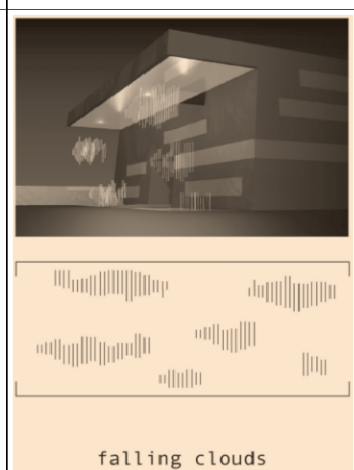
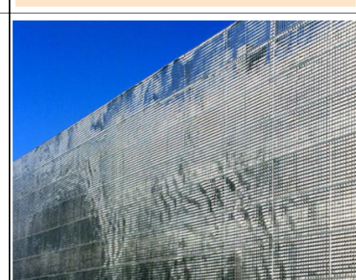
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.1		HelioTrace Façade System	Hoberman Associates and SOM	N/A	2010	Concept	HelioTrace's shade panels can individually move in relation to the time of day and year, providing extended control over the indoor environment and energy savings.	Sun-shading, Heat Gain	Complex series of slats and hinges that move and rotate	Modular External Perforated Aluminum Shade Panels, Glass	Electromechanical actuator with computer-driven climate data, building operating schedule, etc.
6.2		Media - TIC Building	Enric Ruiz Geli of Cloud 9	Barcelona, Spain	2010	Built	Inflatable ETFE cladding moderates daylight and heat gain within the building by inflating or deflating different pieces of the facade. Nitrogen gas is controlled by sensors and pumps to alter the heat gain and inflate the façade, providing a structurally light and unique pillow-like look.	Sun-shading, Heat Gain	Pneumatic	ETFE, Nitrogen gas	Temperature sensors, humidity sensors, pressure sensors, and control pumps
6.3		Pitterpatterns	J. Mayer H. Arkitekten	Stuttgart, Germany	2001	Built	The building treats collected stormwater and pumps out 'artificial rain' through two hundred openings. The walls are reconfigurable with computer-controlled water droplets that can be formed into writing, patterns, and allow access or exits.	Aesthetic	Computer-controlled Water	Water Tank, Filter System, Pipes	Custom Pitterpatterns computer software to control droplets
6.4		Wind Veil	Ned Kahn	Charlotte, North Carolina	2000	Built	A 260' long by 6-story tall facade of a new parking garage was covered with 80,000 small aluminum panels that are hinged to move freely in the wind. Viewed from the outside, the entire wall of the building appears to move in the wind and creates the impression of waves in a field of metallic grass.	Aesthetic, Ventilation, Sun-shading	Hinge	Aluminum Panels	Passive, Wind

Table 6.1. Vertical Plane (1)

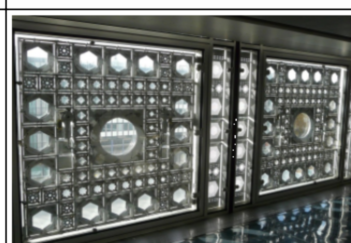
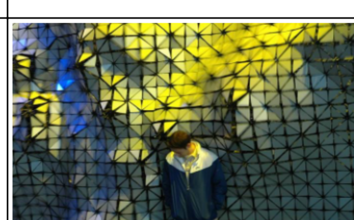
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.5		EWE Arena	Architekten Stuttgart, Arat – Siegel – Schust	Oldenburg, Germany	2005	Built	The mobile sunscreen rotates 200 degrees around the building following the position of the sun.	Sun-shading, Heat Gain, Solar Energy Maximization	Track System	Precast Concrete Ring, 72 Photovoltaic Modules	One powered roller and one freewheeling roller per segment (18 total) driven by an electric motor
6.6		Church of the Sacred Heart	Ilmann Sattler Wappner Architekten	Munich, Germany	2000	Built	The full height church doors rotate open. Smaller doors are located within the doors when the façade isn't open.	Multi-functional Space	Rotating with swivel-joint roller bearing at the top of the column	Steel, Glazing	A hydraulic drive is located in a plant room below ground. The operating switch is regulated by a dead man's control and wind sensor for safety.
6.7		Theresienwiese Service Center	Staab Architekten	Munich, Germany	2004	Built	The center houses a police station, firestation, a red cross location, and is active with Oktoberfest. The design needed to visually simple and non-obtrusive.	Security, Discreetness	Rollers move in a steel channel with an overhead pulley	Copper, Steel Channels	There are two electric motors with cable winches per gate that are in an underfloor channel at the base of the gates.
6.8		The Institute of the Arab World	Jean Nouvel in collaboration with Architecture-Studio	Paris, France	1987	Built	Kinetic geometric motifs have 240 motor-operated apertures that open and close due to the intensity of light. Historically the institute is the seminal kinetic façade project, but sadly the system no longer works due to mechanical problems.	Sun-shading, Heat Gain	Apertures open and close	Glass, Steel	The façade has motor-controlled apertures reacting to sensors measuring the intensity of sunlight. The façade can not be controlled by humans.
6.9		Storefront for Art and Architecture	Vito Acconci and Steven Holl	New York, New York	1993	Built	The exhibit space has a series of hinged panels that blur the inside and outside when opened. The façade is constantly changing as are the exhibits.	Aesthetic, Ventilation, Natural Lighting, Multiple Configurations that can Adapt to the Current Exhibit	12 Hinged, Rotating or Pivoting Panels	Concrete Board Façade	Manual
6.10		Hyposurface Wall	dECOi Architects	Various	2003	Built	The wall is an interactive mechanical screen surface that deforms in real-time based on sounds, movements of people, weather, or electronic input.	Interactive	Flexible panels move forward and back	Faceted Metallic Surface	A matrix of actuators (pneumatic pistons) move based on positional information and an array of electronic sensors.

Table 6.2. Vertical Plane (2)

ARCHITECTURE / STRUCTURE

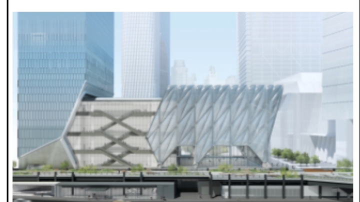
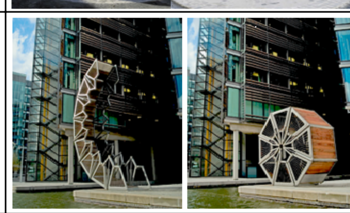
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.11		Gateshead Millennium Bridge	WilkinsonEyre and Gifford	Gateshead, UK	2011	Built	The tilt bridge is operated by hydraulic rams that tilt the structure up and down to allow boats to pass.	Multi-function, Allows Boats and Pedestrians/Cyclists to Share the Space	Tilting, Bearings	Steel	Six Hydraulic Rams and an Electric Motor
6.12		The Shed	Diller Scofido + Renfro	New York, New York	2019	Built	The large architectural envelope slides to expand the capacity to fit an additional audience of 3,000 people. When the shell is closed against the base of the building, the plaza becomes public space. The structure is inspired by Cedric Prices' Fun Palace.	Multi-function, Space Accommodating	Double-Wheel Track Based on Gantry Crane Technology	Four Single-Axle and Two Double-Axle Bogie Wheels, ETFE Panels, Glass	Rack and Pinion drive
6.13		ANZ Stadium	Populous	Sydney, Australia	2003	Built	Renovations in 2003 added movable end stands to the stadium. The stadium offers protection from the elements for 75% of fans.	Protection from the Elements, Multi-functional Space that can Adapt to the Size and Shape of the Event, Passive Ventilation	Folding	Polycarbonate Roof	N/A
6.14		Pfalzkeller Gallery	Santiago Calatrava	St. Gallen, Switzerland	1999	Built	The mouth opens to allow access to an underground space.	Aesthetic, Hide Entrance	Hinged Joint, Fanning	24 Steel Lamellae	Hydraulic Drive
6.15		Rolling Bridge	Heatherwick Studio	London, England	2004	Built	The bridge rolls up to allow boat passage.	Functional Footbridge and Boat Passage	Rolling	Steel, Timber	Hydraulic Pump, Hydraulic Cylinders, 14 Hydraulic Rams
6.16		Shop Entrance	Nickel and Wachter Architekten	Bramberg, Germany	2007	Built	The shop entrance folds out during the day and can be closed at night for security.	Security	Folding, Hinged	Sheet Steel Encasement	The design involves a drive chain with a hand-operated crank handle that turns a ball-bearing-mounted steel crankshaft. The canopy and steps are stabilized by a gas-pressured shock absorber.

Table 6.3. Architecture / Structure (1)

ARCHITECTURE / STRUCTURE

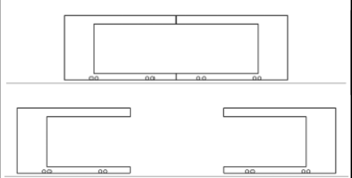
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.17		Spielbudenplatz	Consortium Spielbude Fahrbetrieb Hamburg, Lützow 7 Garten- und Landschaftsarchitekten and Spengler Wiescholek Architekten und Stadtplaner	Hamburg, Germany	2006	Built	Two mobile stages slide on a track system spanning the nearly 1000 foot length of the market square.	Multi-functional Space	Sliding, Rails and Wheels	Hollow Steel Profile, Stainless Steel Mesh	The stages are hydraulically raised before moving allowing the wheels to not bear the weight. Each stage is powered with four electric motors.
6.18		Milwaukee Art Museum	Santiago Calatrava	Milwaukee, Wisconsin	2001	Built	Calatrava designed a sail construction that looks like a flying bird. The kinetic wings have been referred to as brise soleil wings.	Aesthetic, Natural Lighting	Folding	Steel and Reinforced Concrete, 36 Lamellae	Hydraulic pistons operate rotating tubular steel elements connected to one another to create a fluid motion.
6.19		Pegasus Bridge	N/A	Normandy, France	1934 + 1994	Built	The Pegasus Bridge was originally constructed in 1934 and was involved in World War Two. This particular type of moving bridge allows a greater clearance angle.	Clearance, Water Passage	It is formally called a Scherzer rolling lift bascule bridge. The bridge rolls back on curved tread plates attached to the girders of the main span.	Steel	N/A
6.20		Dynamic Tower	David Fisher	Dubai, UAE	N/A	Concept	The skyscraper design consists of 80 floors each able to rotate 360 degrees separately.	Views, Sun Protection	Rotating	The tower's floors would be prefabricated units, made of steel, aluminum and carbon fiber materials.	The rotation would be powered by wind turbines and solar panels.

Table 6.4. Architecture / Structure (2)

FURNITURE

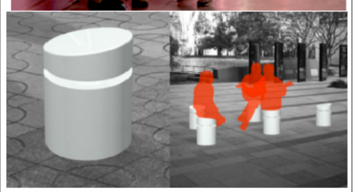
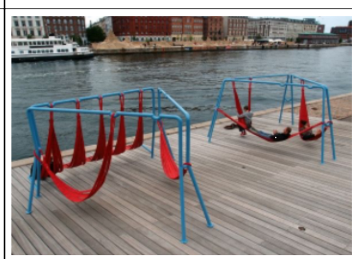
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.21		Erika Mann Primary School	Susanne Hofman Architekten and the Baupiloten	Berlin, Germany	2007	Built	Tables and benches fold up against the wall.	Aesthetic, Space Saving	Folding	Aluminum Sheeting, Pivot Pins, Fabric Webbing, Sliding Stays, Torsion Springs	Manual
6.22		Whirlstools	Yuichiro Takeuchi	N/A	2014	Concept	Whirlstools are interactive urban furniture that dynamically rotate toward each other to encourage conversation.	Interactive, Social Encouragement	Rotating	N/A	N/A
6.23		Coffee Bench	Karolina Tylka of BEYOND	N/A	N/A	Built	The Coffee Bench contains elements that can be rotated around to form different seating and table configurations depending on a user's needs.	Multiple Seating and Table Configurations	Rotating	Options Include: Plywood, MDF, Injection-molded Plastics, Cellulose and Honeycomb Cardboard	Manual
6.24		The Rolling Bench	Sung Woo Park	N/A	N/A	Concept	After a rainy day you can turn the handle on the bench to expose dry seating.	Dry Outdoor Seating	Rolling	N/A	Manual
6.25		Off-ground	Danish Architecture Center	Copenhagen, Denmark	N/A	Built	Off-ground is a playful element where users can choose seating configurations. Options include a low seat, a hammock, and a swing.	Customized Seating Options	Movable Seating Configurations	Rejected Fire Hoses	Manual

Table 6.5. Furniture (1)

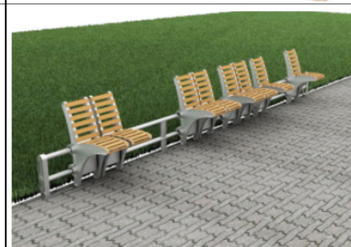
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.26		Ollie Chair	RockPaperRobot	N/A	N/A	Built	Shape-shifting seating is a space saving upgrade to typical metal folding chairs.	Collapsible Seating	Deployable	Wood, Aluminum	Manual with Pull Handle
6.27		Sliding Bench	Muthu Killinger	N/A	N/A	Concept	The Sliding Bench allows users to slide towards or away from other users.	Customization of Seating Arrangement for Groups or Solo Users	Sliding Rails	Wood, Aluminum	Manual
6.28		Adjustable Railing	N/A	N/A	N/A	Built	Bus waiters can adjust the furniture to sit or lean.	Customization of Seating	Rotating	N/A	Manual
6.29		Remote Home - Busy Bench	Tobi Schneidler / Smart Studio	Berlin + London	2003	Built	The remote house is designed as an experiment to test communication between two houses. Sitting on furniture in one country influences the furniture shape in the other.	Interaction, Testing Collaborative Control of Furniture	Strips Bend Up and Down	N/A	Remote Interaction
6.30		Adjustable Airport Seating and Tables	N/A	N/A	N/A	N/A	This airport seating concept has a variety of different configurations to better suit conversations, eating, working, etc.	Multi-configuration	Pivoting, Sliding, Pull Down	N/A	Manual

Table 6.6. Furniture (1)

OBJECT

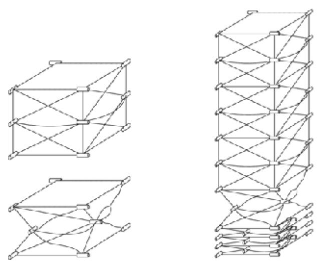
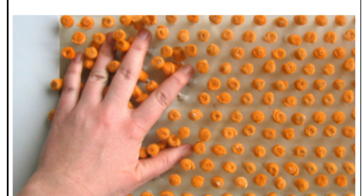
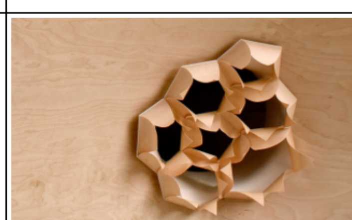
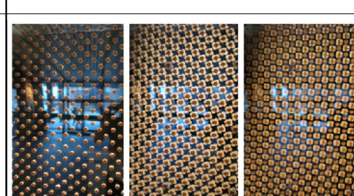
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.31		Hanabi Lamp	Nendo	N/A	2006	Built	When turned on, the heat from the light bulb opens the petals on the lamp.	Aesthetic	Shape Memory Alloy Material	Metal, Bulb	Material Properties Reacting to Temperature
6.32		FAST Mast (Folding Articulated Square Truss Mast)	ATK Aerospace Systems	N/A	2000	Built	Each mast can be stored and then deployed for solar array energy harvesting during International Space Station operations. The mast goes from 8 feet to 115 feet.	Space Saving	Deployable, Folding, Joints	Fiberglass/Epoxy Pultruded Rods	N/A
6.33		Super Cilia Skin	MIT Tangible Media Group	N/A	2003	Built	The skin is a tactile and visual interactive membrane. It consists of an array of computer controlled microactuators (cilia) that are fastened to an elastic membrane. The cilia have ball joints that allow them to move in any direction. The object can move in response to computer relayed patterns and can also copy human or wind implemented movement and play it back.	Harness Wind Energy, Interactive	Ball Joints	Elastic Membrane, Felt	Computer-controlled, or Human/Wind Movement Sensing Actuators
6.34		Hygroskin	MIT Media Lab	N/A	2015	Built	Pine cones have hygroscopic behavior that causes them to swell when moist. This concept is the inspiration behind the material's humidity responsive aperture system.	Move in Response to Humidity	Hygroscopic Apertures	Wood	Humidity Controlled
6.35		4D Printed Self-Folding Cube	MIT Self-Assembly Lab	N/A	N/A	Built	The cube folds when introduced to water. Additionally, several other similar creations move when introduced to heat, light, and sound. 4D printing is adding a fourth dimension of time to a 3D volume.	Prototype for Self-folding Structures	Folding	N/A	Material Reacting with Water
6.36		Adaptive Fritting	Hoberman Associates	N/A	2009	Built	Movable patterns of varying density are made possible by shifting layers of frits.	Control Heat Gain and Light	Shifting	N/A	Motorized

Table 6.7. Object (1)

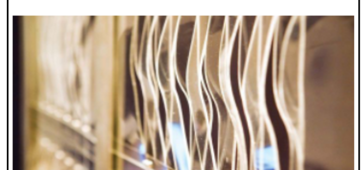
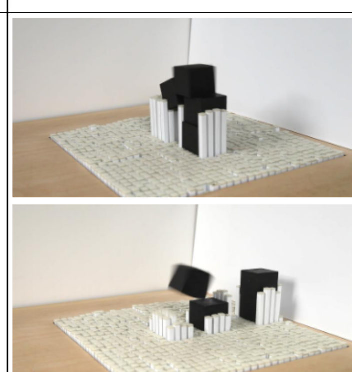
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.37		Rollin	Self-Assembly Lab	N/A	N/A	Built	This was made as an experiment of self-assembly to demonstrate self-sorting and error-correcting structures. When shaken, the parts individually organize themselves into separate color shapes.	Prototype for Self-Assembly	Shape Forming	N/A	Material
6.38		Muscle Tower II	Hyperbody Research Group	N/A	N/A	Built	Pneumatic muscles and jointed bars respond to the surrounding environment. Movement sensors at the four corners move to where the most activity is detected.	Prototype for Kinetic Structures	Bending, Pneumatic Muscles	Aluminum Bars, Iron Connection Spheres	Movement Sensors
6.39		Living Glass	David Benjamin and Soo-in Yang	N/A	2006	Built	The object contains parallel slits that move in the presence of movement. Silicone embedded with the shape memory allow flexinol allows the slits to open and close as the flexinol wires contract. Flexinol can contract 4-5% of its length due to electric currents. The project is thin, transparent, and silent.	The goal was to create "glass" that can open and breath.	Shape Memory Alloy Material	The projects consists of silicone embedded with shape memory alloy flexinol wires.	Microcontroller, Shape Memory Alloy
6.40		Kinetic Blocks	MIT Media Lab - Tangible Media Group	N/A	2015	Built	This object has the ability to move blocks and assemble and disassemble structures. The group tested out three kinds of blocks: plain, magnetic, and kinematic blocks containing internal movable pieces. The object can rotate, translate, catapult blocks and has additional functions with add-on mechanisms.	The purpose was to test the ability to construct and destruct structures using this kinetic object.	900 motorized pins can move 10cm vertically.	N/A	Motorized Pins

Table 6.8. Object (2)

SCULPTURE

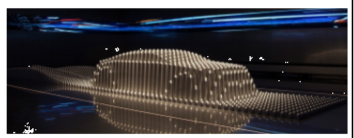
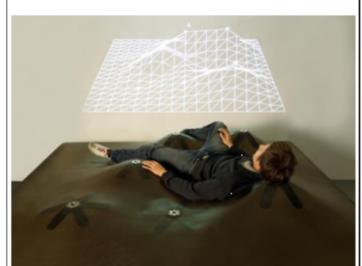
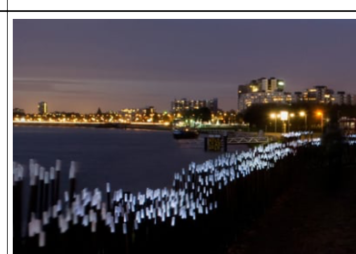
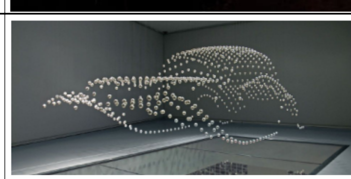
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.41		Ephemeral Structures	ONL (Ossterhuis_Lenard)	N/A	2004	Concept	An inflatable programmable mesh is constrained by structural arms. The mesh works like muscle and reacts to human movement and sound.	Interactive	Pneumatic	Translucent Elastomeric Polymer Skin, Internal LED Lights, Pneumatic Tubes	Pneumatic Actuators, Monitoring Devices of Human Activity
6.42		Hyundai Sculpture	Easywith	Goyang, Korea	2017	Built	The sculpture is formed from moving aluminum pistons. During reactive mode the rods respond to visitors' physical movements.	Advertising	Vertical Piston Movement	1,411 Aluminum Columns	Computer Controlled
6.43		Dynamic Terrain	Janis Pönisch	N/A	2006	Built	Dynamic Terrain is a rubber membrane with mechanical pistons to produce flexible undulations. The spacing of the pistons and the scale of the composition can be modified to fit various needs like an outdoor playground surface.	Flexible Ground Plane, Form-fitting Seating	Mechanical Pistons, Eight Drilling Machines	Rubber Membrane, Metal Structure	Microcontrollers are connected to a computer to operate the drilling machines. The software interface controls a wireframe model in real time. There are also touch sensors on the surface to allow users to move the control points up and down overruling the software.
6.44		Dune	Studio Roosegaarde	Varies	2011	Built	Hundreds of fibers with LEDs and sensors brighten due to the sound and motion of passing people.	Interactive, Lighting	Lighting	LED Lights, Fibers, Sensors, Speakers	Interactive Software
6.45		BMW Kinetic Sculpture	Art + Com	Munich, Germany	2015	Built	The sculpture begins with a chaotic form and takes the shape of a car with a seven minute pre-programmed choreograph.	Advertising	Moving Threads	714 Metal Balls, Metal Threads	Computer Coded Stepper Motors

Table 6.9. Sculpture (1)

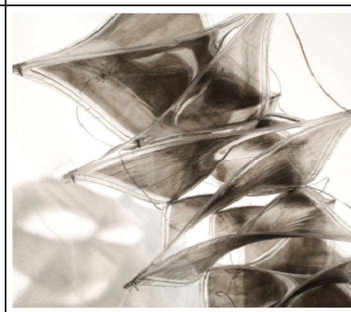
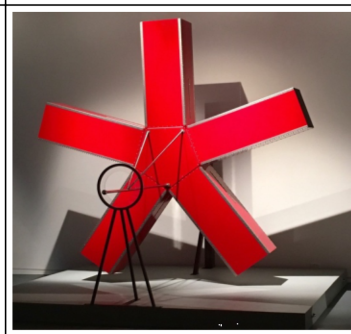
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.46	 	Open Columns	Omar Khan and Laura Garofalo	Buffalo, New York	2007	Built	Th Open Columns reside collapsed in the ceiling and can be deployed in a variety of configurations. The columns can have pre-programmed configurations or are responsive to the environment with a CO2 sensor. CO2 levels increase as people disperse into smaller groups and the columns come down. Vice versa and the columns go up to encourage people to come into the space. If the CO2 levels stay the same the columns cycle through random configurations.	Social Interaction	Collapse and Expand	Composite Urethane Elastomers	Pre-programmed or real time CO2 sensors respond to the environment. The columns have the ability to learn based on what configurations cause a change in CO2 levels.
6.47		Shape Shift	Manuel Kretzer and students from the Swiss Federal Institute of Technology	N/A	2010	Built	Elastomeric films significantly change shape when provided an electrical charge. Panels also influence the form and movement of their neighbors.	Prototype for Kinetic Structures	Shape-shifting	Elastic Silicon Tape, Acrylic Frame, Electrodes	Electrical Charge Causes Material Change
6.48		10 DEGREES	Chuck Hoberman	Cambridge, Massachusetts	2016	Built	Four uniquely moving prismatic structures have one, two, three, and four degrees of mobility. Visitors can tilt, rotate, and expand and contract the different sculptures.	Human Interaction	Tilt, Rotate, Expand and Contract	N/A	Manual
6.49		Strandbeest - Animaris Suspendisse	Theo Jansen	N/A	2014	Built	Theo Jansen has created over 18 different kinetic sculpture beasts. Jansen uses each creature to learn and improve upon the next creature. This specific animal is 42 feet long. Months of computer calculations figured out the perfect lengths of leg rods allowing the sculpture to move. Sails help it 'gulp' the wind, directing air toward pistons that squeeze the air into recycled plastic bottles.	Art, Sense of Wonder	Ability to Walk with the Wind	Plastic Tubing, Recycled Plastic Bottles, Rubber Rings	The sculptures are self-propelling with a complex chain reaction of operating with the wind.

Table 6.10. Sculpture (2)

Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.50		Hylozoic Ground	Philip Beesley	Venice, Italy	2010	Built	Philip Beesley's Hylozoic Ground is a very complicated moving structure that involved the help of an engineer and a chemist. The piece contains tens of thousands of digitally-fabricated components fitted with meshed microprocessors and sensors. Beesley's goal was to push architecture closer to a living system. Human interaction triggers breathing, caressing, swallowing motions, and hybrid metabolic exchanges.	Art, Testing Kinetic and Responsive Possibilities of Architecture	The sculpture is a complex movement of a hyperbolic waffle structure that can be pushed and pulled covered in mechanical fronds, filters, and whiskers.	Stainless Steel, Aluminum, Glass Flasks, Silicone Restraints, Acrylic Mounting Cage, Acrylic Fronds, Copolyester Tongues, and Monofilament	Proximity Sensor, Embedded Machine Intelligence, Shape Memory Alloy Actuator and Lever, Chemical Exchanges

Table 6.11. Sculpture (3)

ROOF / CANOPY

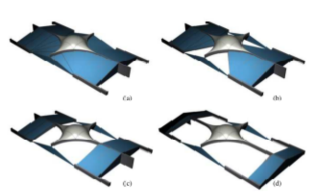
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.51		Alden Biesen Courtyard	NEY + Partners	Bilzen, Belgium	2003	Built	Funnel-shaped foldable umbrellas cover the span of the courtyard. The four overlapping umbrellas have translucent PVC coated polyester canvas that filter in natural light.	Protection from the Elements While Maintaining Natural Light	Deployable Umbrella	PVC Coated Polyester Canvas	Computer-controlled
6.52		Courtyard City Hall Vienna	Schlaich Bergermann Partner	Vienna, Austria	2000	Built	The accordion-shaped membrane is operated with axial rollers and 4 electric motors. The membrane is structured with ridge cables and placed under a glass roof for protection.	Shading	Folding	Membrane, Cables, Rollers	4 Electric Motors
6.53		Fortress Kufstein Courtyard	Kugel Architekten	Kufstein, Austria	2006	Built	The membrane covers a 2000 square meter area. It has 15 support columns and 15 upper and lower cables radiating out from its center with motors operating the membrane. However, the covering requires a high level of maintenance and an active monitoring system due to the large size.	Shading, Protection from the Elements	Expand and Contract	Membrane, Cables, Pressure Ring	Motors, Active Monitoring System
6.54		Tabriz Islamic Art University Courtyard	M. Asefi, Sh. Valadi, E. Ebrahimi Salari	Tabriz, Iran	2013	Concept	This kinetic roof offers various configurations. There is a fixed center with 4 moveable sections. Each section has 6 rigid panels that slide on separate tracks. Wheels and 8 actuating motors allow everything to move. The panels are sloped to direct rainwater and the overall aesthetic is playing to the historic characteristics of the area.	Maintain Aesthetic, Direct Rainwater, Natural Lighting, Ventilation, Protection from the Elements	Sliding, Track System with Wheels, Rotating on Fulcrum	Rubber strip, aluminum, polycarbonate sheets.	8 Actuating Motors
6.55		Mush Balloon	Taneo Oki Architects	Osaka, Japan	1970	Built	Designed for EXPO'70, the cushion of air is suspended by 45 strands of wire that come together at the base. A winch is used to collapse or open the vinylon balloon, while simultaneously blowing air into or venting air out of the structure.	Shading, Protection from the Elements	Pneumatic, Winch	Vinylon Membrane	Winch and Air-Controlled
6.56		Qi Zhong Tennis Center	Environmental Design Institute	Shanghai, China	2005	Built	The roof takes 8 minutes to open like a flower. Each of the eight petals were first constructed on the ground before being hoisted into place. The petals are steel cantilever systems that turn around on a fulcrum allowing the stadium to host indoor and outdoor games.	Open air	Rotating on a Fulcrum	Steel, Glass, Aluminum	Embedded Computation

Table 6.12. Roof / Canopy (1)

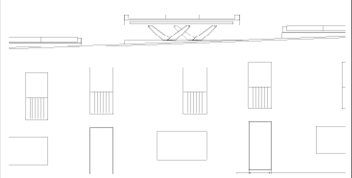
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.57		Lakeside Stage	Werkraum Wien with Hans Kupelwieser	Lunz, Austria	2004	Built	Spectator stands open up to have canopy covered stands to view the floating stage.	Protection from the Elements, Acoustics	Folding	Concrete	By using pumps and hydraulics the weight of water is used to open the stands. The structure is closed by draining the water.
6.58		Rebgassli Housing Development	Amrein Giger Architekten	Allschwil, Switzerland	2004	Built	Nine elevating skylights open the roof of the building.	Natural Light, Ventilation	Lifting, Scissor Levers	Metal Casing, Anodized Aluminum, Chromium Steel	There are two hydraulic rams controlled by a manual switch and safety guarded with sensors and a wind-speed monitor.
6.59		Olympic Tennis Center	Dominique Perrault	Madrid, Spain	2009	Built	Jacks can partially or totally open the three roofs.	Ventilation, Natural Lighting	27 Different Opening Positions, Folding	Aluminum Cladding, Metal Mesh	Hydraulic Jacks
6.60		Iris Dome	Hoberman Associates	Hanover, Germany	2000	Built	The dome can expand and contract demonstrating Hoberman's patented scissor joint technology.	Installation, Aesthetic	Scissor Joints to Expand and Contract	Machined Aluminum	Hydraulics

Table 6.13. Roof / Canopy (2)

GROUND PLANE

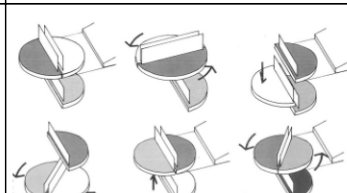
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.61		Courtyard in the Wind	Acconci Studio + Wolfgang Hermann Niemeyer	Munich, Germany	2000	Built	A turbine placed on top of a nearby building captures wind energy that is converted to electricity to rotate the ring slowly. Trees, paving, lighting, and benches all rotate. The landscape turns on a track that houses a set of motors and wheels. It revolves twice per hour, but is still noticeable by visitors occupying the landscape. This is the earliest ground plane kinetic landscape architecture project found during this research that is built.	Aesthetic	Track System	Wheels	Wind generated energy is converted to electricity to power the motors.
6.62		University of Phoenix Stadium	Peter Eisenman and HOK	Glendale, Arizona	2006	Built	The field of real grass slides out of the stadium for outdoor events. It was a cheaper alternative verses having the added expense to create a fully retractable roof. The sliding surface has 5cm of natural grass, 25 cm natural soil with irrigation pipes and sprinklers, a thick geotextile fabric to allow extra water to pass, 15cm concrete with sewage holes, corrugated metal sheets, 45cm iron beam skeleton in which the wheels are embedded, and a computer controller to operate everything. The goal posts are put back post movement as well as panels separating the field from the stands.	Grow grass, Multi-Function, Outdoor Events	Track System	Iron beams, Wheels	Computer-controlled
6.63		Memory Pavement	Franchman and Rojas	N/A	2006	Concept	Memory pavement uses a digitally responsive ground plane to record the footfalls of pedestrians. It displays pathways and emphasizes popular routes. It can encourage pedestrians to examine pathways and to try new ones.	Digitally Responsive, Interactive	Digital	N/A	N/A
6.64		Split Level Stage	N/A	Birmingham, Alabama	N/A	Built	The theater stage can split, rotate, and lift to allow the use of different set designs.	Allows multiple set designs	Splitting, Rotating, and Lifting	N/A	N/A

Table 6.14. Ground Plane (1)

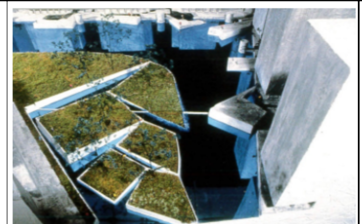
Figure #	Figure	Project Name	Designer(s)	Location	Year	Status	Description	Purpose	Movement	Elements	Operation
6.65		Laakhaven/Hollands Spoor	Acconci Studio	The Hague, Netherlands	1993	Concept	Chunks of artificially created land are floating on water. The pieces of land move from pivot points and provide a new type of experience for visitors to explore.	Experiential	Floating, Pivoting	Water, Concrete	N/A
6.66		Ascot Movable Turf Crossing	SCX Special Projects	Ascot, UK	2000	Built	The movable turf tray is an alternative to an underpass or overpass at a cheaper cost. It was important that the tray fit snuggly so horses couldn't detect shifting or be injured in any way. Its cross-section is in the shape of a wedge, like the keystone of an arch, for this purpose.	Alternative to an Underpass or Overpass	Track System	Turf, Wheels, Steel, Synthetic Grass, Soil, Sand, Plastic Mesh, Drainage Grid, Rails	A digital controller activates the tray. Hydraulic actuators raise and lower the tray and 16 electric motors move it back and forth.

Table 6.15. Ground Plane (2)

Analysis / Conclusion

This section is an analysis of the classification categories shown in the catalog. The projects are exhibited in the previously shown catalog tables and the list shown in Appendix E. Projects were counted for more than one term in the purpose, movement, elements, and operation categories. It should be noted that any analysis in this chapter is based solely on the projects encountered in this research. The data could significantly change based on a larger sample size and should be read with this warning. For example, kinetic art and bridges are the most common kinetic projects but are underrepresented in the catalog and Appendix E and therefore the analysis (Alison 2019). A few of each category were selected due to their extreme prominence and the time limitations of this thesis.

Additionally, reading different literature would result in different projects. For example, MOVE : Architecture in Motion - Dynamic Components and Elements (Schumacher, Vogt, and Schaeffer 2010) was written in German and translated into English; the book has a considerable number of regionally constructed kinetic projects. The same applies to the literature produced in the United States.

<u>Location:</u> Out of the 218 total kinetic projects in Appendix E, 161 had available location data. This means the projects were not a concept or a prototype that would not be associated with an address. The countries with the most kinetic projects are the United States (45), Germany (33), United Kingdom (15), and Spain (13) (*Figure 6.67*). In the United States, the states with the most kinetic projects are New York (6) and California (5). Munich, Germany was the city with the most kinetic projects (7). The placement of kinetic projects seems to depend on a variety of factors including local acceptance, designer knowledge and will, and project budget.

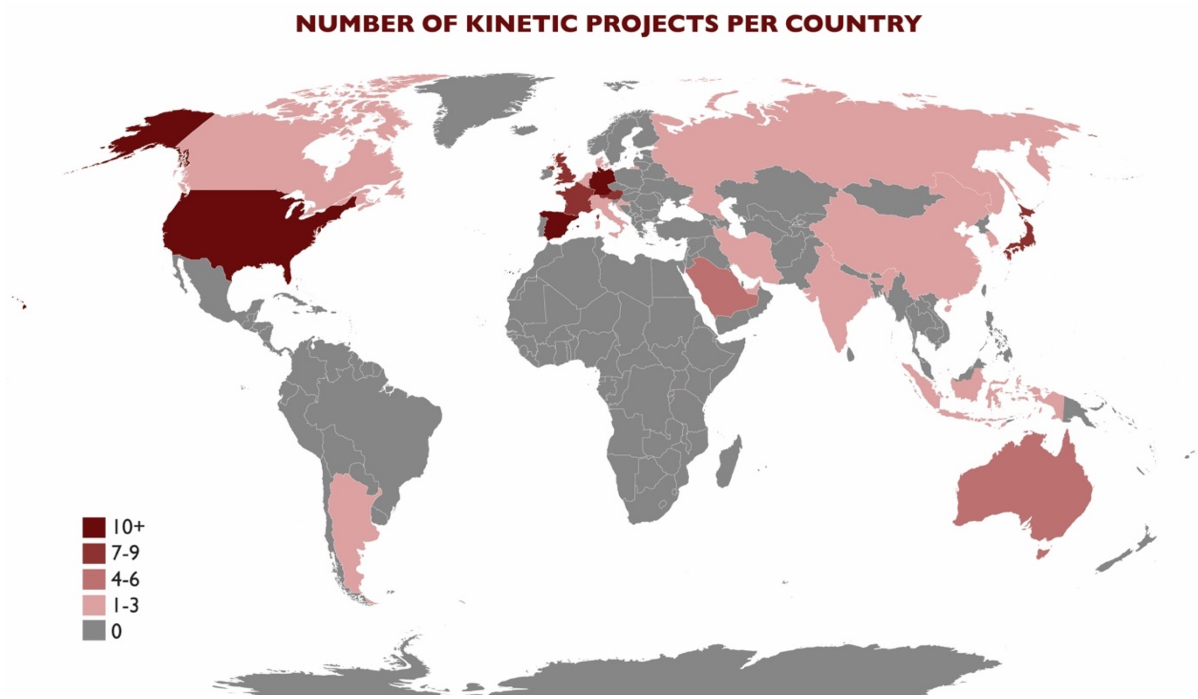


Figure 6.67. Number of Kinetic Projects Per Country

Designers: The designers with the most projects in the catalog were Hoberman Associates, MIT labs, Acconci Studio, and Santiago Calatrava. These designers with more than one project are mentioned in Chapter Two.

Year: The earliest projects include *Pegasus Bridge, Mush Balloon, The Institute of the Arab World, and Storefront for Art and Architecture*. The newest completed projects include *10 DEGREES, the Hyundai Sculpture, and The Shed*. The median year was 2005, with only six projects from prior to 2000. This shows kinetics is still a recent addition to the design field. However, the median year is earlier than expected; it seems as if most projects were built (or conceptualized) between 2000-2010, but not as many have been designed after 2010.

Application: The most popular application was Roof / Canopy with 62 projects. This pairs with sun-shading being one of the most popular purposes for kinetics. This is likely the most prominent category due to the popularity of kinetic stadiums and the eagerness to have an open-air structure for good weather days and a closed structure for undesirable weather. Additionally, all of the categories had ten projects, except for the ground plane category which only had six, indicating the lack of experimentation in this area or the increased complexity.

Purpose

Aesthetic (12)

Sun-Shading (11)

Multi-Function (10)

Natural Lighting (9)

Interactive (9)

Ventilation (8)

Protection from the Elements (8)

Experimental Prototypes (7)

Heat Gain (5)

Customization (5)

Construction (3)

Multi-Configuration (3)

To the author, it was surprising to see ‘aesthetic’ as the number one purpose. It is early in the process of including kinetics in the built environment, and the author’s hypothesis was that functional purposes would take priority when first introducing kinetics to clients. This could be that kinetics can offer a unique, eye-catching quality, and that is what the client desires. Designers could also be testing kinetic mechanisms, and when the project did not demand a kinetic feature, it was then used for aesthetic purposes.

It was also surprising to not see ‘space-saving’ make the list of top purposes. Space-saving is a very functional purpose that designers should take advantage of. It might be that ‘space-saving’ is currently commonly associated with interior environments and that it has not yet reached a level of priority at a structure level or in the exterior environment. The author predicts that ‘multi-configuration,’ and ‘multi-function’ will continue to rise in popularity along with ‘space-saving’ due to limited space and along with ‘customization’ as the built environment continues to become more individualized.

The group of terms relating to controlling natural forces like the sun and weather conditions is ‘heat gain,’ ‘ventilation,’ ‘sun-shading,’ ‘natural lighting,’ and ‘protection from the elements.’ These kinetic purposes might become more necessary with continued climate change affecting the requirements of the built environment. Currently, most of the examples are not in the landscape, but it is reasonable to infer that these purposes will also increase in need in the landscape with climate change increasing the intensity of hot and cold environments.

<u>Movement</u>

Tilting, Pivoting, Rotating (12)

Folding (8)

Sliding (8)

Deployable (6)

Pneumatic (4)

Material (4)

The author expected to see sliding as the most common type of movement, but it is still reasonable to see the easiest types of movement make the top of the list. There are construction materials readily available to make these methods of movement possible as well as a base level of design knowledge to accomplish them.

Elements

Aluminum (14)

Steel (12)

Glass (8)

Membrane (5)

Wood (5)

Concrete (5)

Wheels (5)

These numbers should not be calculated as a percentage of the catalog projects, additional projects featured in the catalog could include these elements, but information was not readily available. It is apparent that most of the time the kinetic projects are constructed with typical construction materials. The author believes that as kinetics further develops in the fields of architecture and landscape architecture that more advanced, non-typical, materials will be used to achieve movements not easily obtainable with common materials. Different materials might also be used with the landscape to blend with natural aesthetics or ecology.

Operation

Motors (11)

Hydraulics (11)

Sensors (10)

Manual (10)

Computer-controlled (9)

The operation category was the most difficult to find information without doing a full case study and contacting the designers. These numbers should not be calculated as a percentage of the catalog projects. Additional projects featured in the catalog could operate with these terms, but the information was not readily available. Kinetic furniture seems to commonly operate manually because of the weight and the need for easy customization without energy requiring operation mechanisms. Manual movement can provide a more minimal aesthetic in a natural environment, which is predictably a desire some designers will have of landscapes.

In conclusion, the catalog is made for landscape architects, but it can be used by any discipline interested in kinetics. It was necessary to create in order to generate the tools shown in the next chapter and is even beneficial to an experienced kinetic designer. The catalog gives enough information for a designer to know if a project is worthy of further research and study. In addition, the catalog and its analysis can give designers an idea of what methods of movement are commonly being used in kinetic design, as well as display trends and quickly show how kinetic design exists today. It begins to illuminate the lack of landscape architecture representation in the array of kinetic design. Even with criteria to choose projects applicable to landscape architecture, landscape architects must get most of their kinetic design knowledge from other fields. Chapter Seven and Eight will discuss in more detail what else is currently missing from the realm of kinetic design.

CHAPTER 7

PROPOSED KINETIC DESIGN TOOLS

This chapter uses projective design to propose two new kinetic design tools that aid in making kinetic design less challenging and more inviting. These products were created from the accumulation of information in the previous chapters. They heavily draw from the existing kinetic design tools presented in Chapter Five. The tools were created to help landscape architects to better understand and use kinetics in the landscape.

Degree of Kinetic Adjustability Chart

The Degree of Kinetic Adjustability chart is a visual metric with the purpose of showing a rating of adjustability in kinetic projects (*Figure 7.2*). The chart does not apply to non-spatial kinetic projects, but it allows all spatial kinetic projects to be plotted, and the projects in the catalog were assigned points to demonstrate how the diagram works. The chart can lead to further analysis of the catalog projects that the catalog alone could not do. The chart compares the variables of the number of usable positions and the number of degrees of freedom (the degrees of freedom are described in more detail in Chapter Four) (*Figure 7.1*). Together the variables create an adjustability rating permitting projects to be objectively analyzed. The plot allows the comparison of adjustability between projects and indicates which projects should be studied to see how high levels of adjustability are achieved. There are eighteen possible points on the plot, projects rated 'R' that have an infinite number of positions and six degrees of freedom offer more adjustability than a project with only two available positions and one degree of freedom that is rated ‘A’.

The X axis measures the number of usable positions with the increments broken into three groups. The term ‘usable’ is included because even though the implemented mechanism could be used in another situation with more positions it is plotted according to the number of positions used in that particular project. The Y axis measures the number of degrees of freedom, not giving preference to any particular degree, or if it is rotational or translational. The chart’s origin signifies a static element with one possible configuration.

Figures 7.3 - 7.5 accompany the plot and have each of the catalog projects sorted according to their adjustability rating with the most adjustable projects at the top. Each project receives a diagram showing their individual degrees of freedom, with the translational degrees on the left and the rotational degrees on the right. In Chapter Five, it was discovered that a visual representation of the movement can be very helpful for understanding how a mechanism moves and this chart aims to do that.

In Chapter Three, the innovation district and open-source streetscape both had goals of testing for the maximum amount of adjustability. In that situation, for inspiration, it would have been helpful to have a chart that indicated projects with a high number of adjustable positions and more degrees of freedom. That way one could look at how those projects achieved a high degree of adjustability.

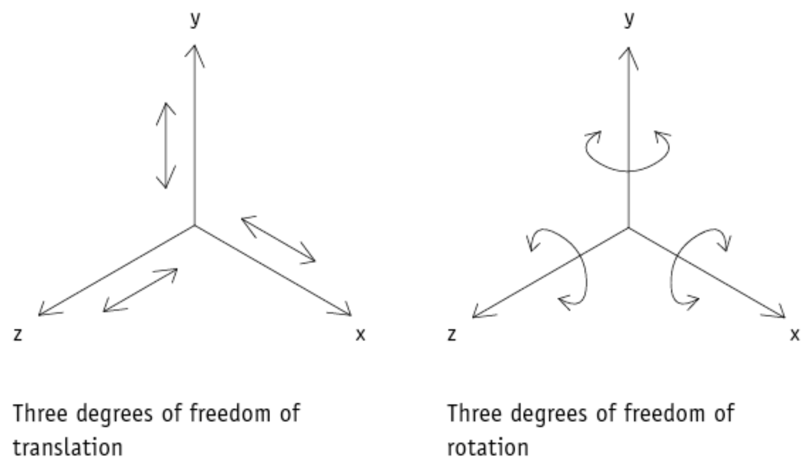


Figure 7.1. Degrees of Freedom

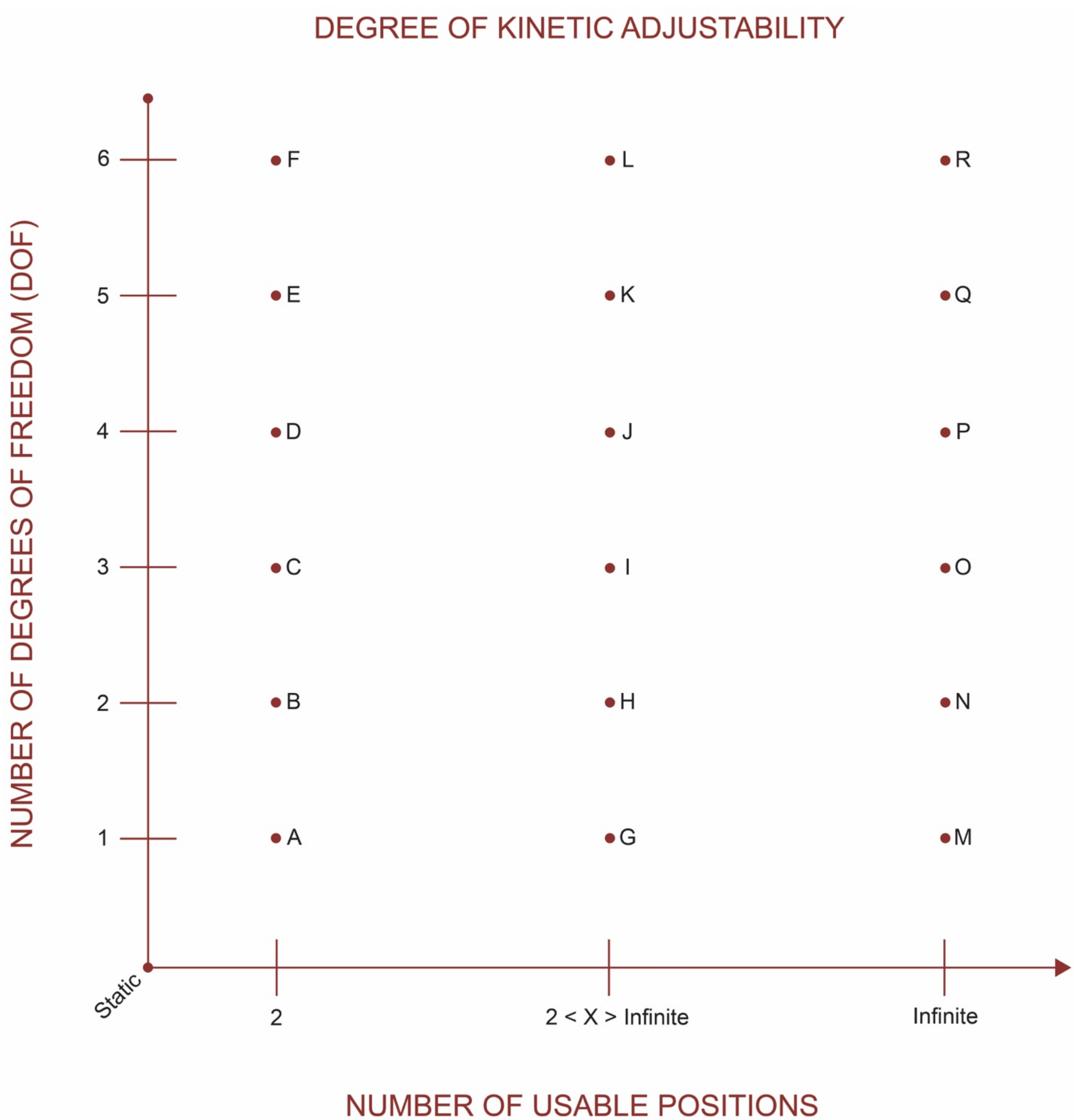


Figure 7.2. Degree of Kinetic Adjustability

Instructions:
Use this chart to objectively analyze projects in the corresponding table on the following pages. The table includes sixty-six plotted projects with associated letter points that match the letters displayed on the above chart. The letters resemble the degree of adjustability that the projects embody; 'R' is the most adjustable and 'A' is the least adjustable. The table also shows the degrees of freedom for each project to diagrammatically represent how each project moves.

Point	Examples	Degrees of Freedom
R	10 DEGREES (*Figure 6.48)*	
Q	HelioTrace Facade System (*Figure 6.1)*	
Q	Ephemeral Structures (*Figure 6.41)*	
Q	Shape Shift (*Figure 6.47)*	
P	Hylozoic Ground (*Figure 6.50)*	
O	Media - TIC Building (*Figure 6.2)*	
O	Strandbeest - Animaris Suspendisse (*Figure 6.49)*	
N	The Institute of the Arab World (*Figure 6.8)*	
N	Storefront for Art and Architecture (*Figure 6.9)*	
N	Memory Pavement (*Figure 6.63)*	
N	Hygroskin (*Figure 6.34)*	
N	Pitterpatterns (*Figure 6.3)*	
N	Wind Veil (*Figure 6.4)*	
N	Muscle Tower II (*Figure 6.38)*	
N	Adaptive Fritting (*Figure 6.36)*	
M	Whirlstools (*Figure 6.22)*	
M	EWE Arena (*Figure 6.5)*	
M	Milwaukee Art Museum (*Figure 6.18)*	
M	Hyposurface Wall (*Figure 6.10)*	
M	The Rolling Bench (*Figure 6.24)*	
M	Dynamic Tower (*Figure 6.20)*	

Figure 7.3. Adjustability of Catalog Projects (1)

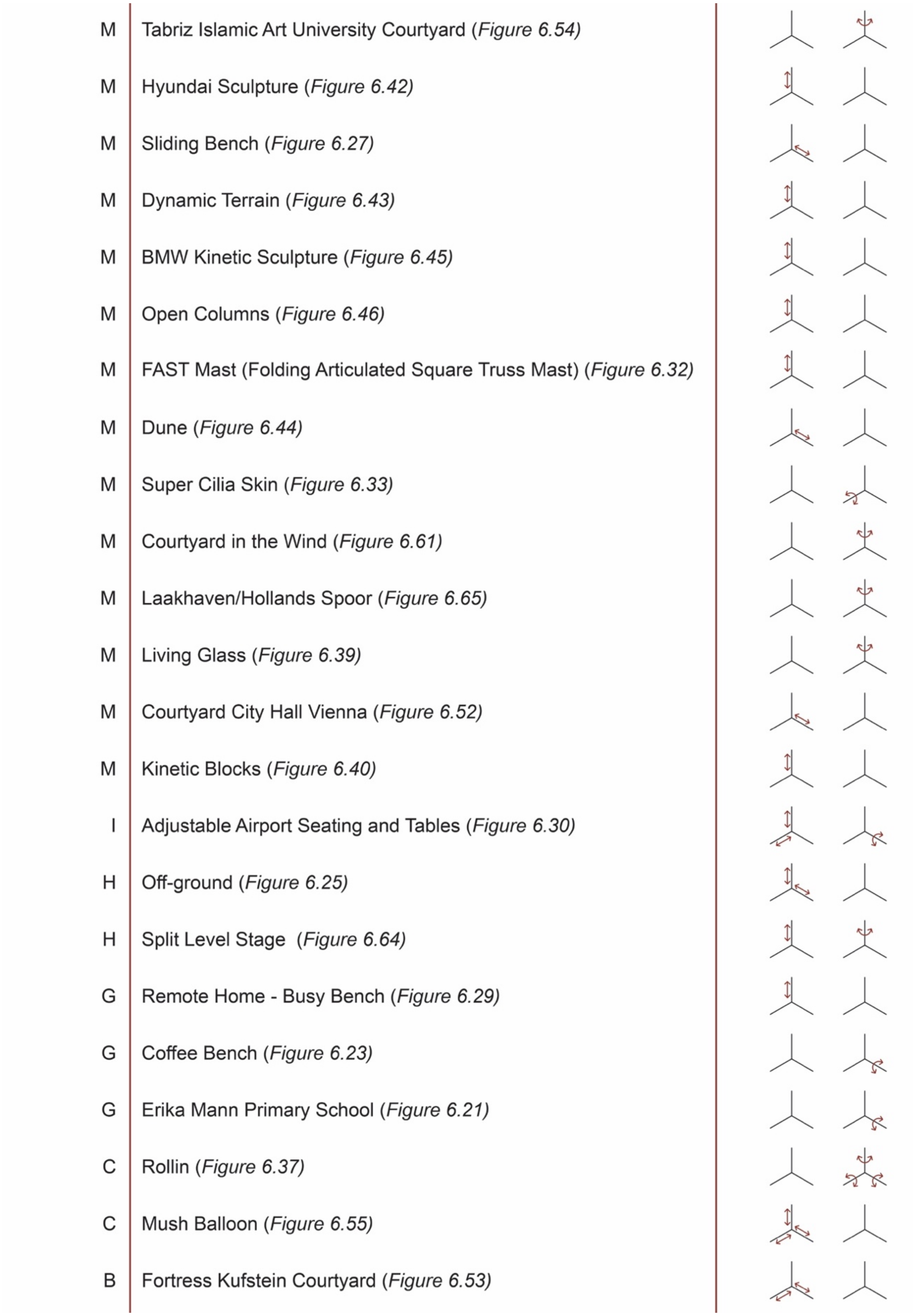


Figure 7.4. Adjustability of Catalog Projects (2)

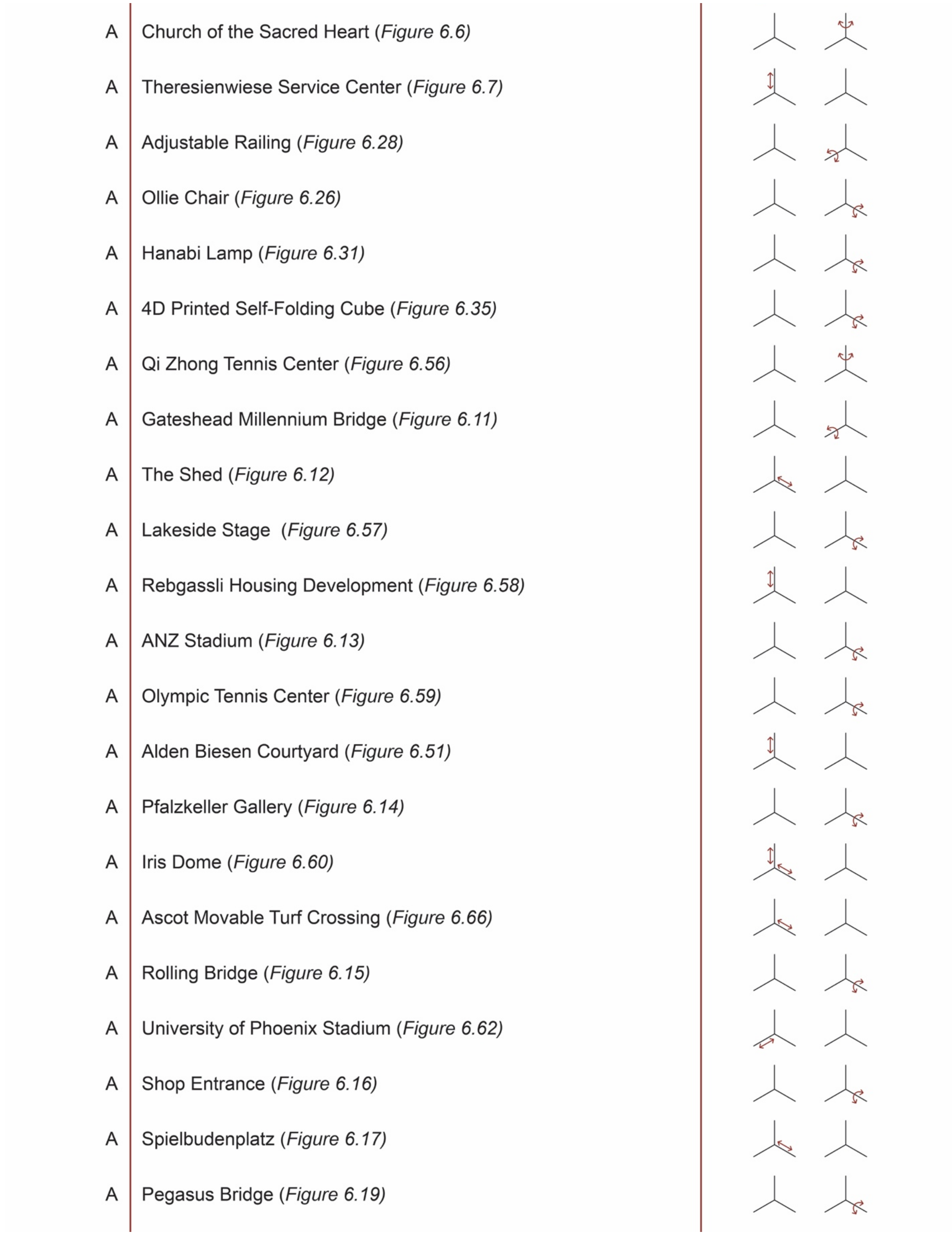


Figure 7.5. Adjustability of Catalog Projects (3)

Kinetic Design Decision Chart

The Kinetic Design Decision Chart shown in *Figures 7.6 – 7.11* consists of a network of primary questions a designer should ask throughout the kinetic design process. The questions are aligned with the design process discussed in Chapter Four, which provides more in-depth detail of each stage that this chart alone cannot provide. The chart does not aim to list all of the potential options for each question, but instead provides examples to understand some of the possibilities. A designer could follow the chart and select an option under each question to form a design, but it is more encouraged to choose options not listed on the chart.

The questions were chosen to cover all of the primary topics a landscape architect would encounter. They were chosen based on the questions or topics encountered in the author's personal design process, the kinetic catalog, and existing classification systems. The catalog allowed a sample of existing traits and inspired many of the options listed in the decision chart. The chart draws on several existing kinetic tools, for example, the question asking if the purpose is for functional or aesthetic purposes comes from Megahed's (2017) Conceptual Framework for Kinetic Classification, as well as the distinction between spatial and non-spatial designs.

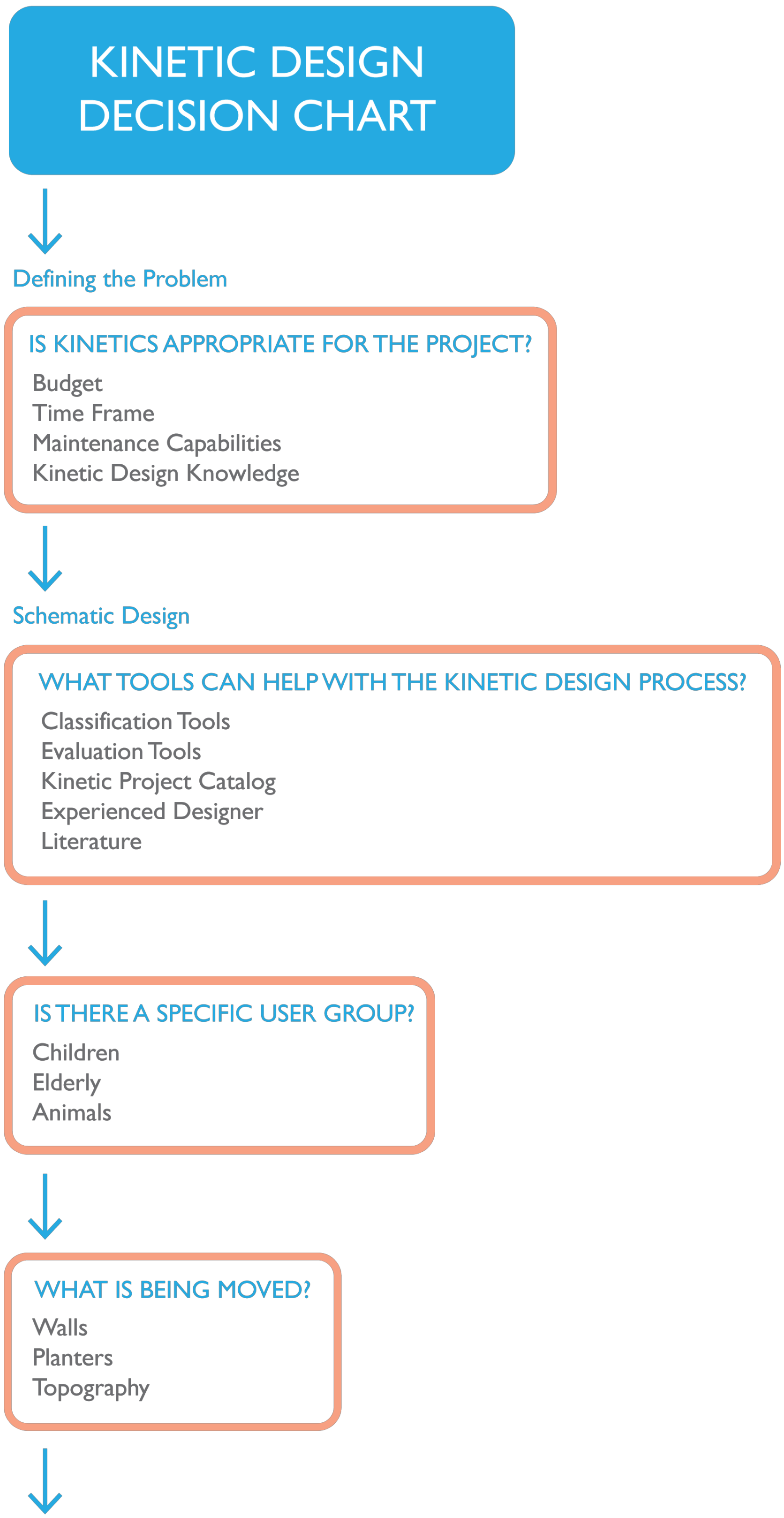


Figure 7.6. Kinetic Design Decision Chart (1)

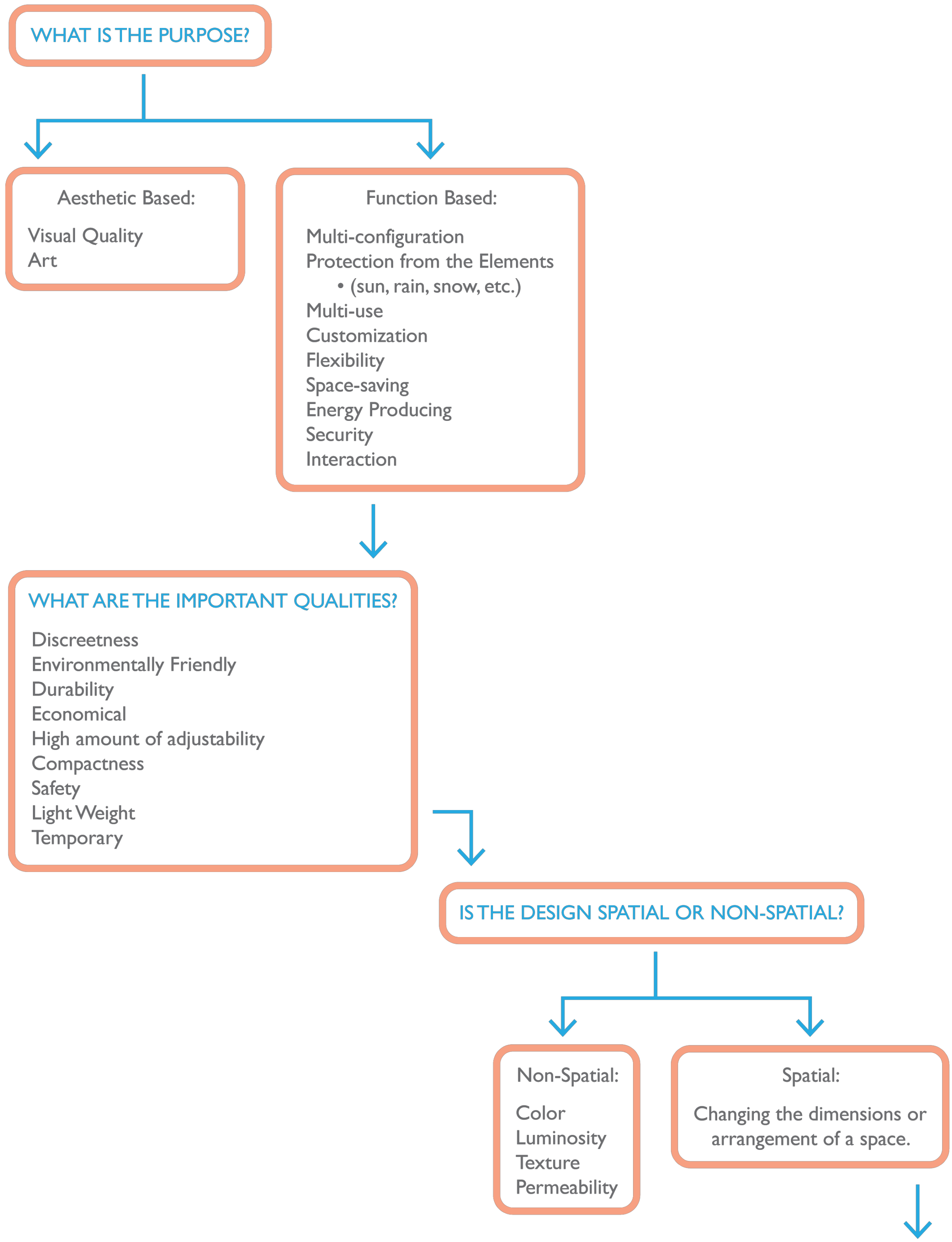


Figure 7.7. Kinetic Design Decision Chart (2)

Design Development

WHO WILL BE SPECIFYING THE DETAILS OF THE KINETIC MECHANISM?

Landscape Architect
Structural Engineer
Mechanical Engineer
Civil Engineer
Architect

↓

Movement

IN WHAT WAY WILL THE DESIGN MOVE?

Ways of Movement (Verbs):

Folding
Sliding
Shrinking
Expanding
Rotating
Telescoping
Cinching
Rolling

↓

WHAT IS THE MOVEMENT DIRECTION?

Translational
Rotational

↓

Figure 7.8. Kinetic Design Decision Chart (3)

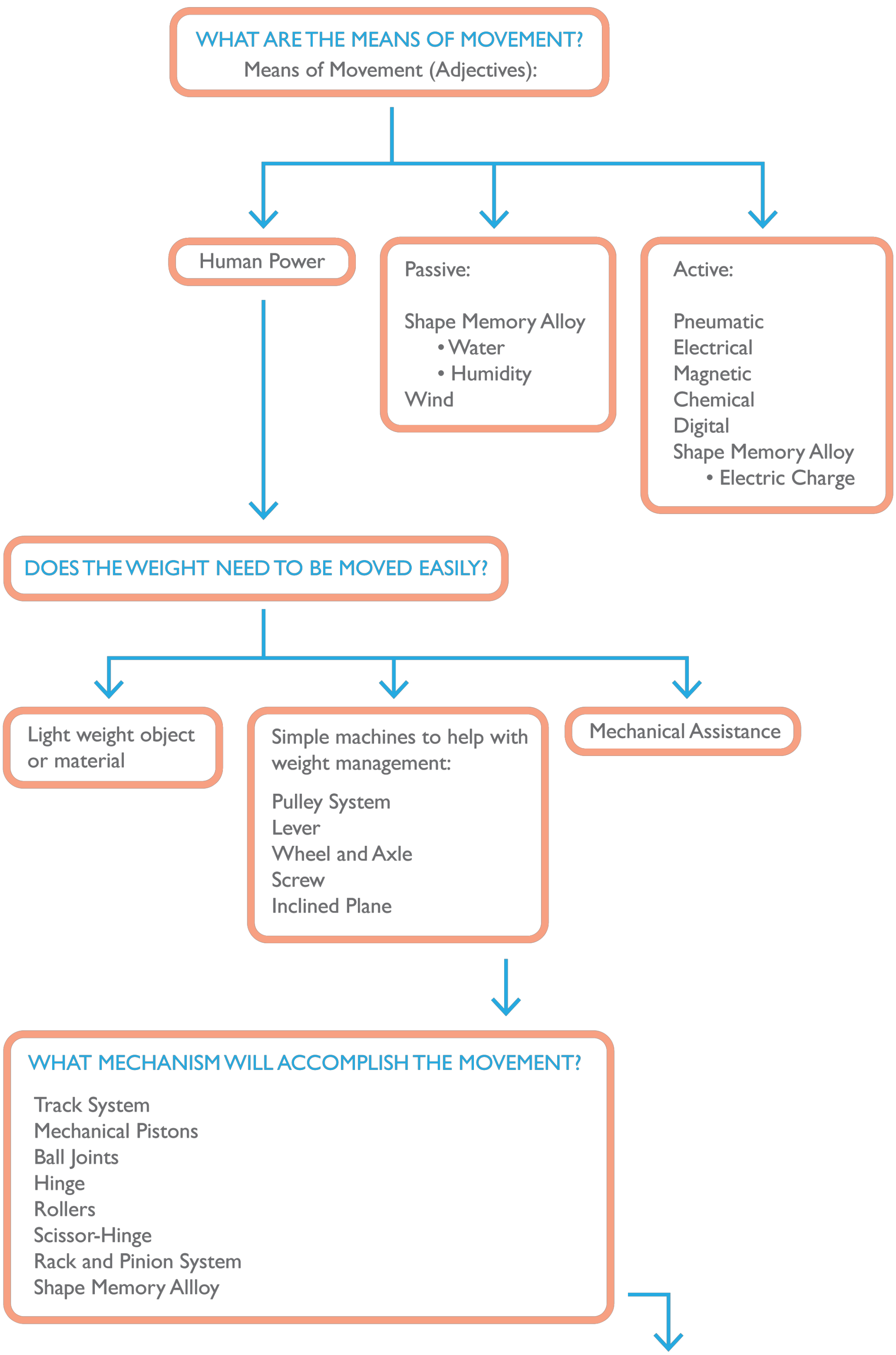


Figure 7.9. Kinetic Design Decision Chart (4)

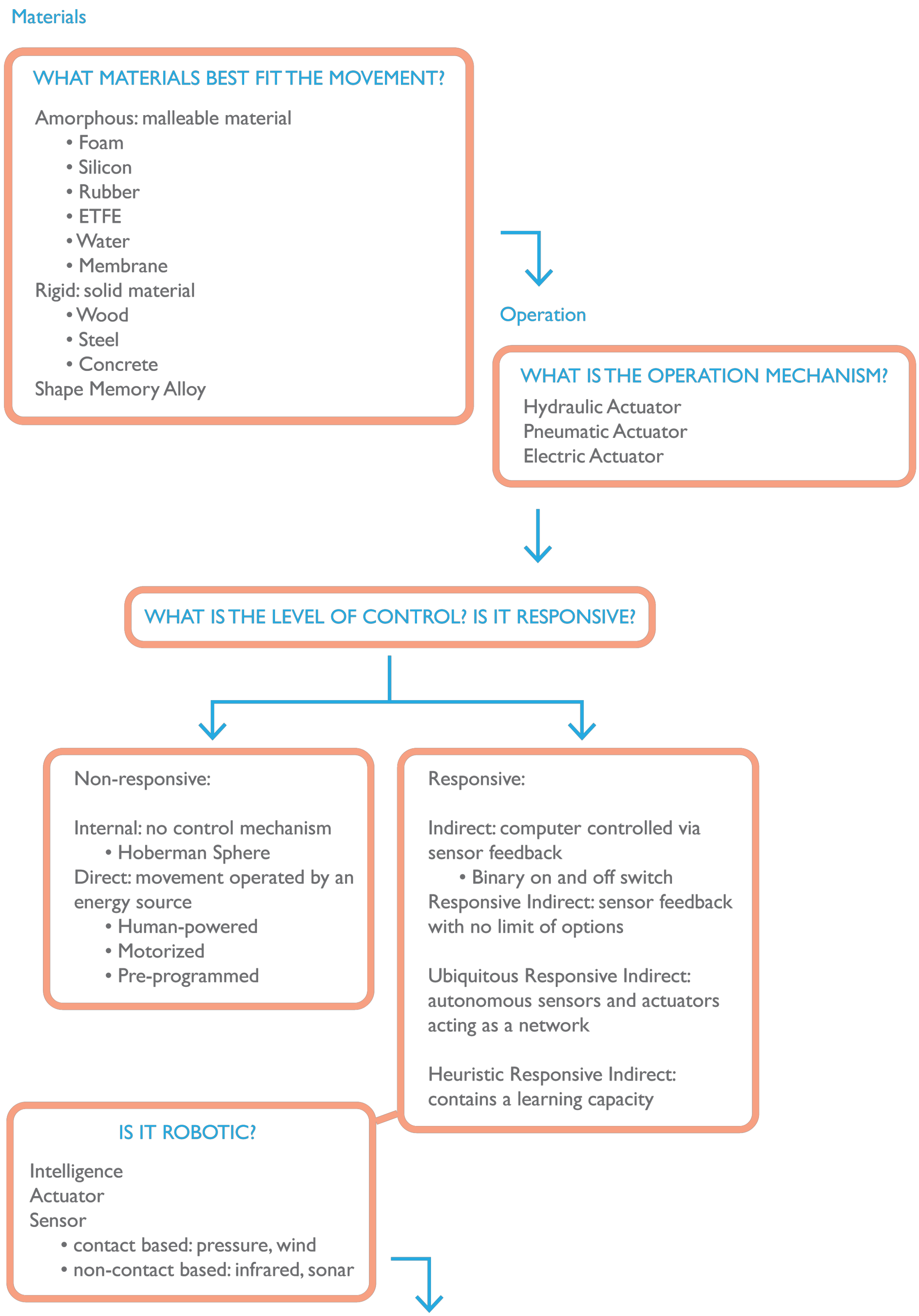


Figure 7.10. Kinetic Design Decision Chart (5)

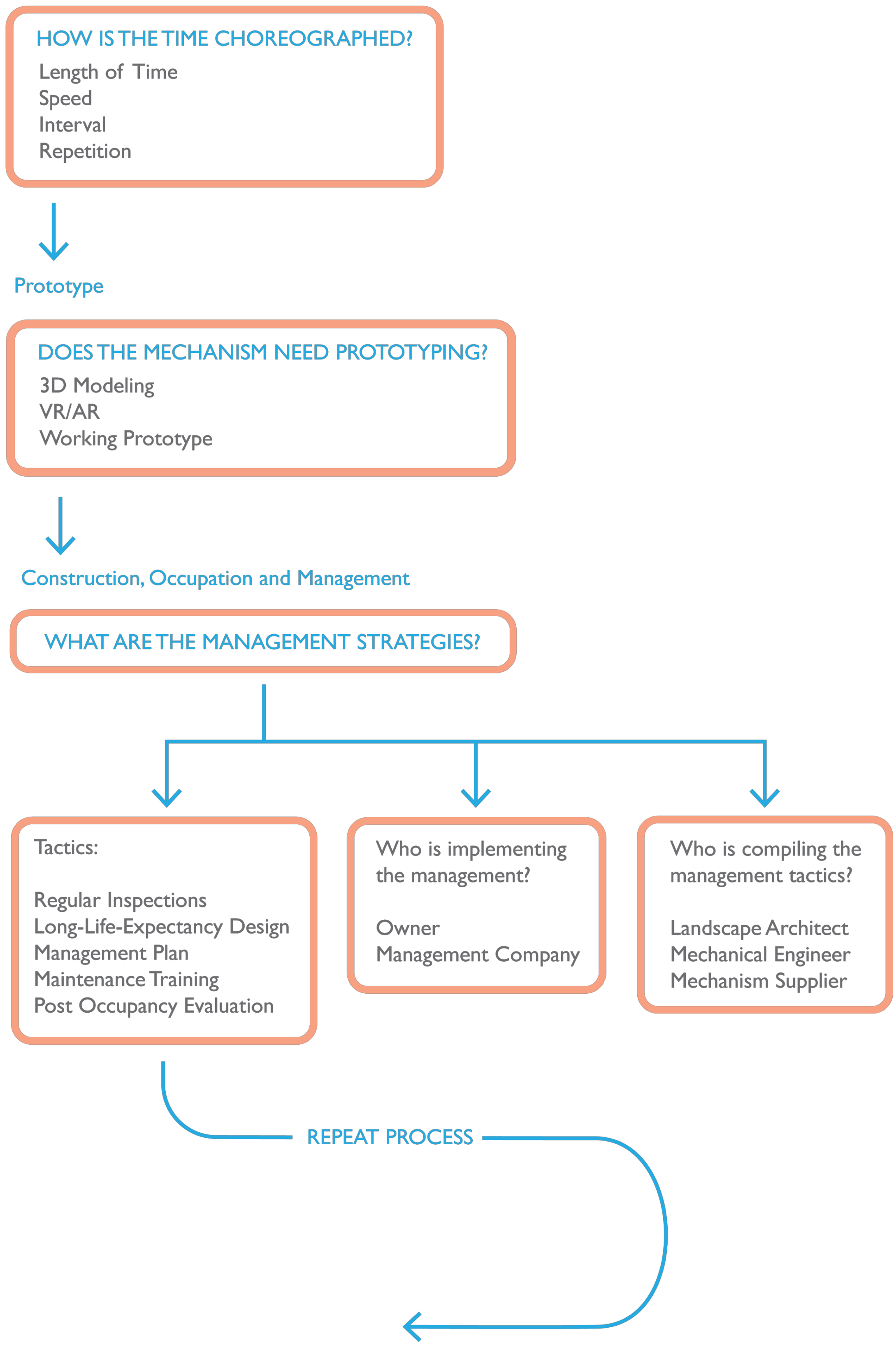


Figure 7.11. Kinetic Design Decision Chart (6)

Analysis / Conclusion

The Degree of Kinetic Adjustability Chart allows an analysis of the catalog projects that was not possible before. In order for the author to create the degrees of freedom diagrams each project had to be researched enough to understand exactly the directions they moved. This was a time-consuming effort but is intended to eliminate the need for the reader to do the same.

The Architecture / Structure category had the least adjustable projects. Which makes sense because they are the most significant undertakings and more difficult to provide adjustability for. Likewise, the sculpture category had the most adjustable projects because of their smaller scale and easier ability to move. Specifically, the most adjustable project from the catalog was *10 DEGREES*. This may be misleading because this exhibit consists of separate sculptures offering different degrees of freedom, but it is not a singular sculpture that has an infinite number of positions and six degrees of freedom.

The next two projects, *HelioTrace Façade System* and *Ephemeral Structures* are both not built. A significant finding is that the combination of pneumatic with some rigid kinetic structures seems to provide a way to achieve a higher level of adjustability. Knowing this meaningful combination can lead designers to include such mechanisms in their projects. Projects containing shape memory alloys (SMA) like *Hygroskin* and *Hylozoic Ground* also offer an easier way to achieve adjustability with only the inherent properties of the materials. Many of the top projects on the list are very complex and do not easily reach a high level of adjustability. For example, *Hylozoic Ground* and *Strandbeest – Animaris Suspendisse* both have a complex chain of reactions and many different movements happening at one time.

Another likely predicable finding is it was most common to have two positions with one degree of freedom and next most common to have an infinite amount of positions with one degree of freedom. The center column is a less likely combination; it is more common to have two positions over a different fixed number like twenty-seven.

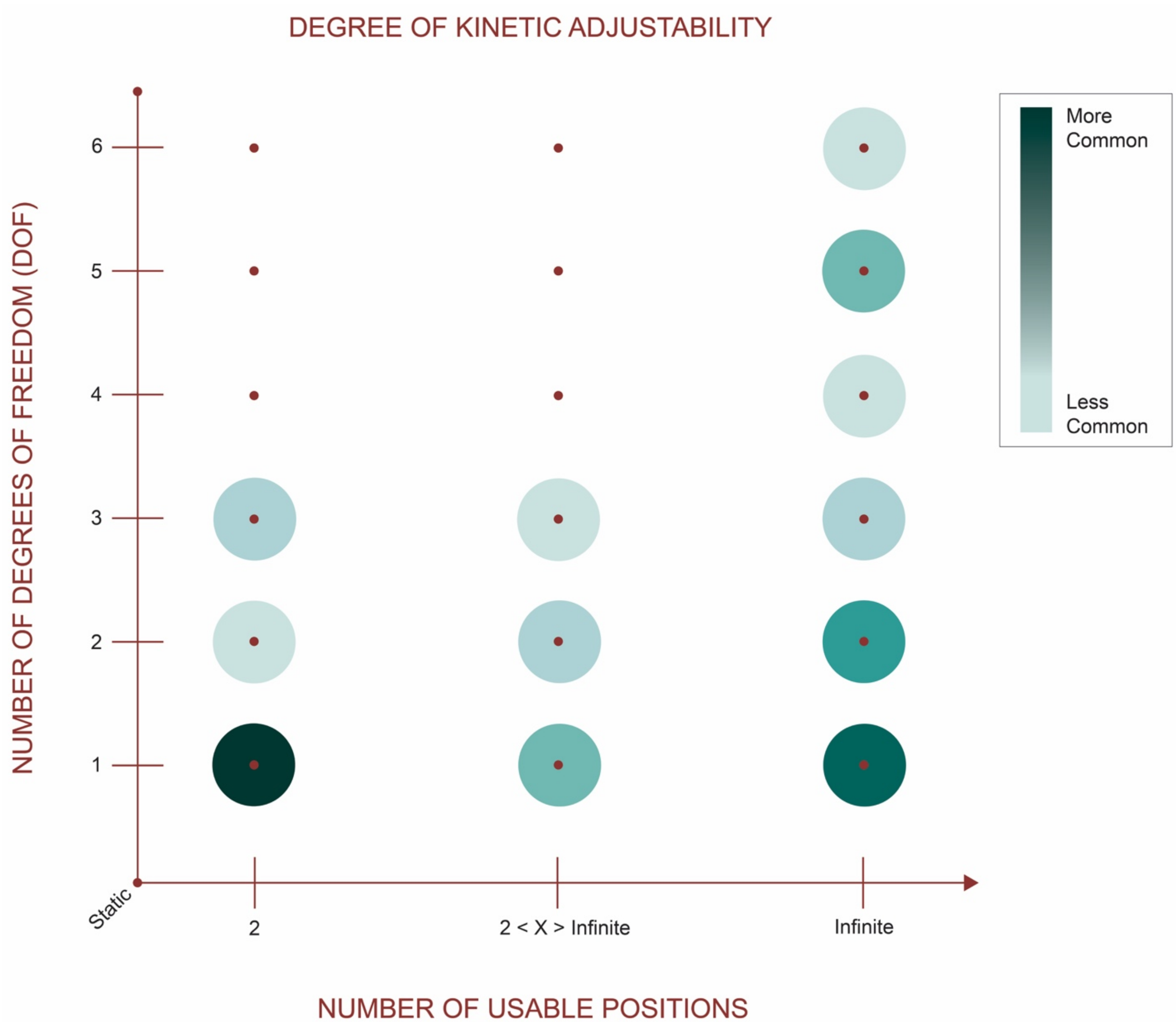


Figure 7.12. Prevalence of Catalog Projects

Both the Degree of Kinetic Adjustability Chart and the Kinetic Design Decision Chart are open for critique. The decision chart will need to be updated relatively frequently as new questions arise and new technologies become possibilities. It needs to be put to the test with several kinetic projects to examine the usefulness of the chart. These presented tools are revolutionary new additions to the body of knowledge and ready for practitioners and academics to use and improve.

CHAPTER 8

REFLECTION

The guiding research question for this thesis was: What can aid in the advancement of the application of kinetics in landscape architecture? This thesis established that kinetics belongs in landscape architecture and has been used in the landscape throughout history. For landscape architects to consider kinetics in their designs, an established knowledge base from which to make informed decisions is necessary. This thesis has attempted to do just that – providing a set of tools based on the problems faced in the author's own studio design projects. The tools provide enough basic knowledge to reduce the complexity of the decision-making process and make the decision to use kinetics less formidable. This thesis offers awareness, knowledge, design tools, and project examples to bridge the current gap. The tools developed to answer the research question set a baseline for future innovation with the hope that this will guide landscape architects on a clearer path.

Analysis / Conclusion

There is no denying that some movement already exists in landscape architecture. There is also no denying that static elements are intentionally used to imitate movement, like grand swooping waves of seat walls or curvaceous topography. However, movement in landscape architecture is far from being adequately addressed or explored theoretically. There is so much untapped potential, it is shocking this research has not been done already. It is too big of a knowledge gap to have missing from our research base.

Kinetics is an infectious and intriguing topic that became an obsession for the author. Even with only locally spreading the awareness of kinetics among friends and colleagues, it has started to catch on and the author has seen it mentioned and used by other students in their projects. It is a new perspective on spatial design and when someone learns of kinetics, they cannot unthink it; they begin to see a kinetic possibility everywhere.

With this newly introduced opportunity for landscape architecture, one of the initial inquiries might be where should landscape architects begin? If any space can become kinetic, what spaces should take priority? The answer is that it is no different than when dealing with static spaces. Decisions like choosing between increasing the ease-of-access for more people in more spaces, climate mitigation, revitalization of underutilized spaces, or an energy producing space, already have to be made. A cost-benefit analysis could be conducted to help choose what parts of a landscape to make kinetic.

There was a large learning curve writing this thesis and there will also be a similar curve for any landscape architect interested in kinetics. Kinetics requires specialized knowledge that is not offered in typical landscape architecture programs in the United States today. Recommendations for increasing student awareness and comfort level with kinetics could be a studio focused on designing a kinetic environment, guest lectures, or an elective interdisciplinary engineering course that covers more than grading, swales, and pipe sizing. This type of course could cover kinetics as well as other important engineering topics that are typically left out like irrigation and structural engineering.

Along with including kinetics in academia, it is equally important to raise awareness with practicing landscape architects and the general public. This can be done with traditional communication methods such as media and community events. Also, museum exhibits like 10 DEGREES can allow people to manually operate kinetics. As for the profession, American Society of Landscape Architecture (ASLA) lectures, webinars, and magazine articles all reach practicing professionals.

Using the collective term 'kinetic design(er)' can unite architects and landscape architects. This research and particularly the catalog allowed the author to see that one architect's building wall or roof becomes an energy source or a design surface for landscape architects. There can still be classification differences between kinetic architecture and kinetic landscape architecture, but as the trajectory of kinetics heads towards a cohesive kinetic built environment, a singular term makes sense. Because kinetics can be very involved, a profession, or at least specialization, could evolve. This may occur as landscape architecture and architecture continue the natural course of specialization. If not 'kinetic designer' then kinetic landscape architect is an alternative.

Advantages / Disadvantages: This is a list of advantages and disadvantages encountered during the process of this research. Not all advantages and disadvantages are present with each project, but it gives a starting point for designers to decide if they personally think the advantages can outweigh any negatives.

ADVANTAGES	**DISADVANTAGES**
Novel Aesthetic Option	Paradox of Choice
Individual Customization / Control	Potential Cost
Potential Ergonomics	Unknown Side Effects
Fits a Diverse Population of People Types	Potential Safety Hazard
Encourages Public Creativity	Potential Continued Maintenance

Gives People a Sense of Ownership	Additional Required Knowledge
Parallels a Continually Changing Society	Hiring Kinetic Specialists
Puts Design in the Hands of the User	Additional Design Time
Space Efficiency	Opposition to Technology
Attracts People to a Place	Opposition to Technology in a Landscape
Can Match the Dynamic Natural Environment	"Unnatural"
Can Create a Flexible Framework for Modification	Not Environmentally Conscious
Allows for Multiple Functions to Take Place	
Provides Choice in a Landscape	
Can Create Jobs for Landscape Architects	
Could Encourage Social Interaction	
Could Provide Complexity and Mystery in a Landscape	
Could Increase the Longevity and Relevancy of a Site	
Could Provide Cost Savings	
Flexibility	
Fits a Diverse Range of Human Desires	
Could Encourage a Longer Length of Stay in a Landscape	

Table 8.1. Advantages / Disadvantages

Future Research Opportunities

As this is the beginning of a definition of kinetic landscape architecture, there are numerous pathways for continued research. The author has established five primary pathways for further research: prototype, design tools, built evaluation, human impact, and interviews.

<u>Prototype:</u> For the author, the next step would be to produce prototypes of possible kinetic mechanisms or landscapes. They can be simple, maybe manually operated furniture first, but eventually advancing to prototypes involving Arduino or something similar would be ideal. Making any kinetic landscape architecture concepts become a reality will only further advance the awareness of and belief in kinetics.

<u>Design Tools:</u> The author invites the newly proposed tools to be improved and critiqued in further research. In fact, many of the existing kinetic design tools can be improved. For example, a fully constructible kinetic landscape should be designed using the decision chart to test for improvements. Due to previously designing kinetic landscapes without this thesis, the author wants to design a kinetic landscape to see the improvement in the design and the new possible innovations that can be created.

<u>Built Evaluation:</u> There is a significant necessity for research in the construction, occupation, and management phases. This will follow the construction of more kinetic projects and specifically kinetic landscape architecture projects. The methodology of the case studies conducted through the Landscape Architecture Foundation's (LAF) Performance Benefit Series could be a valuable way to study the environmental, ecological, and social benefits of a kinetic landscape. Additionally, a comparison between a conventional landscape and a kinetic landscape could be a worthwhile analysis to help landscape architects decide between the two. With exploring new territory, the implementation of novel concepts is always an uncertainty, but the guesswork can be reduced with evaluating constructed kinetic projects.

<u>Human Impact:</u> Another pathway for future research is to test human interests and preferences towards kinetic landscapes. What amount of movement or artificial intelligence will people behave positively towards? Or what kind of kinetic environments will receive negative reactions? Introducing new and potentially alarming qualities to a landscape requires prior thought of how people currently interact with the built environment and how that would change

with a kinetic environment. This signals the need for more research like the Kaplans' with a specific emphasis on kinetics.

Interviews: With more time, the author would have preferred the catalog text be gathered from the designers of each project for more thorough and accurate descriptions. In some cases, the descriptions are vague terms like 'metal' or 'computer controlled', but if an in-depth case study was completed on each project designers would have exact materials and control mechanisms to include in their projects. More conversations with professionals working with kinetics would have been a beneficial addition to the catalog as well as the entirety of this thesis. Their professional experiences and opinions would be useful to other new kinetic designers.

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Figure 2.1. Maritime Youth House. From: Archdaily, https://www.archdaily.com/11232/maritime-youth-house-plot (accessed February 20, 2019).

Figure 2.2. Parkmobiles. From: CMG, https://www.cmgsite.com/project/yerba-buena-district/parkmobiles/ (accessed February 21, 2019).

Figure 2.3a and 2.3b. Hörn Bridge. From: The World Geography, http://www.theworldgeography.com/2013/09/movable-bridges.html (accessed February 25, 2019).

Figure 2.4. Okeechobee Waterway, Florida Swing Bridge. From: Britanica, https://www.britannica.com/technology/swing-bridge (accessed February 25, 2019).

Figure 2.5. Pont Jacques Chaban-Delmas, France Vertical-Lift Bridge. From: The World Geography, http://www.theworldgeography.com/2013/09/movable-bridges.html (accessed February 25, 2019).

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Figure 2.7. Aerial View of Ascot Racecourse. Adapted from Google Maps. Ascot Racecourse, High St, Ascot SL5 7JX, UK. 51.4122° N, 0.6791° W. Google Imagery 2019. (Accessed February 21, 2019).

APPENDICIES

APPENDIX A

Definitions

The following definitions are important to the thesis as a whole, topic specific definitions will be located throughout the thesis as needed. The definitions are in relation to this thesis topic and may not apply if taken out of context.

Kinetic Landscape Architecture: a human-made exterior environment with an additional ability to continually move and/or adjust within the established site.

- Actuator: a machine element that triggers movement like an electric motor. It is the ‘mover’ and requires a control signal and a source of energy to operate.
- Akinetic: without motion.
- Artificial Intelligence (AI): machines capable of intelligent behavior similar to humans with desirable traits like learning, self-correction, emotion, speech recognition, reasoning, and problem solving.
- Cybernetics: a broad science, covering many disciplines, of examining the design and function of regulatory systems involving feedback loops, information, and goals.
- Deep Learning: a form of machine learning with many layers of calculations being made simultaneously, allowing machines the ability to identify objects in images and to recognize and process language.

- Dynamics: branch of mechanics that specifically deals with motion.
- Flexible: the ability to be easily modified; a space easily allowing a variety of uses; a "flex space".
- Kinematics: branch of mechanics studying the motion of objects *without* concern for the cause of motion or force. Kinetics is concerned with the cause of motion or force. Examples of kinematics includes studying velocity, speed, position, and acceleration.
- Kinetic Architecture: architecture with movable structure or elements.
- Kinetic Energy: energy held by an object by being in motion.
- Interactive: involves human and environment interaction with a feedback loop – it is not a one-way interaction.
- Mechanics: branch of physics that studies motion and the acting forces. It involves statics, dynamics, and kinematics.
- Mobile/Transportable: able to move location.
- Morphology: study of form and structure.
- Open-ended Design: a design crafted to allow many uses.
- Responsive: structures that respond to social or environmental stimuli.
- Sensor: component capable of registering physical or chemical characteristics in its environment and transforming these into signals to send to the actuator.
- Shape Memory Alloy (SMA): exhibit the ability to deform from one shape to another and then return to their original shape.
- Smart Material: engineered material that responds intelligently to its environment.
- Soft Robotics: a subcategory of robotics dealing with constructing robots that are pliable and flexible like the body of an octopus.

- Statics: branch of mechanics that specifically deals with motions in equilibrium.
- Topology: the study of deformative properties like stretching, bending, twisting, and expanding of shapes that allow transformative and continuous movement without breaking.
- Transformable: able to take on different spatial configurations.
- Ubiquitous Computing: in contrast to desktop computing, ubiquitous computing is embedded in the world around us, made to appear everywhere, in any format.

APPENDIX B

Significant Literature

The most influential literature providing the greatest impact to this thesis are (1) *Kinetic Architecture* (Zuk and Clark 1970), (2) *Move: Architecture in Motion - Dynamic Components and Elements* (Schumacher, Vogt, and Schaeffer 2010), (3) "Understanding kinetic architecture: Typology, classification, and design strategy" (Megahed 2017), (4) *Building dynamics: Exploring architecture of change* (Kolarevic and Parlac 2015), (5) *Interactive Architecture* (Fox and Kemp 2009), and (6) *Responsive Landscapes: Strategies for responsive technologies in landscape architecture* (Cantrell and Holzman 2015).

Currently, the author considers these the first books and papers to read when introducing a landscape architect to kinetics. If there is a limited amount of time to understand kinetics, these should be read and understood for the foundational knowledge of kinetics a landscape architect would need. As more literature on landscape architecture featuring kinetics arises, this list will change.

Kinetic Architecture (Zuk and Clark 1970) is the seminal text on kinetic architecture and should be read to understand the origins of kinetic architecture. Most authors following Zuk and Clark have referenced their work and strive to build on their foundations. It was important for this thesis as an introductory text on kinetic landscape architecture to draw from how Zuk and Clark introduced kinetics to architecture.

Move: Architecture in Motion - Dynamic Components and Elements (Schumacher, Vogt, and Schaeffer 2010) is a beautifully designed book with the best imagery. It has a large selection of diagrams depicting kinetic mechanisms like the different types of track systems or actuators.

In addition, an extensive set of detailed case studies take up almost a third of the book, featuring construction details of kinetic structures. The diagrams and construction details are very helpful for visualizing and understanding kinetic movements. *Building dynamics: Exploring architecture of change* (Kolarevic and Parlac 2015) and Interactive Architecture (Fox and Kemp 2009) are both similar books to Move. All three include lots of imagery, exciting projects, materials, and technology advancements. Each book includes different examples and should all be read for the best understanding of the latest kinetic advancements.

"Understanding kinetic architecture: Typology, classification, and design strategy" (Megahed 2017) is a recent article presenting several kinetic design tools. The article is concise and provided a good summary of where kinetic architecture is research wise.

Lastly, *Responsive Landscapes: Strategies for responsive technologies in landscape architecture* (Cantrell and Holzman 2015) is an excellent source for the latest technology in landscape architecture. They focus on responsive and not kinetic technologies, but many apply to kinetic landscape architecture. Cantrell and Holzman present exciting ideas of innovation and futuristic concepts that kinetics could play a part in.

APPENDIX C

Categories of the Intellect	Surprise	This is intimately connected with the concept of innovation. The artist is attempting to discover new domains of vision and feeling. There is a kind of pleasure associated with this activity of exploration, as there is in the violation of established rules. At the same time, the artist's intentions may spring simply from a voluntary or involuntary naivete.
	The Humorous	The serious might resemble repetition and machine-like characteristics. The humorous might be awkward or related to the game.
	Astonishment	The marvelous aspects of movement feature particularly in the theater and choreography of the seventeenth century. It has been suggested in this connection that 'the marvelous is in its essence dynamic.'
	Ludic Amusement	There is no doubt that the increasing importance of the element of movement in the plastic arts has reinforced the link between art and games, especially when this has facilitated the incorporation of music and dance.
	The Unexpected	Artists are able to exploit the effects of chance in nature and in the work of art by means of the irregularities of movement, as well as through the choice of a particular obstacle - a fountain, firework display or garden - which will inevitably operate in an unpredictable way.
	The Fantastic	The entire range of imaginary movement - flight, levitation, falling etc. - can be used in the evocation of the fantastic, as can the sensations of strangeness and the extraordinary.
	The Impossible	The impossible may be evoked through the figuration of representation of movement - for instance, by the impression that physical laws like the law of gravity are being broken.
Categories of the Environment	Identification with Nature	Movement like that of the wind and the sea have always inspired artists.
	Life (and vitalism)	Movement in art often gives rise to an aesthetic sense of identification with life. For example, with organic growth, imitating life of the city, or real movement in a biological sense.
	The Machine Aesthetic	The introduction of machine movements in art can be equated with the idea of identification with the industrial and mechanical universe.
Categories of the Sensibility	Hypnosis	The sheer repetition of certain well selected stimuli can give rise to a hypnotic state. Optical effects, repetitions, and lights are common components.
	The Irrational Fear	The subconscious - or unconscious - is a field which provides much evidence for the existence of irrational movements, and particularly those which occur in dreams. Quite a large number of works involving light and movement succeed in evoking the world of dream or delirium, although they may be calculated and sometimes executed with the greatest degree of logic and precision.
	Anguish	Such phenomena as the violent transformation of color, the appearance and disappearance of rainbows, cloudy skies, impressions of vacuity and all forms of menacing movement, which relate to actual or potential danger, lend themselves particualrly welll to this category.
	Displeasure	The feeling can become valid through the effects of light and color interference and of continually changing forms. Movement that is deliberately ugly in character, and gives the spectator a feeling of revulsion, can be used to seek reaction.
	Nostalgia	Art that is prone to nostalgia for the past, the ideal or experiences that are irrecoverable.
	Pure Sensation	The modern attitude towards movement, which consists in reaching the senses of the spectator, without any intermediary. The immediate aim of art can be to reach the spectator's perception and so to encourage his participation.

Appendix C. Common Characteristics Found in Kinetic Art. Based on: Popper, Frank. 1968. Origins and development of kinetic art: New York Graphic Society.

Categories of Action	The Agogic	Speed and tempo can vary from the extremely rapid to the almost imperceptible (Bury). GRAV have made an intelligent use of optical acceleration in their Labyrinths. Schöffer has succeeded in programming a complex sequence of slow and fast movements.
	Sexuality	Sexual movement can be inspiration .
	Grace	Guyau write, with reference to Spencer: 'What kind of movement gives us the impression of grace, when we ourselves are performing it or when we are watching it? It is the kind of movement in which all muscular effort seems to have disappeared and the limbs work freely, as if supported by air. '
	Ballet, Acrobatics, Sport	There is a very distinctive flavor about the way in which artists have given expression to choreographic movements ever since prehistoric times. Schöffer has devised a number or cybernetic sculptures which can themselves take part in choreographic spectacles.
Categories of Transcendence	Time and Eternity	A large number of artists have intentionally tried to incorporate time or space-time into their works. Sense of time, eternity, irreversibility of time, and the use of 'micro-time' are a few examples.
	Freedom and Constraint	Movements that suggest freedom are usually connected with the artist's desire to emphasize the need for escape. Pollock tried to express sense of liberty in a period which was characterized by constraint. Bury uses real movement to convey a sense of liberation from physical forces.
	Evolution (progress)	Connected with the idea of modernity.
	Rupture	This category would include all linear or cyclic movements which involve a period of interruption or a sudden change in direction. It is often to be equated with the notion of progress taking place through a series of revolutions.
	Spiritual Energy	Association of ideas between movement as a force and the figurative representation of movement.
	Synthesis	One of the most well-attested features of movement in art is its tendency towards the spectacle.
	The Sublime	Pure excellence can inspire great admiration or awe.

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APPENDIX D

Criteria	Evaluation of transformable tensile membrane structures
Design	
Expansion and flexibility	The stability of the structure in different stages during transformation is limited. However, transformable tensile structures that keep their pre-tension states during transformation can create more flexible architecture. This type of structure is usually used in fully deployed and fully open configurations. Modular design is applicable- several individual modules can be assembled to create both fully enclosed and semi-enclosed spaces. Membrane structures can be combined with many type of structures and can create transformable hybrid structures.
Compactability and transportability	The structure can be folded to a very compact state due to the flexibility of membrane material. However, the selected transformation mechanism and type of material may affect the degree of cmpactness. Due to the high degree of compactness, they are very good alternatives transportable architecture. Transformable membrane with movable supporting structures usually have lower degree of compactability.
○ *Structural stability and deformability*	The structure is usually stable only in the fully open configuration if the appropriate form is designed and the membrane is in pre-stress state. Very limited deformability as any load changes may drastically affect the structural stability

Appendix D. Evaluation of Transformable Tensile Membrane Structures. From: Asefi, Mazier. 2010. *Transformable and Kinetic Architectural Structures: Design, Evaluation, and Application to Intelligent Architecture*. Saarbrücken: VDM Verlag.

	and consequently result in the collapse of the structure. The influence of transformation on architectural spaces greatly depends on the selected transformation mechanism. However, the supporting structure and operating systems specially in cases that they do not move during transformation and remain in place can interfere with the architectural spaces usually by casting shadow. Special arrangements are also required to protect the membrane in the folded state
General architectural consideration for pneumatic transformable architecture	Similar to tensile fabric structures, they have low architectural flexibility. However, air-inflated architectural modules can be assembled and can create a variety of configurations with a high degree of flexibility. This type of structure is quite vulnerable to changing environmental loads and may be suddenly deflated. However, due to the lightness of the membrane material, they are still safe and efficient alternatives to be considered for transformable architecture. They have low mechanical complexity and do not require complex operating systems High to medium degree of compactness depending on the type of pneumatic structure (Air-supported or air-inflated tubes)
Construction and operation	Medium to high degree of operational reliability. Failure

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Reliability and safety	during transformation is possible as the control over the transformation of the membrane is limited. However, due to the lightness of the membrane material, the collapse or failure of the structure is less dangerous in comparison with many other types of transformable structures and the membrane is easy to be repaired or replaced in a short period of time
Auxiliary equipment	Lifting equipment may be required for the deployment of the structure depending on the size of the structure and the types of compressive supporting components especially when the structure is to be used temporarily. Additional tensioning cables and anchoring equipment may be required in order to stabilise the structure in the final deployed state. Compressors are also needed for pneumatic transformable structures.
Manufacture and shipment	Manufacture of the structure is complex as it involves careful cutting of the membrane and the assembly of individual sections on the basis of the structural form. The degree of flexibility of the membrane fabric also affects the complexity of the manufacture and shipment
Maintenance and costs	
Life-expectancy	The life-expectancy of the structures is greatly dependent on the life-cycle of the material membrane, which is usually less than 30 years and the frequency of the opening and closing of the membrane. The type of operating and supporting structure and environmental condition of the destination also affect the

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	whole-life cycle of the structure.
Maintenance management strategies	Regular inspection is necessary to make sure both membrane and supporting structure are in fully working order. The membrane needs to be cleaned periodically if it does not have an anti-adhesive surface. The maintenance management strategies should carefully consider the need for responsive maintenance due to the vulnerability of the membrane material to environmental changes and any malfunction of the operating and driving system
Costs	The running and maintenance costs depend on the characteristics of the membrane material and are also affected by the type of use, compatibility of the membrane and operating system scale of the structure and the frequency of opening and closing.
Application	Good alternatives for temporary shelters, portable architecture and for small to medium scale projects. Their application for large scale building such as stadium building is possible. However, it is greatly dependent on the suitability and life-expectancy of the membrane material for specific application. For large-scale buildings, special attention should be paid to the design of the transformation mechanism and its reliability and safety

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APPENDIX E

Verticle Plane	HelioTrace Façade System	N/A
	Media-TIC Building	Barcelona, Spain
	Pitterpatterns	Stuttgart, Germany
	Wind Veil	Charlotte, North Carolina
	One Ocean – Thematic Pavilion for EXPO 2012	Yeosu, South Korea
	National Aquatics Center	Beijing, China
	Digital Water Pavilion	Zaragoza, Spain
	Wind Fins	Walnut Creek, California
	The Institute of the Arab World	Paris, France
	Nordic Embassies	Berlin, Germany
	Malvern Hills Science Park	Malvern, UK
	LIGO Science Education Center	Livingston, Louissiana
	Storefront for Art and Architecture	New York, New York
	Hyposurface Wall	N/A
	Waterwall	N/A
	Digitized Field	Santa Rosa, California
	Council House 2	Melbourne, Austrailia
	REX Towers	N/A
	Target Field	Minneapolis, Minnesota
	BIQ House	Hamburg, Germany
	Chain of Ether	San Diego, California
	Digital Graffiti Wall	N/A
	Torre Agbar	Barcelona, Spain
	BRAUN Headquarters	Kronberg im Taunus, Germany
	Q1 Headquarters Building	Essen, Germany
	EWE Arena	Oldenburg, Germany
	POLA Ginza Building Façade	Ginza, Tokyo
	Al-Bahr Towers	Abu Dhabi, UAE
	Simons Center	Sttony Brook, New York
	Articulated Cloud	Pittsburgh, Pennsylvania
	Church of Sacred Heart	Munich, Germany
	Metro Station Saint-Lazare	Paris, France
	Theresienwiese Service Center	Munich, Germany
	Kiefer Technik Showroom	Bad Gleichenberg, Austria
	University of Washington Gould Hall Green Wall	Seattle, Washington
	Fabio's Restaurant	Vienna, Austria
	St. Ingbert Town Hall	St. Ingbert, Germany
	House at the Milsertor	Hall, Austria
	Wind Screen	Cambridge, Massachusetts
	BWM Training Academy	Munich, Germany
	Shimmer Wall	Philadelphia, Pennsylvania
	Turbulent Line	Brisbane, Australia
	Wind Portal	San Francisco, California
Roof/Canopy	Alden Biesen Courtyard	Bilzen, Belgium
	Courtyard City Hall Vienna	Vienna, Austria
	Fortress Kufstein Courtyard	Kufstein, Austria
	Tabriz Islamic Art University Courtyard	Tabriz, Iran
	Miller Park	Milwaukee, Wisconsin
	National Centre for Popular Music	Sheffield, UK
	Qi Zhong Tennis Center	Shanghai, China
	Fukuoka Dome	Fukuoka, Japan
	Mush Balloon	Osaka, Japan
	Izumo Dome Stadium	Izumo, Japan
	Civic Arena in Pittsburgh	Pittsburgh, Pennsylvania
	Starlight Theatre	Rockford, Illinois
	Rothenbaum Tennis Centre Court	Hamburg, Germany

Appendix E. List of Kinetic Elements Encountered During this Research. By Author.

	Rogers Centre	Toronto, Canada
	Gardens by the Bay	Singapore, Singapore
	Riva Waterfront Promenade	Split, Croatia
	Venezuelan Pavlion EXPO 2000	Hanover, Germany
	Merko Serono Headquarters	Geneva, Switzerland
	Safeco Field	Seattle, Washington
	Iris Dome	Hanover, Germany
	Hoberman Olympic Arch	Salt Lake City, Utah
	Valencia Swimming Pool	Valencia, Spain
	Jaen Amphitheater	Jaen, Spain
	Munich Olympic Stadium	Munich, Germany
	Georgia Dome	Atlanta, Georgia
	Suncoast Dome	St. Petersburg, Florida
	Allianz Arena	Munich, Germany
	Mecca Umbrellas	Mecca, Saudi Arabia
	Al-Masjid an-Nabawi Mosque	Medina, Saudi Arabia
	Hohenems Castle	Hohenems, Austria
	Olympic Stadium Montreal	Montreal, Canada
	La Plata Stadium	Tolosa, Argentina
	Venezuelan Pavilion Expo 92	Seville, Spain
	Seville Olympic Swimming Pool	Seville, Spain
	Ariake Coliseum Roof	Tokyo, Japan
	Wembley Stadium	Wembley, England
	Arthur Ashe Stadium	Queens, New York
	Gerry Weber Stadium	Halle, Germany
	Tecklenburg Open-Air Stage	Tecklenburg, Germany
	Bad Hersfeld Theater	Bad Hersfeld, Germany
	Cologne Folding Umbrellas	Cologne, Germany
	Zaragoza Bull Ring	Zaragoza, Spain
	Kuwait Pavilion EXPO 92	Seville, Spain
	Rebgassli Housing Development	Vienna, Austria
	Valencia City of Arts	Valencia, Spain
	Kansas City Twin Stadium Roofs	N/A
	University of Akron Auditorium	N/A
	Chase Field	Phoenix, Arizona
	Aldar Central Market	Abu Dhabi, UAE
	Johan Cruyff Arena	Amsterdam, Netherlands
	Hoberman Transformable Canopy	N/A
	Olympic Tennis Center	Madrid, Spain
	Lakeside Stage	Lunz, Austria
	Genzyme Headquarters	Cambridge, Massachusetts
	Leaf Chapel	Yamanashi Prefecture, Japan
	F House	Kronberg im Taunus, Germany
	Wimbledon Stadium	London, UK
	Campus of Justice, Appeals Court	Madrid, Spain
	University of Phoenix Stadium	Glendale, Arizona
	Transformable Dome	Abu Dhabi, UAE
	Mercedes Benz Stadium	Atlanta, Georgia
	City Creek Center	Salt Lake City, Utah
	Florida Polytechnic University	Lakeland, Florida
Architecture/Structure	Gateshead Millennium Bridge	Gateshead, UK
	Kinetic Edge	N/A
	Graphisoft Slider	N/A
	The Shed	New York, New York
	E-Motive House	N/A
	Tatlin's Tower	N/A

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	ANZ Stadium	Sydney, Australia
	Dynamic Tower	N/A
	Tower Bridge	London, UK
	Villa Girasole	Marcellise, Italy
	Puente de la Mujer	Buenos Aires, Argentina
	Blur Building	Yverdon-les-Bains, Switzerland
	Ernsting's Family Distribution Depot	Coesfeld, Germany
	Meridian Buildings, Astrophysical Institute	Potsdam, Germany
	Spielbudenplatz	Hamburg, Germany
	Living Room House	Gelnhausen, Germany
	Pegasus Bridge	Normandy, France
	Push Button House	N/A
	Weekend House	Treflez, France
	Rotatable Housing Cube	Dipperz, Germany
	Pfalzkeller Gallery	St. Gallen, Switzerland
	Shop Entrance	Bramberg, Germany
	Rolling Bridge	London, UK
	Reiman Bridge	Milwaukee, Wisconsin
	Milwaukee Art Museum	Milwaukee, Wisconsin
	Theater Arts Building	N/A
	Maison Bordeaux	Bordeaux, France
	Sliding House	Suffolk, UK
	Falkirk Wheel	Falkirk, Scotland
	Flying Seed Pod Dome	N/A
	Pierre Chareau's Maison de Verre	Paris, France
	Schroder House	Utrecht, Netherlands
	Heliotrope House	Freiburg, Germany
	Woodrow Wilson Bridge	Washington D.C., USA
	17th Street Bridge	Fort Lauderdale, FLorida
	Johnson Street Bridge	Victoria, BC
	Sharifi-ha House	Tehran, Iran
Ground Plane	Courtyard in the Wind	Munich, Germany
	University of Phoenix Stadium	Glendale, Arizona
	Memory Pavement	N/A
	Split Level Stage Birmingham-Southern College	Birmingham, Alabama
	Laakhaven/Hollands Spoor	N/A
	Sapporo Dome	Sapporo, Japan
Furniture	Whirlstools	N/A
	Erika Mann Primary School	Berlin, Germany
	Coffee Bench	N/A
	The Rolling Bench	N/A
	Off-ground	Copenhagen, Denmark
	Ollie Chair	N/A
	Sliding Bench	N/A
	Adjustable Railing	N/A
	Adjustable Airport Seating and Tables	N/A
	Remote Home Busy Bench	Berlin, Germany and London, UK
Sculpture	Ephemeral Structures	N/A
	10 DEGREES	Cambridge, Massachusetts
	Field of Air	Denver, Colorado
	Wind Leaves	Milwaukee, Wisconsin
	Open Columns	Buffalo, New York
	Dune	N/A
	Do Nothing Machine - Eames	N/A
	Emergent Surface	New York, New York

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	Hylozoic Ground	Venice, Italy
	Strandbeests	N/A
	Liquid Shard	Los Angeles, California
	Expanding Heliocoid	Akron, Ohio
	Shade Shift	N/A
	Hyundai Sculpture	Goyang, Korea
	Dynamic Terrain	N/A
	BMW Kinetic Sculpture	Munich, Germany
Object	Super Cilia Skin	N/A
	Hygroskin	N/A
	4D Printed Self-Folding Cube	N/A
	Flare	N/A
	Dynaflex P01 Model	N/A
	FAST Mast (Folding Articulated Square Truss Mast)	N/A
	Sonomorph	N/A
	Commonwealth Aerostat	N/A
	NASA's STAC-BEAM Geometry Model	N/A
	Caress of the Gaze	N/A
	Progrmmable Knitting	N/A
	Leibinger's Kinetic Wall	N/A
	Kukkia	N/A
	Inflatable Dam System	N/A
	Adaptive Fritting	N/A
	Hoberman Sphere	N/A
	Chiral Self-Assembly	N/A
	Variable Geometry Truss	N/A
	IM BLANKY	N/A
	Sound Proof Window	N/A
	Muscle Tower II	N/A
	Responsive Skylights	N/A
	Expanding Video Screen	N/A
	Hanabi Lamp	N/A
	Living Glass	N/A
	Kinetic Blocks	N/A

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