TURING KEY KNOWLEDGE EXCHANGES WITHIN THE DESIGN PROCESS OF TRANSFORMABLE SHADING SYSTEMS

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ABSTRACT

In the field of sustainable architecture, transformability is an important way of actively responding to ambient conditions while also meeting the needs of occupants and addressing issues of building performance. This research contributes knowledge for architects about the potential of kinetics for the shading system to respond effectively to changes in its environment. Within contemporary architecture, there is a growing interest in motion; buildings and their parts are gradually shifting from static to dynamic. However, contemporary activities in architecture are evidence of a lack of a holistic approach to the design of motion in architecture, and the design of motion as an alternative mode of design thinking is still in its infancy. Consequently, the existing tradition of static forms being the sole forms taught in architectural studies should be reevaluated as a design strategy.

This research is a step in the direction of better understanding the key knowledge exchanges within the design process of transformable shading systems. It will seek to investigate, explore, and propose how the concept of transformability in designing shading systems can be suggested, depicted, or physically incorporated in building envelopes.

In order to get the full potential of the design process of transformable shading systems, this study presents a design workflow of a specific case, called AURA, that helps to create openings for establishing a proper design methodology of transformable shading systems. While the workflow will be concerned with identifying the key decision nodes, it

is anticipated that in depth development will determine critical parameters addressing transformation itself as a design parameter of transformable shading systems.

Two studio-based courses offered at Virginia Tech and Texas A&M by the author will become a testing ground for evaluating the key decision nodes found in the design process of AURA within the context of architectural programs, bringing forth the opportunity to expand the current domain of transformable shading systems to a broader perspective of architecture pedagogy. In this case, this research is a step towards adding values directly into the content of the curricula, and thus into the field of design education as a whole.

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1 Chapter 1: Introduction

1.1 Background

Building envelope design is a central issue in the design of energy-efficient buildings. Due to the improvement of building services application such as in lighting, heating, ventilation and air-conditioning (HVAC), most current building envelopes have gradually lost their role as a moderator of energy. As a consequence, these building envelopes, instead of actively adapting to provide acceptable levels of comfort and controlling the flow of energy, mainly serve as a layer of insulation.

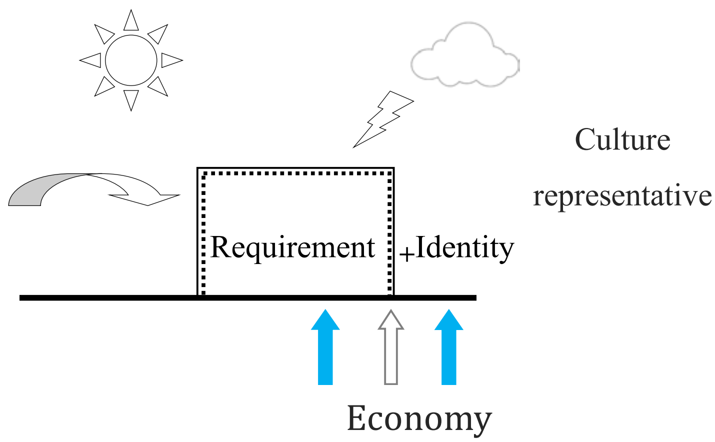

Figure 1: Inside and outside environments are constantly changing. Buildings are usually thought of as being static constructions, when in reality they are dynamic, responding to changing thermal, wind and lighting conditions. Unfortunately, these dynamic are seldom formative in architecture.

Conventionally, the building envelopes are not capable of adapting and responding to various changes that they are exposed to since the external environmental boundary conditions are designed to be "static" (Figure 1).

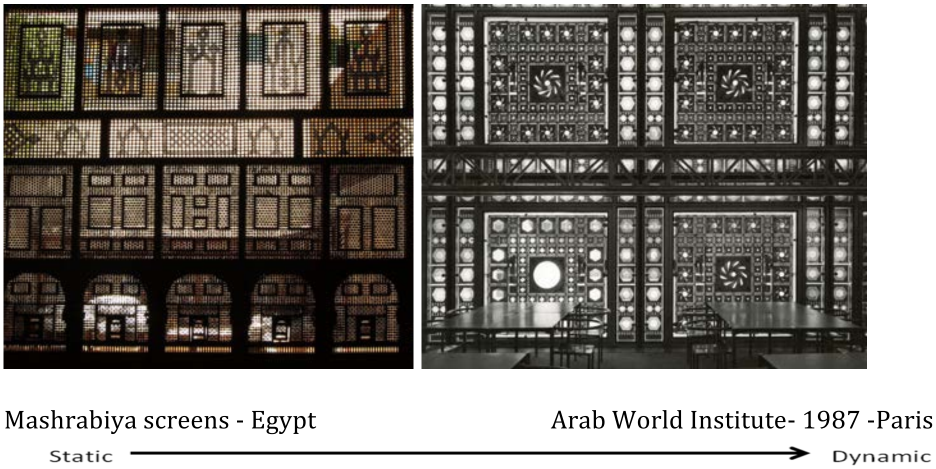

Figure 2: From Static Shading to Dynamic to provide acceptable levels of comfort

In order to retain the function of building envelops to accommodate dynamic environmental conditions, one of the most promising and innovative strategies for the next generation of building envelope is based on an adaptive and integrated solution that is able to optimize thermal performance, integrate active elements and systems, and exploit energy from renewable sources. This façade type system is great over periods of time, and allows for any adaptable control of the building environment throughout the life of the building (Figure 2, Figure 3). Among the most appropriate parts of building envelopes to apply this idea are shading systems (Figure 4, Figure 5).

Figure 3: The same shading concept in old and new buildings. Shading devices are the layer that can accept most of adaptive concepts. They can control light, glare, view, air quality and the amount of heat transfer.

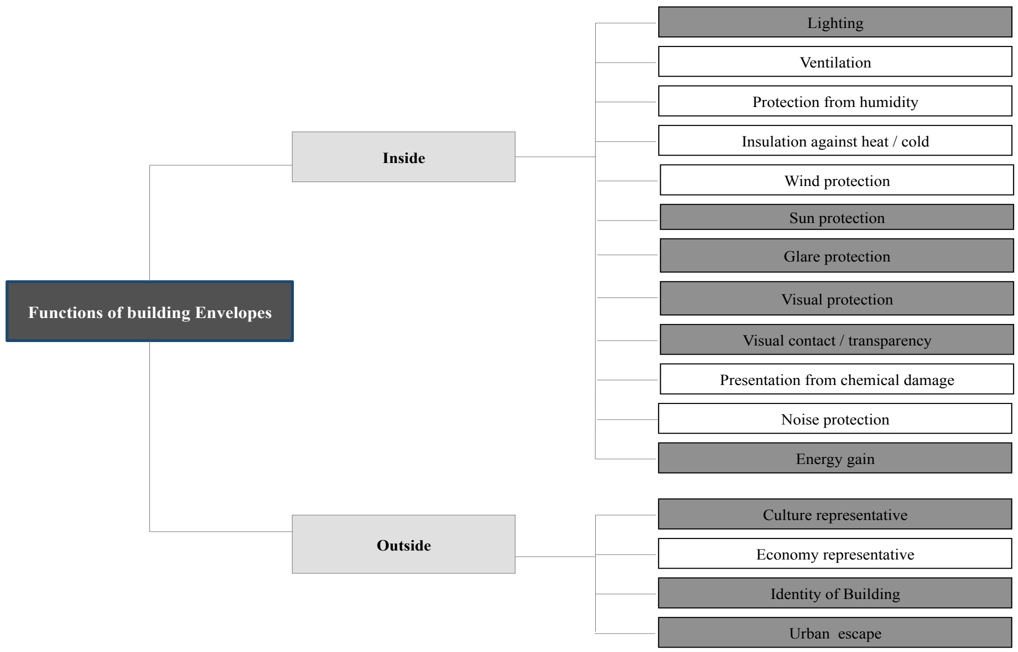

Figure 4: Functions of building envelopes related to the inside and outside. The colored boxes present issues that shading devices can play a significant role.

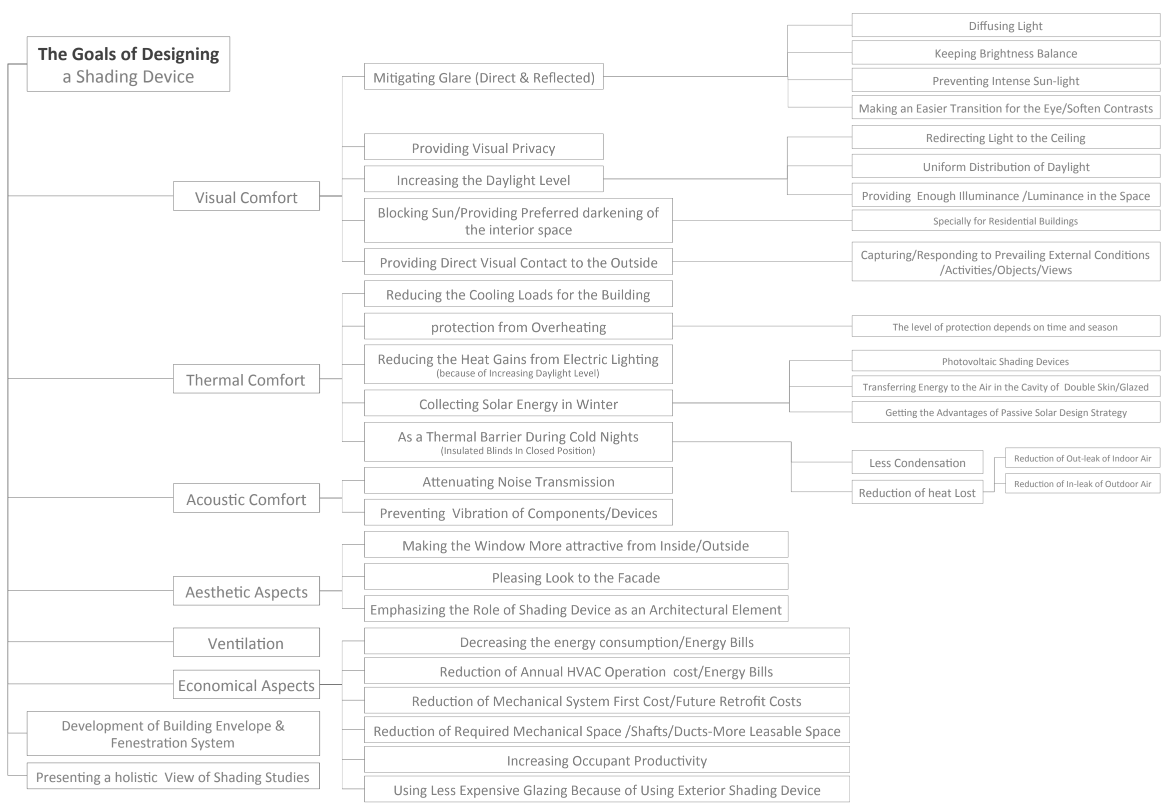

Figure 5: The goals of designing a shading device

In order to accommodate dynamic environmental conditions, transformability is an adaptive design strategy that tries to achieve an acceptable level of performance through adaptation of functions, configuration, features or behavior. For this, transformable shading devices tend to underpin the concept of the “adaptive building envelope.” Transformable shading systems can be part of an adaptive building envelope to create buildings that are more responsive to their surrounding environment while meeting the needs of the occupants.

By mitigating various environmental problems to regulate the indoor environment and add to the occupants’ comfort, transformable shading devices can reduce the need for mechanical systems. Although these devices are not anticipated to replace the mechanical systems, they could lessen the energy demands of the building significantly (Hansanuwat 2010). Transformable shading devices could be used to generate electricity as well.

With the goal of understanding the full range of terms that are used to describe shading devices, an in-depth study of related literature is first carried out. Although, in many cases, shading systems are described by the words that are used for adaptive design strategies, most shading devices do not adjust to dynamic environmental conditions. Shading devices are typically designed for the extremes (peak summer conditions) and consequently there are limited opportunities for the users to adjust them for other conditions[1].

In the implementation of transformable shading devices, designers can take advantage of both the perceptual and the functional qualities associated with motion as the visual, acoustical and thermal properties of kinetic shading devices are not fixed. Kinetic shading devices can contribute to greater satisfaction with the visual and thermal comfort

[1] This may be of particular concern for glare.

conditions within the building while providing an adaptable interface between the dynamic outdoor environment and the more habitual climatic preferences of the inhabitants inside.

In a broad sense, any shading device with operable parts can be considered as a kinetic system. However, the emphasis here is on systems that go beyond the ordinary. For the proposed research, a Transformable Shading System (TSS) has specific geometric rules that result in a visually stunning appearance and movement in response to both the indoor and outdoor environments and user needs. Because of the underlying geometry, the systems can be scalable and adaptable to a variety of architectural goals.

1.1.1 Motivation

As Parkes states "*utilizing movement is a natural mapping for interaction, reflecting the fact that human beings possess a deeply rooted response to motion, recognizing innately in it a quality of 'being alive'*"(Parkes 2009).

Fascinating and impressive to watch, kinetic compositions never cease to amaze the author. Movable objects capture her imagination and keep her entertained for hours as they spin, twirl, flex or glide as if they have a life of their own. Likewise, when a set of motionless objects suddenly spring to life and move, their stunning vibrancy delights the author 's senses and sometimes mesmerizes her. The author has realized that manipulating and running movable objects can engender pleasure in her. The authentic pleasure of watching motion always retains a certain sense of joy and cheerfulness for her as well.

The author's design inspiration predominantly derives from playful objects and most of her designs are playfully dynamic. She has noticed that these designs are analogous to deployable toys that captivate everyone who plays with them. Moreover, many people perceive some of her designs as an inspiration because of their contingency and vivacity.

The author was drawn to the vibrancy and excitement of transformability sixteen years ago. At that time, she had a unique opportunity to work with a research team at the Art of

Engineering Lab that was on the front lines of research in the field of transformable structures. In the Lab, several portable and movable projects were explored, some of which were built. Therefore, she is conducting this research from the perspective of having worked as an architect designing transformable structures in different scales both alone and collaboratively. The author has designed several transformable structures and interactive projects that she has not yet seen before and may carry some particular implications for establishing a TSS.

This study is derived from her previous research projects: "Building Skins and their characteristics"[2] and "Transformable structures and kinetic systems; potential applications in Architecture."[3] These two projects helped her ponder the question of "adaptability" in building envelopes as a "responsive," sustainable solution to environmental changes. Consequently, this study speculates on the advantages of thinking about building skins in terms of "adaptation,"[4] evolving from the idea of "motion" in architecture. In regard to the background study, Figure 6 shows the chronological design and models built previously by the author. It demonstrates her involvement in different transformable design-research projects.

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[2] Kalantar Mehrjardi, Negar, (2005). Building skins; concepts and characteristics, Master of Architecture thesis, Shahid Beheshti University

[3] This was a research project in the "Art of Engineering Lab," at Shahid Beheshti University.

[4] In her master of architecture thesis, the author concluded that there were nine characteristics for sustainable building skins, such as being adaptable, energy-positive, durable, healthful, comfortable, and integrated. affordable, and intelligent.

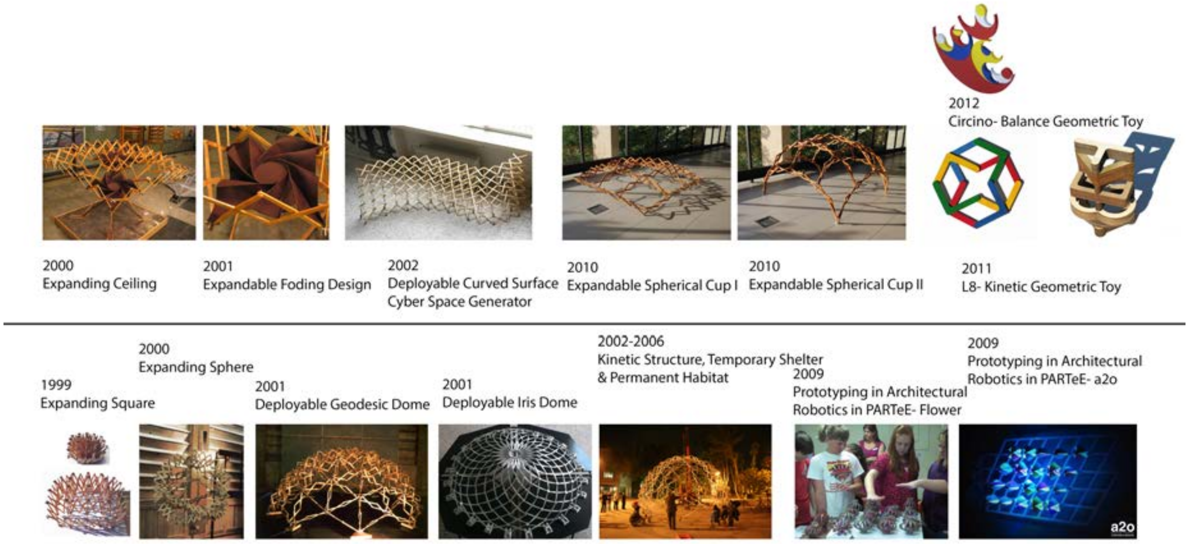

Figure 6: Author’s Kinetic Design-Research Background

1.1.2 Importance of Building Envelopes

Historically, the building envelope was more protective layer against the weather and enemies. Beside the protective responsibility, gradually this layer accepted additional roles such as communication medium (Socio- cultural reference), and regulatory functions to control light in the interior, an adequate air change rate, and a visual relationship with the surroundings.

Although in some cases architects focus on creation of successful external appearance for their buildings, the building envelope is becoming more a subject for design-research because of the importance of this layer with respect to energy consumption and possibilities for utilizing natural forms of energy.

The building envelope is the boundary between the interior of the building and the outdoor environment. The building envelope plays an important role in regulating interior temperatures, humidity, air velocity and radiation. The building envelope acts a dynamic filter between outdoor environment and indoor environment. This layer has three influential functions: Support the structural and mechanical loads of building, control the flow of matter and energy, and provide the human appeal inside and outside of building. Building envelope can act as absorber, filter, and reflector in respond to the solar radiation and temperature in protecting the building (Figure 7).

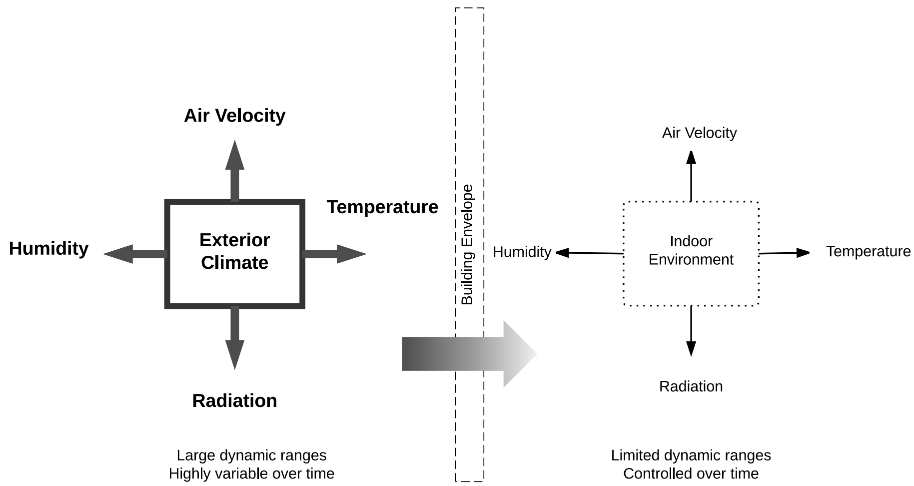

Figure 7: Building Envelope as Dynamic Filter (Herzog, Krippner, and Lang 2004)

1.1.3 The Importance of Windows and Fenestrations

Fenestration and building envelope share a lot of responsibilities to control interior environment. They both act as separating and linking elements between inside and outside. Each window has protective functions and regulatory functions. One of the essential responsibilities is windows impact on the total energy consumption of building. The U.S. buildings sector, which consists of over 85 million existing residential and commercial buildings, accounts for approximately 41% of the United States' primary energy consumption in 2010; more energy than any other end-use sector (U.S. Department of Energy 2014). 42% of U.S. residential building energy consumption was consumed for space conditioning, including both heating and cooling.

In the commercial buildings sector, lighting was the largest category of energy end use in 2010, consuming 20% of commercial building sector energy consumption. Space heating and cooling also consumed significant portions of commercial building energy consumption in 2010. Space heating consumed 16% of commercial building energy consumption, while space cooling consumed 14% of commercial building energy consumption. Space heating, space cooling, and lighting end uses across residential and commercial buildings consumed 21 quads of energy or nearly 52% of overall building energy consumption (Figure 8).

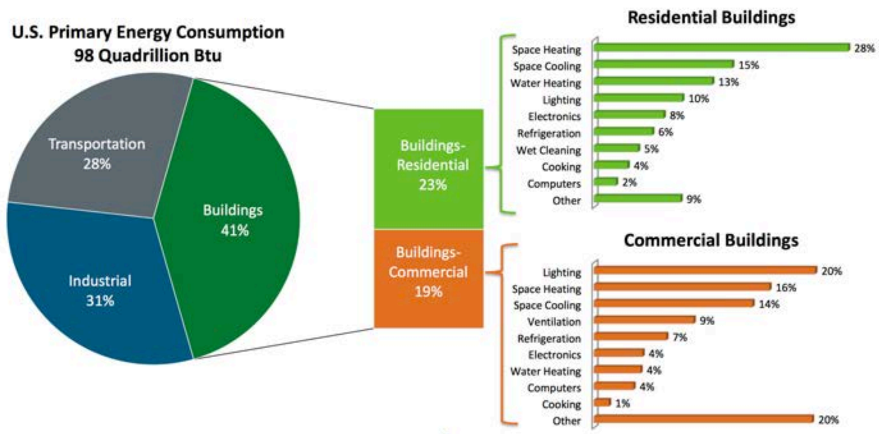

Figure 8: 2010 U.S. primary energy consumption[5]

Windows and building envelope technologies, have considerable potential to decrease energy consumption in buildings by consuming less energy from heating, ventilation and air conditioning (HVAC) due to improvement in windows and shading devices. Therefore, the windows and building envelope research areas has identified as priority areas of interest for Department of Energy. (Windows and building envelope research and development: Roadmap for Emerging Technologies, Feb 2014)

1.1.4 Potential Benefits of Windows

Generally, building envelopes roles can be summarized as insulation/separation, seals/barriers, filters, storage, redirection, physical barriers, regulatory functions, controlling/regulating, and responding/changing in order to increase or reduce the effect of conditions specific to the location, solar radiation, temperature, humidity, precipitation, wind, sources of noise in the surroundings, amount of gas and dust,

[5] Source: Energy Information Agency 2013d; Office of Energy Efficiency and Renewable Energy 2011b; Office of Energy Efficiency and Renewable Energy 2011e

mechanical loads, electromagnetic radiation, urban/formative surroundings, local resources, and socio-cultural context (Herzog, Krippner, and Lang 2004). The building envelope and windows can affect the lighting, heating, and cooling needs of the building. Windows can regulate the environmental energies (specific to the location) and provide a comfortable interior space (Figure 9).

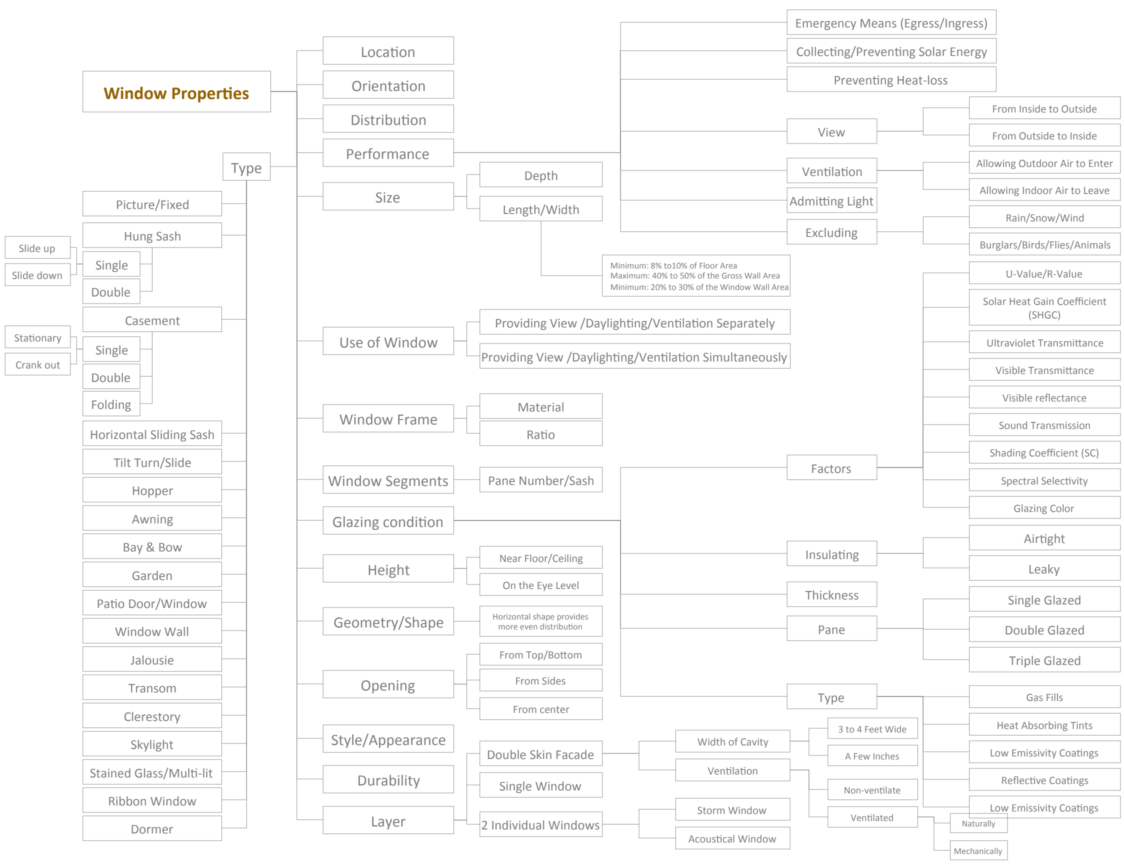

Figure 9: Window properties

Daylight:

Table 1 presents daylighting performance parameters.

Table 1: Daylighting performance parameters

Daylighting performance parameters	Visual performance	**Illumination**
		Glare
		Distribution
		Directivity
	Visual comfort	Outdoor view
		Health
		Social performance
		Color
		Appearance
		Privacy
	Energy saving	Lighting energy
		Thermal comfort

In nearly all climates controlling and diffusing natural illumination will improve daylighting. However, for daylighting to be "good" glare must be controlled. This is critically important when it is realized that the cost of office workers (salaries, benefits, etc.) is typically about 100 times higher than energy costs. The Transformable Shading Systems can directly address this issue by functioning as a dynamic glare control system. Able to open and close similar to the pupil of the eye, the kinetic system can reduce glare in daylit spaces.

The efficacy of daylighting in terms of saving energy is measured not only with economic methods, but also by psychological and aesthetic benefits that translate into financial benefits.

Visual performance

Studies indicated that the illuminance that comes from windows is about 450 lux/m² and above, every space has its own illuminance standards, for example indoor offices need about 850 lux/m² (Rea and Illuminating Engineering Society of North America. 2000). Designer should calculate the glare by daylight analysis software parametrically, glare should not exceed 45 percent, and it is preferable to not be below 30% (Alkhayyat. j, 2013).

Visual performance parameters are employed to decide if the provided lighting situation enables view or visibility and are directly linked to the physiology of the eye. Usually, decent vision is described by a sufficient amount of light for the predictable visual process, steady illuminance, luminance distribution, appropriate directionality to model three-dimensional series of faces and masses (direction of case light from the sides or from above), the non-existence of glare, and suitable comfort to render colors precisely when needed (International Energy Agency 2000).

Illuminance

Illuminance is the whole illuminating influx fallen on surfaces per unit area, it is actually a measurement mode for the amount of the fallen lighting that illuminate the surfaces, wavelength measured by the brightness purpose to interact with epidermal illumination perception (IEA, 2000).

Distribution

Illuminance and luminance distribution is a quantity of in what manner lighting differs from spot to another towards planes or surfaces. For good field of view, it is suitable to have a few amount of consistency towards the action planes. Bad visibility and visual harassing possibly will consequence eye enforcement to adjust itself very rapidly for an extensive domain of light levels (IEA, 2000).

Directivity

For many tasks, sufficient directivity is needed to model and assess three-dimensional masses and faces, the higher the quantity of diffused light, the lesser amount of shadowing takes place, decreasing ability for an occupant to assess the depth, form, and texture of a surface. A balance between scattered and directional light allows an occupant to determine the surface softness, glossiness, and other attributes (International Energy Agency 2000)

Passive Solar:

In cold temperate climates winter sun entering windows can positively contribute to passive solar heating; *"The sunlight that pours through a typical 4 by 8 foot window section in an afternoon can heat 15 to 30 gallons of water to a temperature hot enough to take a shower"(Rabin 2006).* Windows are one of the key components of most passive solar systems. They are collectors of sunlight enters the building. In climates that are appropriate for passive solar heating, windows (mostly south-facing ones) can let the heat into the building during the cold seasons.

Privacy and Views:

Beside the role of regulatory of the window, it provides a connection with the environment. Careful placement of windows and providing the means of control (such as controllable shading systems) allows for selection and modification of views. In addition to providing views, windows provide the visual communication between inside and outside, therefore the residence can monitor the outside environment. A window must provide the right level of privacy for the inhabitants as well. Transformable shading systems allow full range of individual control and create the right level of privacy for the users and accommodate changing view and privacy needs.

Energy Saving:

Rabin believes "*Good daylighting design can save up to 75% of energy used for electrical lighting in a building*"(Rabin 2006). Among other factors, in building envelope and windows design process, particular attention is given to daylighting in order to maximize visual comfort or to reduce energy use. Energy savings can be achieved from the reduced use of artificial (electric) lighting. "Good daylighting design can save up to 75% of energy used for electrical lighting in a building"(Rabin 2006).

The most important energy-concerning design purposes of a daylighting technique are to deliver useful daylight for a specific weather or structure kind for an essential period of the year that permits artificial lighting to be neutralized by natural daylight, air conditioning and heating systems loads to be decreased (International Energy Agency 2000).

1.1.5 Potential Problems of Windows

Excessive heat gain:

By admitting sunlight into a building, the building energy consumption will be impacted in different ways in different seasons. Although in winter, sun can definitely contribute to passive solar heating, in summer, unwanted solar heat gain results in greater energy consumption due to the increased cooling load requirement. Particularly, in hot climates, the main and critical design strategy for windows is to control heat gain by keeping solar energy out, while allowing enough visible light transmission for views and day lighting.

Stein (2006) states, "*Perhaps the single most important energy related component for passively cooled buildings is the sun shade*", claiming that if a building intercepts the sun before it enters the building, the cooling load can possibly be cut in half. (Stein 2006)

Glare:

Providing enough daylighting to the internal space may cause some undesirable side effects such as glare. Beyond adding windows or any type of fenestrations to a building, it involves carefully balancing glare control and daylighting. Inappropriate glare is actually occurred whenever intraocular light[6] spread takes place inside the eye, the

[6] Intraocular is the fluid pressure inside the eye.

difference in the retinal picture is decreased (usually at a lower light levels), and eyesight is partially or even completely obstructed, for example, once the eye faces front lights of approaching vehicles) (IEA, 2000). Distress glare is an experience of irritation due to large or non-uniform distributions of radiance in the range of sight. The physical system of inconvenience glare usually is certainly not properly recognized, an evaluation of inconvenience glare is depending on volume, luminosity, and quantities of glare sources (IEA, 2000).

1.1.6 Kinetic Shading Systems Reduce Potential Problems of Windows

As discussed, shading systems are one possible solution to the increased need of mechanical systems for comfort. Shading systems can be categorized as fixed or operable (Figure 10). Although fixed shading systems are designed to control the environment, these systems use when they are most necessary. Fixed shading devices cannot moderate and adapt to various settings. By optimizing the tradeoffs between shading, daylighting, and natural ventilation, the efficiency of a shading system is increased if it can adapt dynamically to the changing environmental conditions around itself (Figure 11, Figure 12). Givoni (1994) claims, "*Operable shading devices can admit all of the solar radiation when this is desirable, as it is in winter. Therefore, they are inherently more effective than the fixed shading*".

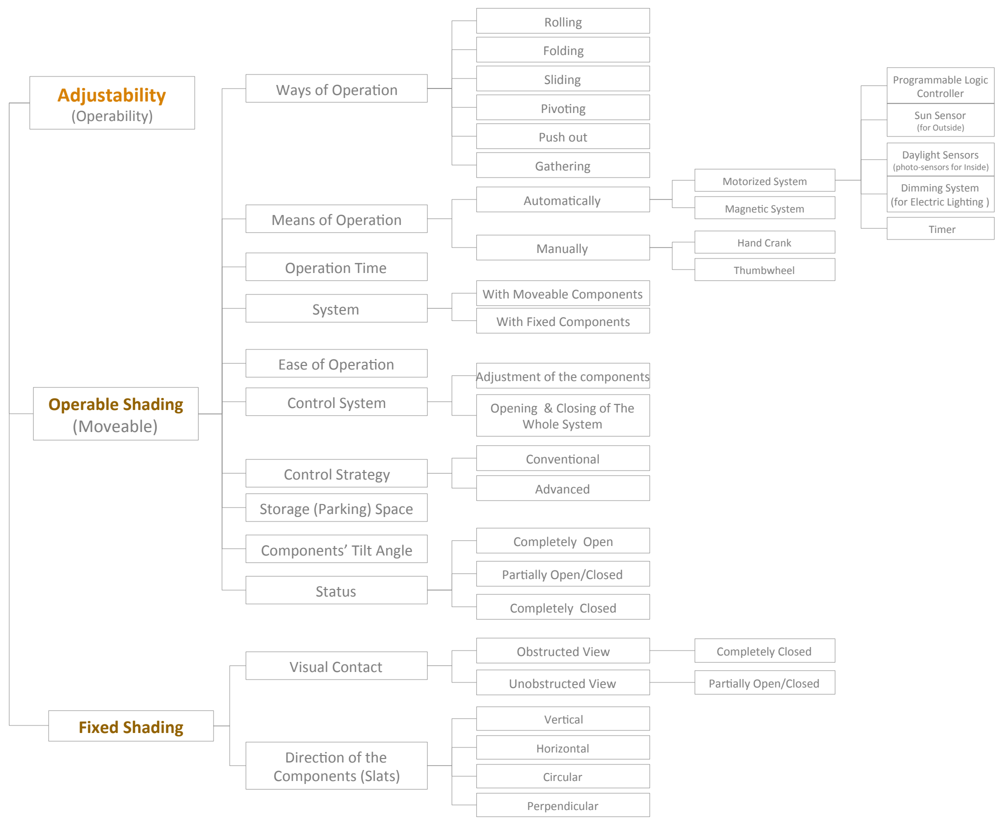

Figure 10: Type of shading devices

Kinetic shading devices can significantly reduce building highest cooling load and corresponding energy consumption and enhance daylight utilization in buildings. Depending on the amount and location of fenestration, reductions in annual cooling energy consumption of 5% to 15% have been reported. Shading devices can also avoid glare by reducing contrast ratios of building interior. Sun control and shading devices can also improve user visual comfort by controlling glare and reducing contrast ratios. This often leads to increased satisfaction and productivity.

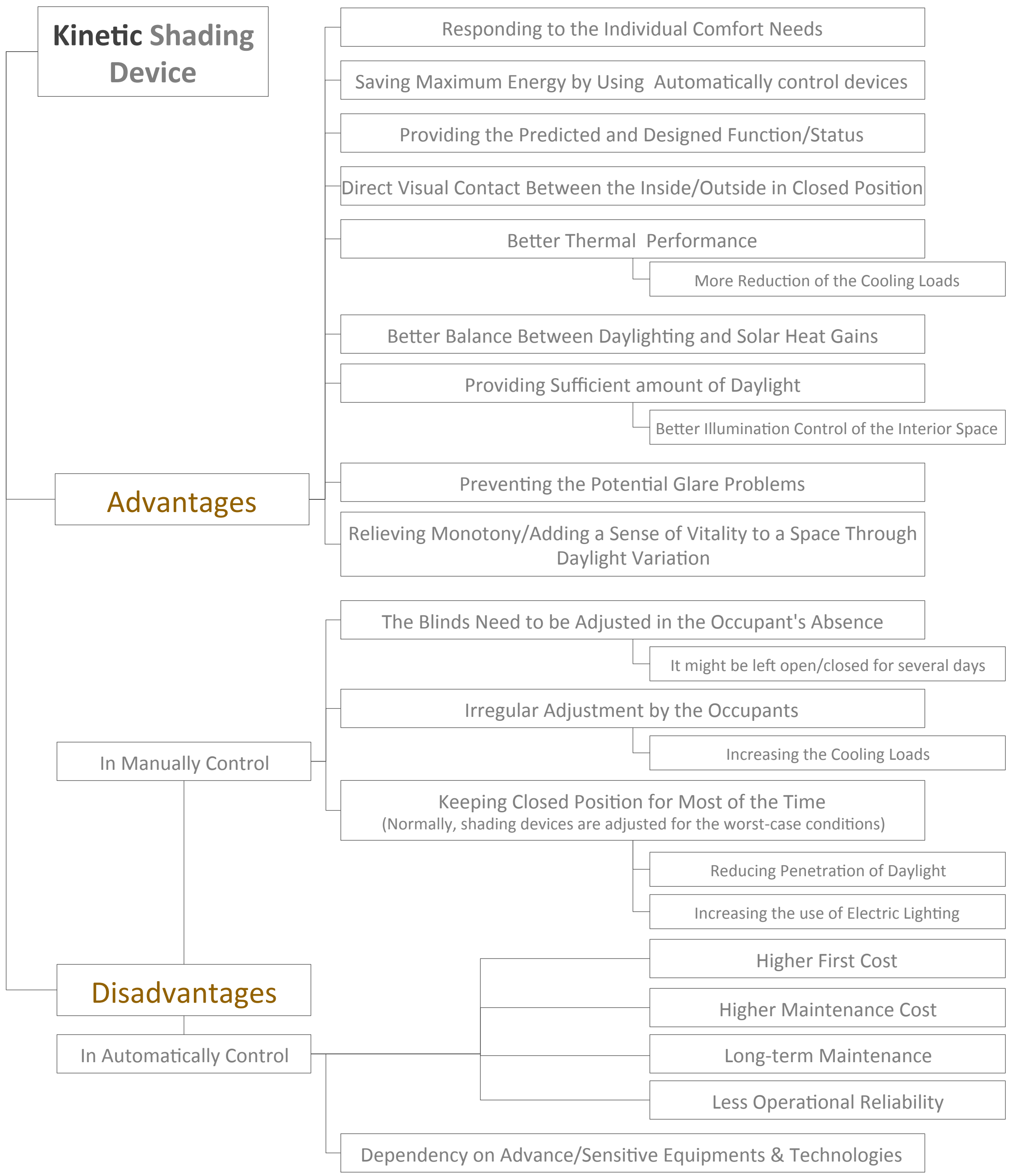

Figure 11: Advantages and disadvantages of kinetic shading systems

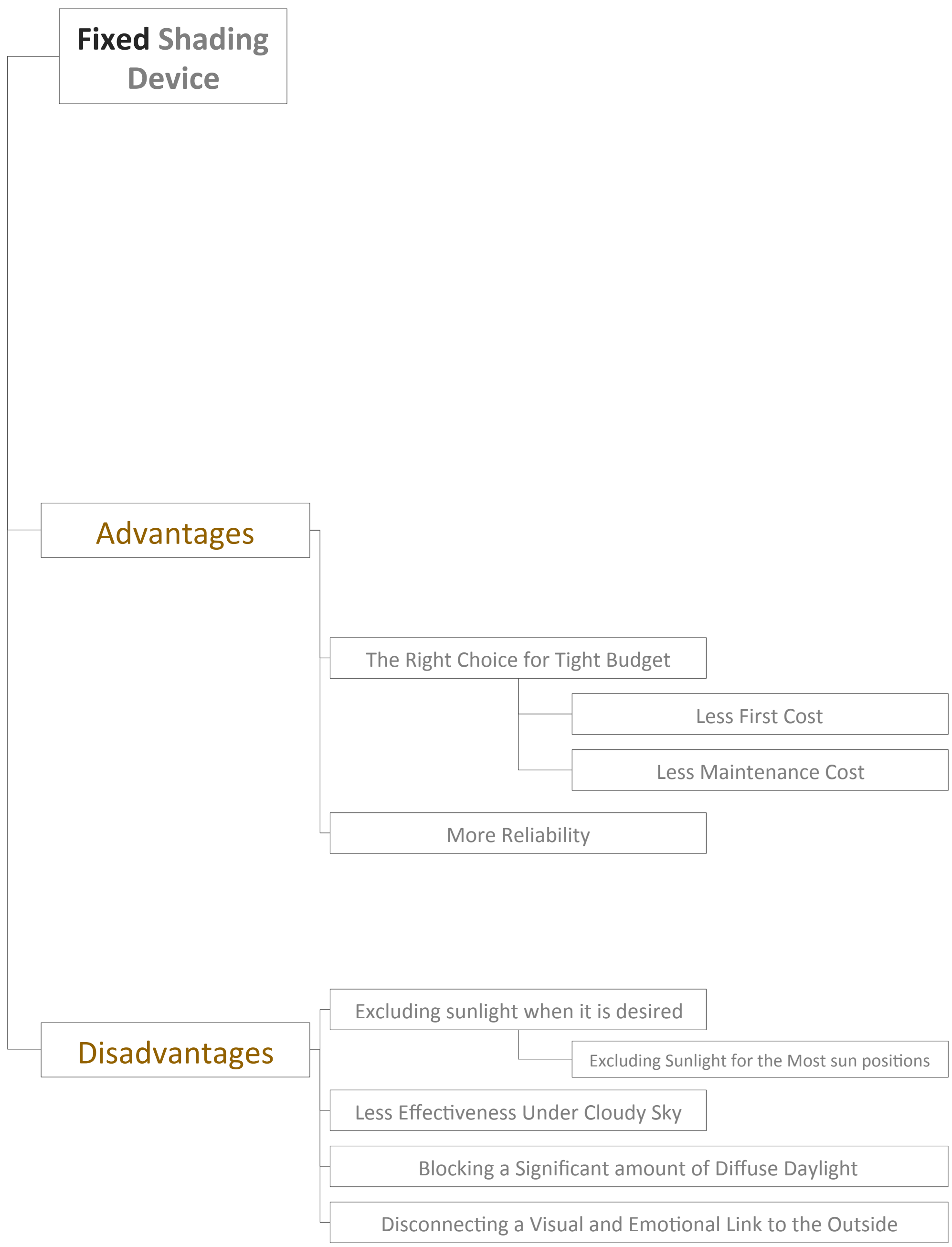

Figure 12: Advantages and disadvantages of fixed shading systems

When it comes to daylighting, the intense contrast of sunlight to the luminance of interior surfaces recommends shading systems. Natural light has to be controlled and distributed properly throughout the space. This is not a new issue: historically, human has learned to shade interiors from direct sun, developing some exterior solutions, such as awnings and overhangs, and interior solutions ranging from curtains and sheers to blinds, louvers, and roller shades.

Because the sun moves while the building remains static, almost all static shading systems are imperfect. Therefore, the static shading systems work well during certain seasons or during certain hours of the day, but they are ineffectual during others. Moreover, on cloudy days the shade often is undesirable in order to get enough light inside the space. The need for dynamic shading has resulted in a number of solutions. Most currently available kinetic shading systems are either louvered or roller blinds and consequently do not contribute to the aesthetic quality of the building.

The design and implementation of adaptive building envelopes is being encouraged by organizations and agencies such as the U.S. government. The U.S. federal research and development agenda mentions: *"....in order to meet the demanding Zero Energy Building performance goals windows must change their role from that of a static element to a dynamic element since performance requirements change by hour, season, and weather conditions.* "[7]

In addition, the inclusion of user controls can have a direct effect on the comfort range of occupant. A 2004 study by UC Berkeley (Brager, Paliaga, and De Dear 2004) for the American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE) showed that while the thermal environments of two different spaces could tend to be the same, the occupants response to those environments varied by the amount of control they had over the space. They found that, "[…] *occupants experienced surprisingly similar thermal environments (as well as CLO and MET levels), independent of the proximity to and degree of personal control they had over the operable windows. Despite the similarity of their thermal exposures, however, their reactions were significantly different*." ASHRAE standards also now have an Adaptive Comfort Model for naturally ventilated buildings

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[7] U.S. Federal Research and development Agenda- Net Zero Energy (High Performance Buildings (2008)), U.S. Department of Energy, National Science and technology Council (NIST), U.S. Department of Commerce and U.S. Department of Defense

that takes into account user control and adjusts the comfortable temperature range accordingly.

Furthermore, summery report 2012 of Department of Energy (DOE) Windows R&D Program states that dynamic shuttering is one of six recommended domains that need to be invested in and investigated by DOE ((DOE) 2012). Shading devices offer the opportunity of differentiating one building facade from another. This can provide interest and human scale to an otherwise undistinguished design.

Table 2: DOE Multiyear Performance Goals

Characteristics	Units	Calendar Year				
		2003 Status	2007 Status	2010 Target	2015 Target	2020 Target
Energy Consumption Improvement*	**Reduction in Window Energy Use**	**Base ENERGY STAR (Low E)**	**20-30%**	**30-40%**	**40-50%**	**40-60%**
1. Dynamic Solar Control	Incremental Price ($/ft²)	85-100	50	20	8	5
	Size (ft²)	8	16	20-25	25+	25+
	Visual Transmittance	60 to 4%	60 to 4%	65 to 3%	65 to 2%	65 to 2%
	SHGC	0.50 to 0.10	0.50 to 0.10	0.53 to 0.09	0.53 to 0.09	0.53 to 0.09
	Durability (ASTM Tests)	Medium	High	High	High	High
	Dynamic Response (speed/variable tint)	Slow/on-off	Slow/ On-off	Slow/ On-off	Moderate/ variable	Fast/ variable
2. Highly Insulated Windows	U-Value	0.33-0.50	0.20-0.25	0.17	0.10	0.10
	Incremental Cost ($/ft²)	IG Base Cost: 3	5	6	4	3
3. Daylight Systems	Lighting Energy Savings	40%	50%	50%	60%	60%
	Perimeter Zone Depth (ft)	12	15	20	20	30
	Incremental Cost ($/ft²)	3	8	8	6	6
4. Enabling Technology Research for Efficient Products	Tool Capability for Residential (R), Commercial (C) and New Technology (N)	R – Yes C – No N – No	R – Fully C – Partial N – No	R – Fully C – Partial N – Partial	Assess need for industry support	Assess need for industry support

TSS can reduce energy consumption associated with solar gain and space cooling. In many buildings a large portion of cooling loads are attributable to solar gains through windows, this suggests significant potential impact through technologies that directly reduce these loads. From this, a TSS could reduce energy consumption and can reduce the cost of energy used in buildings. In European countries, due to the higher energy costs TSSs are more frequently used. However, in the U.S. most of applications of TSS are driven by aesthetic considerations of architects or owners.

Adaptable kinetic external shade will reduce energy consumption associated with solar gain and space cooling. According to the U.S. Department of Energy Building Energy Data Book 2010, for commercial energy end use in the U.S., 14.5% of Primary energy was attributable to space cooling (2.60 Quadrillion Btu). Furthermore, the Aggregate Commercial Building Component Loads breakdown (1998) indicates that 32% of cooling loads are attributable to solar gains through windows. This suggests significant potential impact through technologies that directly reduce these loads. Using these figures, for a typical commercial building in the US the transformable shading system could reduce energy consumption by at least 5 percent. Also for buildings with longer cooling seasons, in warmer climates these savings would be significantly higher.

Optimizing Environmental Performance of Building Envelopes

In recent years, the building envelope has increasingly become the focus of research and development as a result of a growing awareness of the system's importance for meeting resource conservation goals.

In the last decade, there has been shift from trying to optimize a static design solution to making the façade kinetic. TSS can contribute to resource conservation as well as improve thermal sonic and visual comfort.

Building envelope needs mechanisms that allow it to become connected to its environmental context. This could be achievable by continually monitoring and responding to the environmental variables that influence the building envelope performance. TSSs involve dynamic permeability of the window sub-system in the way light enters and filters into the building. A well-designed TSS can optimize solar gain and light quality. As a dynamic system the thermo-physical and optical properties of windows can change over time. In this study, the main environmental impacts of TSS are summarized as follows: Resource Conservation and Solar Control and Daylighting and Glare Control.

1.2 Qualitative Aspects of Transformable/ Kinetic Systems

Despite the complexity and relatively high cost of TSSs, four architectural factors, if taken into account, might help to maximize the capabilities and use of transformable systems. They are: 1) adaptability to adjust to the external variables (the coexistence with the environment that they inhabit), 2) humanistic values (adaptability to accommodate internal demands and comfort factors), 3) the aesthetic composition and design requirement (the interface with the visitor and observer), and 4) optimizing environmental performance of envelopes.

Adaptability to Adjust to the External Variables

The ambient environment surrounding buildings is constantly changing. These changes are inevitable, and in order to respond to such changes and the needs of the building occupants, focus is placed on the important role of the building envelope as a critical element to mediate between changing indoor and outdoor environments

TSSs have the ability to respond to changes such as weather, day/ night rhythm, and seasonal changes. TSSs allow these changes to be expressed and informative in the design of building envelopes.

Humanistic Values: Adaptability to Accommodate Internal Demands (Comfort Factors)

This might include the goal to maintain an optimal thermal comfort level for inhabitants within the building while providing an interface between the unpredictable environmental conditions outside and the more habitual climactic preferences of the user inside.

One of the primary roles of the building envelope is to regulate the influence of the surrounding external conditions in order to ensure comfortable conditions in the interior. Similar to the external environment the internal conditions related to the comfort also vary hourly, daily, seasonally and yearly. The main comfort factors are indoor air temperature and average surface temperature, air change rates, humidity, and luminance and lighting intensity. Beside the physical comfort factors, there are psychological aspects such as privacy and views. Due to their transformability kinetic shading devices can adapt to different external conditions in order to achieve desirable comfort conditions in the interior.

The Aesthetic Composition and Design Requirement (the Interface with the Visitor and Observer)

Besides their environmental benefits, TSSs should be evaluated in terms of impacts on user well-being that might be unobtainable for a fixed system. The characteristics of these systems encourage architects to take into consideration the aesthetic of movement and the interface of transformable shading devices with the visitor and observer.

TSSs can be both appealing for their visual appearance and meaningful in terms of communicating a response to dynamic conditions (Figure 13). Transformable shading devices, as a part of the building envelope serve interior space yet contribute to the urban setting. These devices play a major role in the building appearance and help to integrate envelopes within the urban realm. TSS produces a stage upon which social, economic and physical changes play out based on the needs and expectations over a building's lifecycle. TSS can offer architects several indirect opportunities associated with regional identity.

As mentioned before, transformable shading devices have the unique ability to respond to changes occurring within both exterior and interior environments and allow these changes to be an expressional ornament. Movability produces an opportunity for functional ornament(Moussavi 2006) as a new design domain. Here, motion can play on the dichotomy of form and function producing architecture as rich in function as it is in aesthetics. By integration of motion within a shading system, functional ornament is able to be stitched with the cultural and urban fabric of the surrounding context. Transformable shading devices can be expressive out of an internal order that can "communicate".

Figure 13: Aesthetic aspects of kinetic shading systems.

The kinetic shading device discloses a different appearance at every stage of the motion and it will also affect the overall architecture of the building in a distinct way during this process. It can play with light, shadow and colors simultaneously in a way that reminds us of old shading devices in Eastern Countries.

1.3 Barriers and Constraints for limited application for Kinetic Shading Systems

Although fixed exterior shading devices are used in buildings for centuries, TSSs are seldom used. This is, in part, because the development and application of a TSS with movable parts is challenging. It is essential to take a look at why there are not enough transformable shading devices and why the potential of these devices is generally neglected.

Most currently available movable shading devices are either louvered or roller images of each blinds that do not contribute to the aesthetic quality of the building. This could be a limiting factor for market acceptance. Also, past research concerning shading system performance was limited to energy reductions while other key issues such as fabrication, installation, assembly, cost, etc. were not studied. Partly because of limited knowledge concerning kinetic shades, architects and building owners have been slow to use these systems. Architects are typically uncertain of the cost benefits of these systems and lack of knowledge concerning the benefits of the system nor issues related to design nor mechanical, structural or fabrication. On the other hand, clients are reluctant to invest in the use of innovative architectural systems where there is uncertainty about the cost and benefits. Some of these issues are addressed in following:

Lack of Precedence and Theoretical Studies

There are very few coherent theoretical references, nor is there sufficient building evaluation data to critique the type of kinetic façade design that could be adopted for environmental control (Fortmeyer and Linn 2014),(Moloney 2011). The architectural design principles and construction methods of kinetic facades have been under explored (Park, 2011). Even though kinetic patterns have been used as a responsive component for creating kinetic facades since the 1960s, there is no smooth genealogy tracing the development of the kinetic facade (Linn, 2014).

Lack of performance evidence

Performance-based technologies such as kinetic shading have infrequently lived up to their full potential. For example, the physical characteristics of shading devices have remained largely unchanged; suggesting improvement is necessary if the more demanding performance issues of today are to be addressed.

Higher cost

Although a large percentage of the building budget depends on the cost of its façades, building services can account for much more. By using a TSS, the cost of building services can be reduced. In this case, the cost of the façade system be made up by the decreased cost of HVAC and lighting systems. Wiggington (2002) states, "[…] *a variable building fabric, integrated with good 'passive' design, could redistribute investment costs from building services into building fabric, and thus reduce energy costs in use*". He continues, "*The façade of a building can account for between 15% and 40% of the total building budget, and may be a significant contributor to the cost of up to 40% more through its impact on the cost of building services*." [8]. In order to improve the

[8] Wiggington declares, "In complex buildings, the mechanical and electrical services can account for 30-40% or more of the total building budget. Associated research being carried out on the program suggests that between 30% and 35% of the capital costs of a well-serviced, high-specification office building is

competitiveness of TSS, it is necessary to assess its performance over a wider frame of reference and clarify differences in performance of fixed and operable shading systems over the lifetime of a building.

Unfortunately, TSSs represent only a small market segment, they are often more expensive than fixed shading devices. One of the considerable limitations of kinetic shading systems is high cost, although, the saving in cooling equipment cost may pay for the shading or at least the large part of it. In addition, some shading systems can limit heat loss in winter and thus decrease space heating needs. The payback period may be different based on location and type of buildings, and efficiency of shadings.

Reasons other than performance are seldom accepted

Designers of transformable shading devices should consider the combined effects of the functional and spatial qualities of the system. Most research concerning the kinematic has concentrated on the engineering aspects of the system while much less attention has been paid to the more architectural attributes, including the ability to change shape and pattern. This dynamic condition could be expressed particularly through kinetic structures as a part of the building envelope. A more holistic approach to transformable shading design could contribute to the increase use of shading devices to control light levels, solar gain, glare and privacy.

Less Exploration on Architectural Aspects of Kinetic-More Technical

A part of TSS design tasks are influenced by the field of engineering mechanics. Since the role of TSS is mainly determined by its functionality, the spatial aspect of movement as a main component of architecture is lacking. The spatial quality of a movement is not a by-product of its functional or energy optimization. Thus, it is necessary to express movement as part of the architectural design and go beyond the purely practical. As William Zuk's states "*a sense of motion, itself*" (Zuk and Clark 1970).

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attributable to building services, with 13-15% being attributable to what might be called environmental services: those services devised to control the internal thermal and ventilation environment."

Performance assessment procedures are not well understood

One of the biggest hurdles in advancing the development of kinetic facade designs and the components that emerge from them is a struggle to design and evaluate the performance of actuated systems (Moloney 2011).

Although, most of kinetic facades might be able to respond appropriately to changes in environmental conditions, there are minimal descriptions on how effective the kinetic mechanisms or composition are designed. There is no clear verification on how those mechanisms are adopted to the performance of building in response to environmental conditions. In many cases, there are not enough indications on how much energy is needed to run and control these kinetic facades. In addition, there is less evidence of efficiency of transformable facade projects in the eyes of manufacturers and users.

Domains of knowledge between design and performance are not well understood

To develop a further understanding on the potential of kinetics to contribute to environmental response in facades, there is less systematic breakdown of aspects and parameters that inform TSS design process. Among the required parameters, a conscious and deliberate consideration of performance analysis is a necessary and integral part of the TSS design process. The current simulation tools mainly center on static design. Since a transformable shading device does not have a single form, but continuous revolving shapes, there is no single parametric generative modeling software and simulation tools that allow designing the behavior of a TSS and its consequences in an integrated manner.

Interdisciplinary nature of design process is not well understood

Despite advances in building technologies, and material sciences, there are relatively few projects with kinetic facades. This may be due to the complexity in designing such systems where often knowledge of fabrication, assembly, systems integration and actuation in addition to performance is required. These issues must be balanced with appearance in the design process. Unfortunately, there has been little published research related to the process of designing TSS.

There is an extensive body of knowledge in other disciplines such as mechanical field. This research is about how to take this existing potential in the mechanical field to the next level and search for other possibilities in building envelopes design.

Lack of understanding for the design process

Kinetic systems are introducing new design challenges, as (Leupen, Heijne, and Zwol 2005) explains, "*Designing for the unknown, the unpredictable, is the new challenge facing architects today. 'Form follows function' is giving way to concepts like polyvalence, changeability, flexibility, disassembly and semi-permanence*."

Contemporary activities in the field of kinetic architecture are evidence of the lack of holistic framework for the study of motion. Except for a few works, the body of literature related to kinetic study does not explicitly identify any design methodology. The lack of content provides a challenge for the study of kinetic design and highlights the need for further study.

The scarcity of precedents and the need to step outside the formal traditions of static building envelopes provide a challenge for this new field of design research, as there is no coherent body of theory to reference, nor are there sufficient designs to critique. As we transition from static to kinetic systems for building envelopes, we encounter new design problems- how do we visualize and design for the physical processes of transformation? How do we 'fabricate' and 'evaluate' such systems? Therefore, making informed design decisions requires the management of a large amount of information concerning the detailed properties for alternative design options and the simulation of their performance. Understanding this will be a goal for this research.

1.4 Statement of the Problem

In the field of architecture, transformability can be considered as an important way to respond more actively to ambient conditions while meeting the needs of the occupants. Within contemporary architecture, it seems there is a growing interest in motion; buildings or their parts are gradually shifting from static to dynamic, but there is a shortage of design knowledge to support this new domain.

For most of the existing kinetic projects, the architectural aspects of movable systems are not considered with functional or technical constraints or the performance goals or operability of the system. This is because most designers do not have knowledge related to these issues and consequently their design process does not support including TSSs.

Lack of understanding for interdisciplinary knowledge domains resulted in the current state of an inappropriate design process for TSS. Designers do not understand how to synthesize the necessary inputs and design decisions into the design process of TSS.

Within present-day architecture there is a rising concern in kinetics. As verified by adaptive facades, the potentials are for a responsive skin that adapts to varying environment situations and user residence (Wigginton and Harris 2002).

As Parkes states "*As we move from static to dynamic, we are confronting a new range of design problems- how do we visualize, imagine, and design the physical processes of transformation? How do we 'prototype' the metamorphosis of such parallel physical computational interactions through time and space? While designers have numerous techniques and tools at their disposal to improve the interaction and appearance of objects, similar methods for creating ways to model transformation through space and time are lacking. Therefore there is a need to create a foundation on which to guide designers through the physical process of transformation*" (Parkes 2009).

Many of the projects with transformable shading devices failed to meet performance goals and/or did not operate as planned. Some reasons for their failures include:

- Requirement for a broad knowledge-base and involvement of multi discipline experts
- Architects and structural engineers involved often have little experience related to TSSs and lack of appropriate design knowledge
- Lack of collaboration between architects and engineers during the design process. Design complexities of transformable systems involve many issues from architecture to structural, mechanical and material engineering to mention only a few.

- The difficulties in designing transformable structures are often not recognized nor well documented.
- Lack of appropriate references and building codes or standards for TSS.
- Lack of periodic monitoring, adjustment, replacement and load reversals. Wear and tear of operational and mechanical devices causes loss in performance. TSSs often require regular maintenance and skilled worker for installation.
- Mechanical and operational devices failure results in system failure.

As discussed, the limited application of TSS is mainly the result of the lack of knowledge concerning the TSS design process. The current literature does not comprehensively address the design process of TSS. The published literature sources rarely contain information that addresses kinetic design methodology. The information contained in current resources does not present a deep understanding of the fundamental principles factors and decisions that govern TSS design process. Therefore, to expand the knowledge and application of kinetic shadings, establishing a design process model for TSS that addresses the above-mentioned subjects is essential.

1.5 Solution

As discussed, an alternative approach to the process of designing and developing the appropriate kinetics for a transformable shading system in the early design phase is required.

The process of designing transformable shading system is complicated by the integration of kinetic systems and physical interactive reconfigurations for a facade's performance (i.e. responding to changes in light). Traditional development design tools center on static design, where the need to design transformable systems is a process that involves interactive elements that are essential in order to ensure effective function. As a result, this requires an alternative approach to the process of designing and developing the appropriate kinetics for a transformable shading system in the early design phase, in response to design requirements.

As previously suggested, one of the main limits for the application of TSS is a lack of a cohesive design process model which inform the initial early design. The need to establish design strategies when designing transformable systems to assist designers in discovering the constructability and workability during the early design stage raises the question of: "*What is the key knowledge that is effective in designing transformable systems and helps designers during the early design stage*?"

Therefore, to better accommodate kinetic shading systems in architecture the process of design must be better understood and structured. To improve our understanding of the interplay of interdisciplinary knowledge domains, this study is a step toward understanding and developing a design road map for establishing a TSS design process model.

1.6 Goal of Research

This research attempts to unfold the hidden design process aspects of Kinetic Shading Systems. This research follows these goals:

A catalyst for the evolution in the building envelope design process

This study offers a catalyst for rethinking building envelopes that could interact with their surrounding environment. Better understandings of TSS design process can point toward new areas of adaptive building envelop research.

A catalyst for increasing the frequency of implementation of transformable shading systems

The wide acceptance of transformable shading devices depends on the degree of participation of researchers and architects throughout the design and development process. Architects cannot apply a TSS effectively unless they are directly involved in how the process of actuation, fabrication, assembly, operation and maintenance together can inform the design of a TSS. Through participation in thinking the way a kinetic shading system is made and assembled, this study enhances the level of involvement in design and fabrication processes to expand the use of kinetic shading devices.

By understanding, structuring and mapping the design process for TSS the process can be shared with students of architecture. The new design process map will become a mechanism for knowledge sharing for TSS that will increase the implementation of TSS in new buildings.

1.7 Objectives of Research

This study is presented with following objectives in view:

To improve our understanding of TSS design process

This study aims to determine a strategy for developing kinetic shading systems in architecture through an immersive case study approach. Designing a TSS requires a broad understanding of the whole processes in terms of a variety of aspects including design context, accuracy, complexity, quality, durability, efficiency, time, expenses, appropriate use of resources and procurement. All these aspects need to be seen as a kind of testing ground for any proposed concept of a TSS and this study attempts to enhance the awareness of them simultaneously. The opportunities for achieving an appropriate design are embedded in all the above aspects. This study aims to establish principles of kinetic design through the exploration of a systematic approach to motion construction and manipulation: motion prototyping as a methodology for design thinking, learning and communication.

To identify the major decision-related nodes in the design process of TSS

This study attempts to identify what major decisions need to be made in the design process of TSS. Decision making is a process that a designer need to understand and define the problem, Identify the alternatives, determine the decision criteria, evaluate and choosing an alternative (Grisham 2009). The TSS design process would be structured with this critical decision related nodes.

To identify the key knowledge and information exchanges within the design process of TSS

This study attempts to explore the knowledge and skills required to combine design, mechanical and structural knowledge to bridge emerging technologies, fabrication and performance in kinetic shading devices.

To graphically represent the second and third objectives as a workflow that can be shared with other architects

A workflow can act like a map, which can give coherence strategy for designing kinetic systems.

To test and evaluate the provisional design process model in architectural studios

After establishing the provisional design process model based on self-immersive case study, the author will design and run two transformable design studios to test the provisional design process model with architecture students.

1.8 Scope of the Study

The TSS design process model aims to make the whole design process more transparent. Although, a comprehensive study of transformable shading system should encompass all phases of generating TSS from conceptual design through fabrication, maintenance, operation, and the entire lifecycle (Figure 14), in this dissertation the author is mainly focusing on the early design and prototyping phases as the most important domains and others will be left for future research. Due to scope of research, this research has to narrow its focus in envision phase[9] of design process owing to lack of time and research capacity.

[9] As Mendel (2012) describes, there are four steps in any design process: "discover, reframe, envision, and create".

Understanding a TSS design process model requires significant effort. By focusing in depth on envision phase of TSS design process model, the key decision nodes of a transformable shading system can be articulated. The envision phase provides a framework in which designers can identify possibilities, explore alternatives, and envision new realities that are derived from in kinetic shadings. During the envision phase, ideas are generated, evaluated, and prioritized and several influential factors that inform the whole process are contemplated. A variety of obstacles and problems should be found and resolved cautiously in this phase, rather than during the process of fabrication or operation. There are some decision nodes such as operation, cost and maintenance that will be evaluated indirectly in this phase.

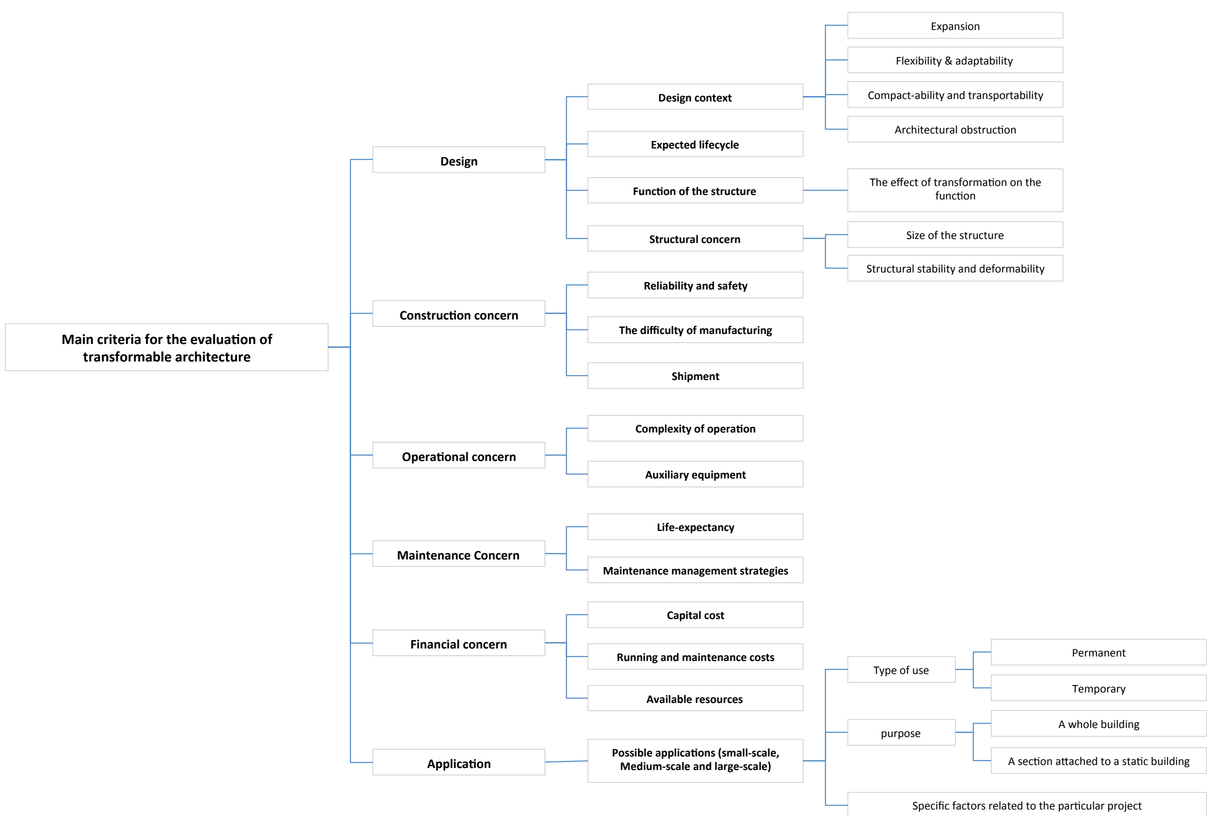

Figure 14: Main criteria for the evaluation of transformable façade

1.9 Overview of Methodology

This research has embraced the theory of reflection-in-action from Donald Schon (1983). In this theory Schon closed the distance between action and reflection that is involved in architectural design. This is a useful method for dealing with multidisciplinary design domains such as designing kinetic facades and particularly transformable shading systems, which provide a considerable amount of information for the designer in the decision making process – or the capacity to 'think', 'do' and 'test' simultaneously. In "*reflection-in-action*," "*doing and thinking are complementary. Doing extends thinking in the tests, moves, and probes of experimental action, and reflection feeds on doing and its results. Each feeds the other, and each sets boundaries for the other*"(Schön 1983).

Reflection-in-action is the thoughtful form of knowing-in-action. Within the qualitative research paradigm, an immersive case study is the primary research tactic that will be implemented in this study. Through an immersive case study, theoretical and practical skills are gained to construct a clear design case to develop a TSS. As a researcher who immerses herself in the actual design process of a TSS, I will be involved in the majority of the process decision-making. Then through modeling and prototyping of the proposed system, important factors, knowledge, information and decision procedures of the architect will be identified.

In addition, design process of TSS generated what Downton (2003) describes as 'design knowing', where the process of designing and making produces new visions and understanding for the designers. The moments of knowing in this process become knowledge and the moments of decision making become knowledge, which has the potential to develop, spread and become recorded as collective knowledge(Downton 2003). Downtown further describes this subject, by stating that "*designing is an ability which requires and utilizes both doing and reflexive thought about that doing. Part of the process is constantly concerned with reflecting on the process and improving it*".

Simultaneous Divergent and Convergent Design Thinking Approaches:

To understand the interactions between making choices and creating choices, this study is centered on a series of divergent and convergent design thinking approaches. This study engages in design, development and fabrication and does not confine itself to just one concept or approach for TSS. In the design process, the applicability of motion in relation to shading devices is exemplified in a series of design concepts explanations. Accordingly, this design process is highly iterative and tries to consider all the possibilities before making a decision.

Knowing in Action: Self-immersive Case Study

Spradley delineates about participant observation, that the highest level of involvement is when researchers study a situation in which they are already participants (Spradley 1980).

Through an self-immersive case study, by total immersion in the process, the researcher is the main "measurable device" to capture the hidden and detailed aspects of the design process, which results in a learning process that can be presented to other designers (direct learning and learning about learning). Self-immersive case study is the most effective tactic for this research based on the following:

1- Limited projects, designers and experts in the field of TSS

2- The scarcity of available information about the design process of a TSS

3- Limitation of access to TSS design process information (very few people working on this topic)

4- Researcher background

1.10 Contribution to the body of Knowledge:

It is anticipated that this research will bring seven major contributions to the body of knowledge as follows:

1. It will be the first attempt to model the design process of transformable shading systems.
2. It will provide a design roadmap for architects who are designing kinetic compositions for shading systems.
3. It will identify the key knowledge and information exchanges within the design process of transformable shading systems.

4. It will be an attempt to understand the boundary between the abstract motion concepts and the functional implications of motion in a shading system.
5. It will identify the major decision-related nodes in the design process of transformable shading systems.
6. It will be the first attempt to model the envision phase of design process of transformable shading systems in which designers can identify possibilities, explore alternatives, and envision new realities.
7. In addition to a written document detailing the design process model, a series of working prototype of kinetic systems will be created. Those will be designed based on a thorough understanding of current systems and developing new ones in an iterative process.
8. It will evaluate the provisional design process model in architectural design studios at Virginia Tech and Texas A&M.

1.11 Audience

This research study has the potential to address the interests of academic and professional audiences. Including:

- Architects, designers, environmental specialists, and decision makers related to building envelopes (specially working with teams on large projects).
- Educators concerned with defining pedagogy of adaptive and transformable design.
-

1.12 Definitions of Terms

There are some key terms that need to be defined in order to understand the workflow of transformable design and to communicate with other parties in the field such as designers, engineers and fabricators.

Transformable Shading In a broad sense, any shading with operable part can be considered as a transformable system. However, the

System (TSS)	emphasis here is on systems that go beyond the commonplace. A TSS has specific geometric rules that result in a visually stunning appearance and movement in response to environment and user. Because of the geometry, the system is scalable and adaptable.
Underlying geometry	Underlying geometry of kinetic structure is described as the geometric constraints of motion.
Overlaid configuration	The overlaid configuration is a secondary issue, as compared to the underlying geometry. Overlaid configuration is an additional design, mainly symmetric or asymmetric patterns. The overlaid configurations could be derived from materiality, degree of permeability, environmental, technical and economical considerations, or cultural and aesthetic references.
Prototyping	Prototypes are working models for exploring or demonstrating how design principles can translate into tangible experiences in a context of use. The fidelity of prototypes varies depending on the stages of design development.
Concept models	Primarily models for visualizing the concept.
Constructive (form-fit) models	Models for visualization and assembly (how well parts fit together), basic motions/functions, and checking the underlying geometry.
Operational models	Functional model for testing, material, scale, dimensions, and detailing.
Driving mechanism	The whole mechanism which opens and closes a transformable shading device. The mechanism includes

	various kinds of equipment, such as driving devices, locking devices (if applicable) and control systems.
Control system	The system that controls the motion of TSS.
Base structure	The part of the building structure, which supports the shading system.
Open state	In a strict sense, the state in which the kinetic shading system is completely open and fixed by the locking device.
Closed state	The state in which the kinetic shading system is completely closed and fixed by the locking device.
Semi-open state	The state in which the kinetic shading device is midway between the open state and closed state, and fixed by the locking device.
Operational state	The state in the device is being changed from open state to closed state, or from closed state to open state.

1.13 Structure of Dissertation

The structure of this dissertation reflects the action research methodology that the author explored between theory and practice. These two components inform one another and are presented in such a way to emphasize the evolving nature of the research.

Chapter One: Introduction.

Chapter Two: Background and Related Work.

Chapter Three: Research Methodology.

Chapter Four: AURA knowing in action: an immersive case study.

This chapter describes the immersive case study of the development of the aura system, from initial design through prototype fabrication and lesson learned.

Chapter Five: knowledge capturing in design studios: to test and refine the provisional design process model for transformable shading system.

This chapter describes the outreach evaluation by applying the provisional design process model in two design studios.

Chapter Six: Conclusion.

The chapter discusses lesson learned through AURA's design process and two design studios. Also, the last chapter concludes the dissertation with a summary and perspective on the future research.

2 Chapter 2: **Literature Review**

Introduction

By establishing design process of transformable façades, designers can methodologically explore the possible range of kinetic forms through a shared set of terms. Consequently, the design process of transformable façades can inform critique and evaluations.

To recognize the variables that determine transformable façades and shading devices, this chapter reviews the relevant case studies analysis, information, attributes, and theories around transformability in architecture. In this case, extracting applicable principles from the literature review can guide creating valid design strategies.

In the field of transformable architecture, the relevant cases to the research subject are very limited. Among a few number of cases that are existed, the author attempts to review selected cases that are rich in their concepts of transformability and meet different principles of motion design or theoretical arguments.

Constructed with various materials, scales, and kinetic patterns for various conditions and locations, the kinetic movements of transformable facades are very diverse, ranging from the simple manually operated sunshade, to the complex mechatronic systems. Due to durability and maintenance issues, some of the case studies do not work properly or exist yet. Many of potential cases they are still in their conceptual stages as well.

Among six main sources of case study data gathering including documentation, archival records, interviews, direct observation, participant observation, and physical artifacts (Yin 1994), this chapter is based on documentation and archival records as main sources for data collection methods. Although these two sources could be categorized as the secondary data collection methods in comparison with direct observation or participant observation[10], they are chosen to enhance the literature review section through different

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[10] Due to various conditions and locations of transformable façade cases, it is hard to apply the primary data collection methods and plan to do site visit.

medium, such as books, journals, magazines, publications, websites and multimedia files like videos and audios (Gray 2004).

2.1 Main Types of Motion in Architecture

In Architecture, there are two main categories of transformation: physical and visual (Table 3). These categories are summarized in the following table:

Table 3: Main types of motion in architecture

<table>
<tr><td rowspan="10">Motion in Architecture</td><td rowspan="4">Physical Transformation</td><td>Physical motion of the occupant</td><td colspan="2">The body of occupant in movement to experience architecture.</td></tr>
<tr><td rowspan="3">Physical motion of the building or its components</td><td rowspan="2">Smaller scale</td><td>Weathering of materials(Mostafavi and Leatherbarrow 1993)</td></tr>
<tr><td>Deformation of materials</td></tr>
<tr><td>Larger scale</td><td>Geometric transformations(Terzidis 2003): changing geometry in stable condition of variation</td></tr>
<tr><td rowspan="6">Visual Transformation</td><td>Perception of motionless images, objects or spaces</td><td colspan="2">Visual effects</td></tr>
<tr><td rowspan="4">A sensation of motion by altering environmental situations</td><td rowspan="2">Lighting</td><td>Changing light intensity</td></tr>
<tr><td>Changing light direction</td></tr>
<tr><td colspan="2">Humidity</td></tr>
<tr><td colspan="2">Wind conditions</td></tr>
<tr><td colspan="3">Representation of movements by animated forms</td></tr>
</table>

Figure 15 demonstrates the motion of changeability in transformable architecture. This research is mainly concentrated on the geometric transformation of building components.

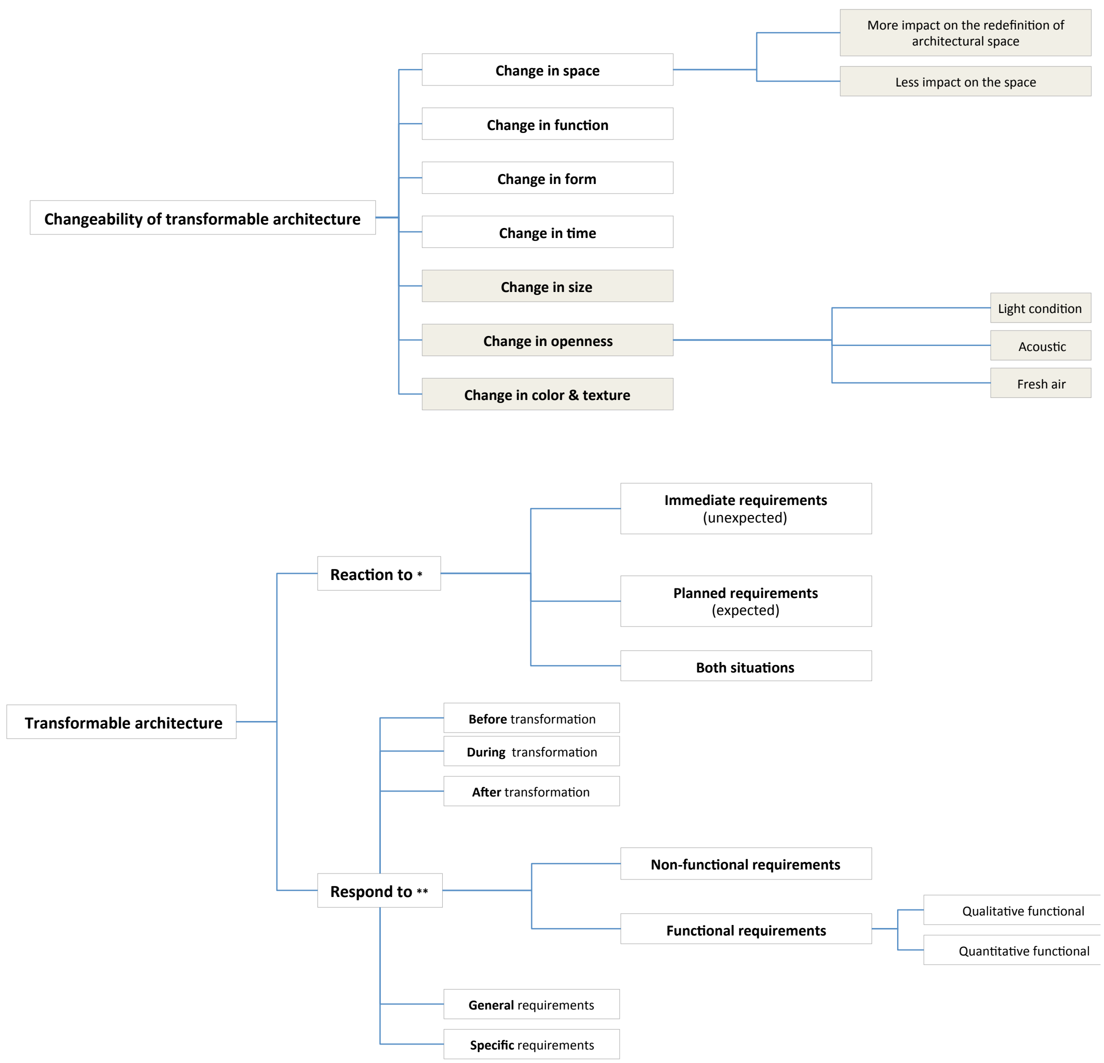

Figure 15: Changeability of transformable architecture

2.1.1 Main Types of Physical Transformation

In physical transformation, there are two main types of transformable products, interfaces or structures in which kinetics behavior are embedded: "continuo-dynamic" and "stato-dynamic" artifacts. In continuo-dynamic artifacts, the intended functionality can be accomplished only in a motion state. Although transformation of one state to another one is a way to fulfill the anticipated functionality of stato-dynamic artifacts, these designs can persuade their embodied purposes in static state as well (Parkes, Poupyrev, and Ishii 2008). This research is focused on stato-dynamic building façade.

2.1.2 Main Types of Stato-dynamic Buildings

In terms of broad general classification of stato-dynamic buildings and their parts, there are two main categories in which kinetics are manifested including “transportable” and “transformable” systems (Table 4).

Transportable system includes deployable structures. By performing similar functions in various locations, these structures are easily portable[11] which are applicable in disaster relief, prefabrication, and dynamic living situations. Changing locations when desired, or to expanding as needed can be the means of environmental mediation. (Bergdoll et al. 2008) (McQuaid et al. 2002).

Opposite of the transportable systems, transformable system is fixed to a location and consists of two sub-systems: dynamic and embedded. Existing within a larger architectural whole, the dynamic system acts independently with respect to control of the larger context. Regardless of the building type or location they are placed upon, the dynamic systems do not make changes to the building as a whole (Fox, 2001). Although this system is fixed to a building, but may offer little benefit to the environmental aspects of the building[12]. The embedded system exists within a larger architectural whole in a fixed location, but unlike the dynamic system does not act independently of the building (Fox, 2001). Designed for the particular building, location, and function, the embedded system is usually connected to the architecture.

[11] Ranging from travel home to high-tech “plug-in” systems.
[12] One example of the dynamic system is the media type facades.

Table 4: Stato-dynamic typologies

<table>
<tr><th colspan="3"></th><th>Location</th><th>Architectural Context</th><th>Environmental Impact</th></tr>
<tr><td rowspan="3">Stato-dynamic Typologies</td><td>Transportable</td><td>Deployable</td><td>Various Locations</td><td>This system can change its location and context when desired.</td><td>By changing its location, this system can mediate its surrounding environment.</td></tr>
<tr><td rowspan="2">Transformable</td><td>Dynamic</td><td>Fixed locations</td><td>It exists within a larger architectural whole, but it is independent of the building it is placed on.</td><td>It offers little benefit to the environmental aspects.</td></tr>
<tr><td>Embedded</td><td>A Fixed location</td><td>This system is designed for the particular building, location, and function it is placed upon. It is dependent on a larger architectural whole.</td><td>This system tends to mediate the built environment.</td></tr>
</table>

In the context of this research, the kinetic façade systems are of the transformable type. Transformable facades are usually a part of the building as a whole, acting upon the building through the envelope or skin. Transformable facades are usually fixed in location and do not act independently of the building. Therefore, transformable facades that mediate their environment are categorized into the embedded type. By having a direct impact on the building, the embedded systems are able to control light, thermal comfort, and ventilation of the interior space.

Each of the above mentioned categorizations come with their own merits and drawbacks (Figure 16). For instance, the dynamic systems do not adapt themselves to their immediate environment, but they have their own benefits ranging from aesthetics and social purposes to dynamic information systems[13]. Since the value of the embedded system is based upon its performance, the performative aspects of transformable facades as the embedded system is measured by its cost versus benefit value[14].

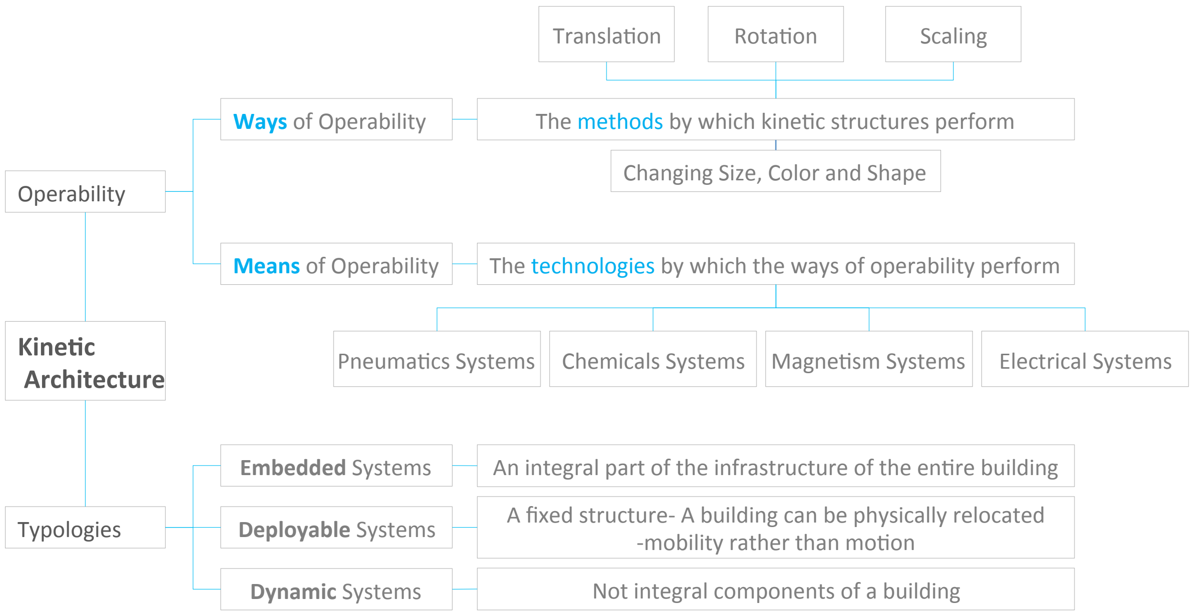

Figure 16: Typologies of Kinetic Architecture (Fox,M.,& Kemp,M. 2009)

2.2 Type of Transformable Facades

It is important to differentiate between two main types of transformable façade systems: "mediator façade" and "media facades"[15] (Table 5). Mediator façades can directly impact their surrounding conditions by mediating the interior and exterior spaces. In contrast,

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[13] The Aegis Hyposurface is an example of the dynamic skin system with interactive capabilities. Another example of dynamic facades that function without concern of mediating the indoor environment from the outdoor environment is the BIX façade at Kuntshaus Graz. The BIX façade is constantly changing for no other reason than to present information or aesthetics.

[14] Such as energy savings.

[15] As Moloney (2007) states, "there are currently two areas in which active kinetics are being implemented: intelligent skins are being designed with an environmental science agenda; while in a parallel line of inquiry, there is experimentation with a range of approaches to embodying information, known as media facades."

media façades do not change constantly to adapt themselves to their immediate environment. Instead, media façades employ technologies for an aesthetic (artworks) appeal or purposes that date should be transformed to animated graphics at an urban scale. Media facades are not generally based on the actual kinetic patterns[16] to create spatial movements[17]. (Hansanuwat 2010) (Alkhayyat 2013).

Table 5: Type of transformable facades

Transformable Facades	**Embedded System**	**Mediator Facades** (Directly related to the mediation of the environment)	Interactive	With constant change and adaption, such as Adaptive Facades
			Reactive	For instance Ned Khan's vertical surfaces function as a shade by casting a physical pattern of the wind
	Dynamic System	**Media Facades** (No direct impact on the immediate environment)	Embodying information and transforming data to graphics	
			Aesthetic Appeal	

2.3 Main Type of Movement

This study recognizes three main strategies to achieve the actual movement, including: mechanical, material and behavior (Table 6). These categories can include numerous categories and sub-categories as well.

[16] The implementation and integration of computational devices within architectural components can pose opportunities to develop a new level of environmental mediation systems. Fox (2003) says "there is a critical need to focus such novel technologies towards an important architectural responsibility; namely, sustainable strategies in buildings."

[17] Such examples are the BIX façade for the Kunsthaus Graz and the Enteractive façade in Los Angeles, which introduce an interactive device to the façade.

Table 6: Type of movement

Strategies to Achieve Movement	**Mechanical**
	Material
	Behavioral

The actual movement of components has three basic geometric transitions in space: translation, rotation, and scaling (Figure 17). Translation explains motion of an aspect in a vector direction, rotation enables movements of an object around its axis, whilst scaling represents expansion or contraction in size. Motion through material deformation[18] is considered to be a complex geometric transformation. This type of motion is not discussed in this study. Combinations of these basic kinetic types can create composite movement as more advance geometric transitions in space, like twist or roll (Ebert 2003). These few composite movement are combined and generate more comprehensive movements (Figure 18).

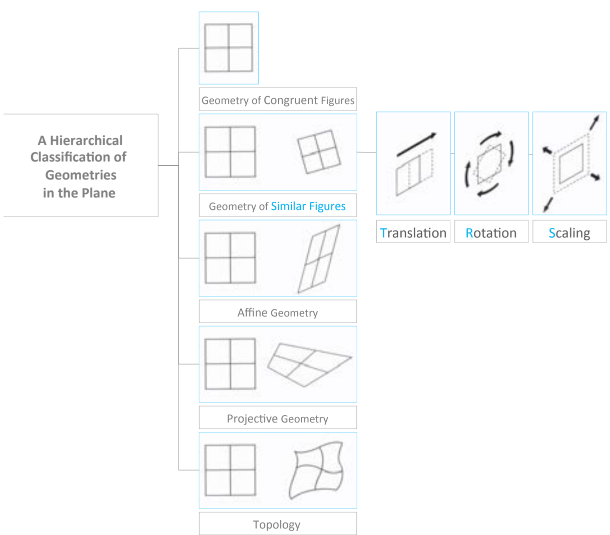

Figure 17: A hierarchical classification of geometries in the plane (Mortenson1995), (Moloney, 2011)

[18] The deformation of materials can be considered as combinations of geometric transitions, for example, melting wax can be considered as a combination of translation and scaling.

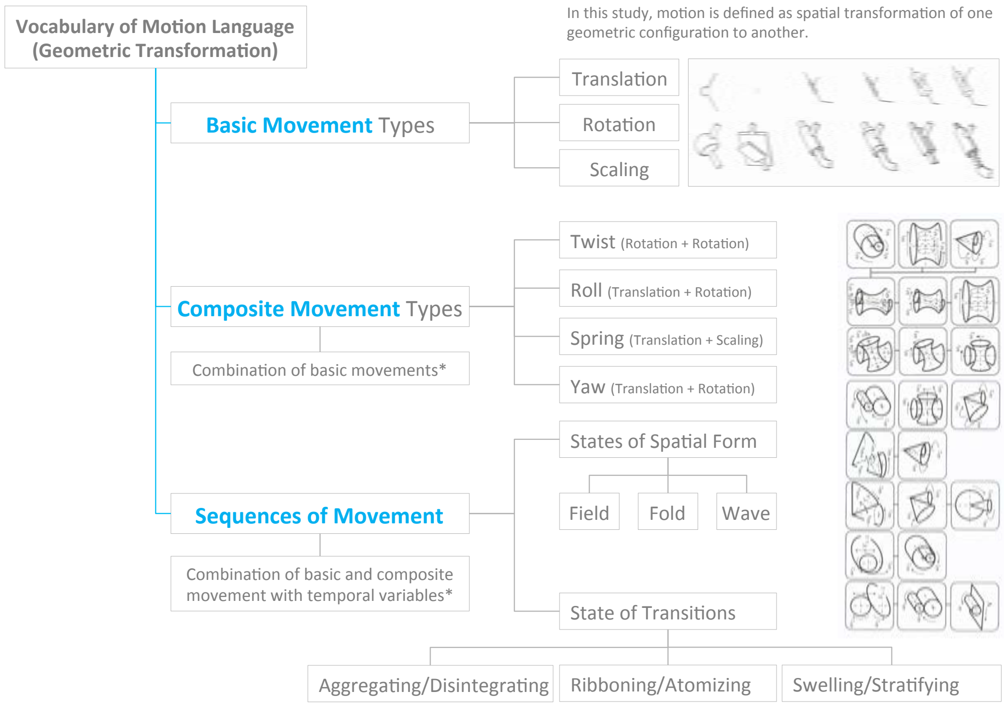

Figure 18: Main types of motion

2.4 Literature Review- Mediator Facades

There are not many examples of kinetic buildings that perform as environmental mediators[19]. Among different aspects to interact with the environment such as solar thermal control, daylighting control, ventilation control, and energy generation, historically, kinetic facades rarely have performed for more than aspects and most often have focused on solar radiation only. In recent years, the use of dynamic kinetic facades as an environmental mediator can be in the control of more environmental variables.

In this section, different mediator facades are studied based on their main methods of performing movements such as pivoting, folding, sliding, rolling, gathering, and push out (Figure 19).

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[19] Moloney (2007) describes that architecture resists building kinetics, with one exception: "one aspect in which kinetics would appear to be acceptable is at the building periphery."

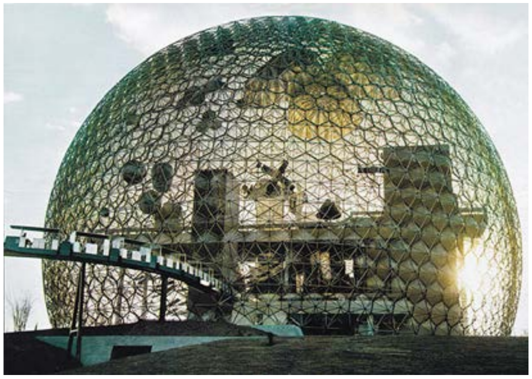
Figure 19: Typology of transformable facades and shading systems.

Rolling Systems – Horizontal/Vertical Rolling

- **Pavilion 67**

An early example of kinetic façade application for adapting to the changing of environmental conditions is referred to the United States Pavilion at Expo 67, designed by Buckminster Fuller in 1967 (Figure 20, Figure 21). In this project, Fuller tried to integrate light sensors, actuators and motors to a self-regulation shading system to thermostatically control the interior environmental conditions and shield the occupant from direct sun exposure while maintaining the greatest possibilities of openness (Massey 2006). Based on a technical analysis that conducted during Expo 67 by Eber[20], the mechanically actuated sunshades were controlled by 600 motors that mounted over the center hub of each group of three interior hexagonal frames. Striking the sun's rays at a predetermined angle could activate the sensors. In turn, the sensors made active the motors. When the motor went into action, they could pull three sets of cables that were attached to window-shades. These sensors allowed the shades only to respond directly to solar stimuli rather than being governed by computerized feedback loops (Sharaidin, 2014).

[20] I. Kalin, Expo '67: Survey of building materials, systems and techniques used at the Universal International Exhibition of 1967, Montreal, Canada.



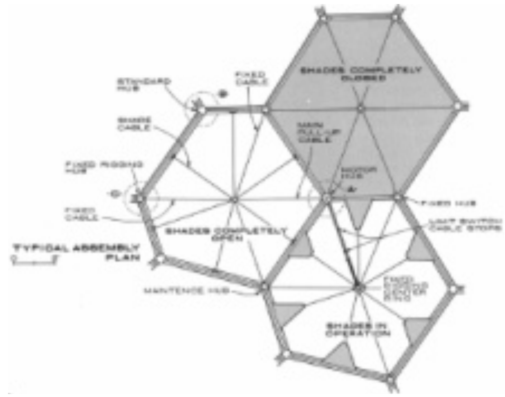


Figure 20: American Pavilion 1967, designed by Buckminster Fuller (Left)

Figure 21: Hexagonal Shutter of American Pavilion 1967, designed by Buckminster Fuller (Massey, 2006)

By designing autonomic process to create a perfected environment[21], the US Pavilion was a testing ground of what Fuller calls an "environmental valve" (Sharp, 2006) to provide more active barrier between the interior and exterior. Fuller's highly visionary approach to responsive skin was ahead of his time in terms of technology and it was not fully implemented. In Fuller's exploration of kinetics, he conceived retractable shades that permitted the enclosure to breathe[22] and regulate light, air and moisture[23].

Pivoting Systems - Axis Perpendicular to Plane-Reduced

- **Institute Monde de Arabe**

As one of the earliest examples of a highly technical and complicated kinetic facade system, the Arab World Institute' main facade[24] (1980) was designed to actively respond to varying light intensities in its environmental conditions by changing the level of

[21] This Expo pavilion was called a "Garden of Eden" as well.

[22] To realize this idea, Fuller indented to make his idea with plastic and photo-chromatic glass, overlaid with tinted and metalized plastic film that feature "oxygen porous silicon firms" (Massey 2006).

[23] Fuller explained "One could be a screen, others breathing air, others letting light in", he continued, "and the whole thing could articulate just as sensitively as a human being's skin" (Massey 2006).

[24] Designed by Jean Nouvel

openness or closeness (Figure 22). The central interest of this facade was to create active boundary conditions and a modulating microclimate (Hensel 2013).

Adopted from the geometry of traditional Arab screens called Mashrabiya, the south of the facades is composed of a 24’ x 10’ grid of square bays. The intention of the 197 feet high facade was to operate 270 rotating camera like irises of varying sizes that were motorized and sat within a smaller grid of irises in order to mediate the sun, lighting levels, heat entering the space. Providing the building interior with a dynamic setting and offering a visually appealing façade, this transformable façade as described by David Leatherbarrow, attempted to serve legible articulation between appearance and the operational performance (Leatherbarrow 2009). Unfortunately, the whole façade no longer functions due to the complexity of the mechanical systems and an overly intense maintenance need of the 25,000 photoelectric cells (Mazzoleni and Price 2013), (Moloney 2011).

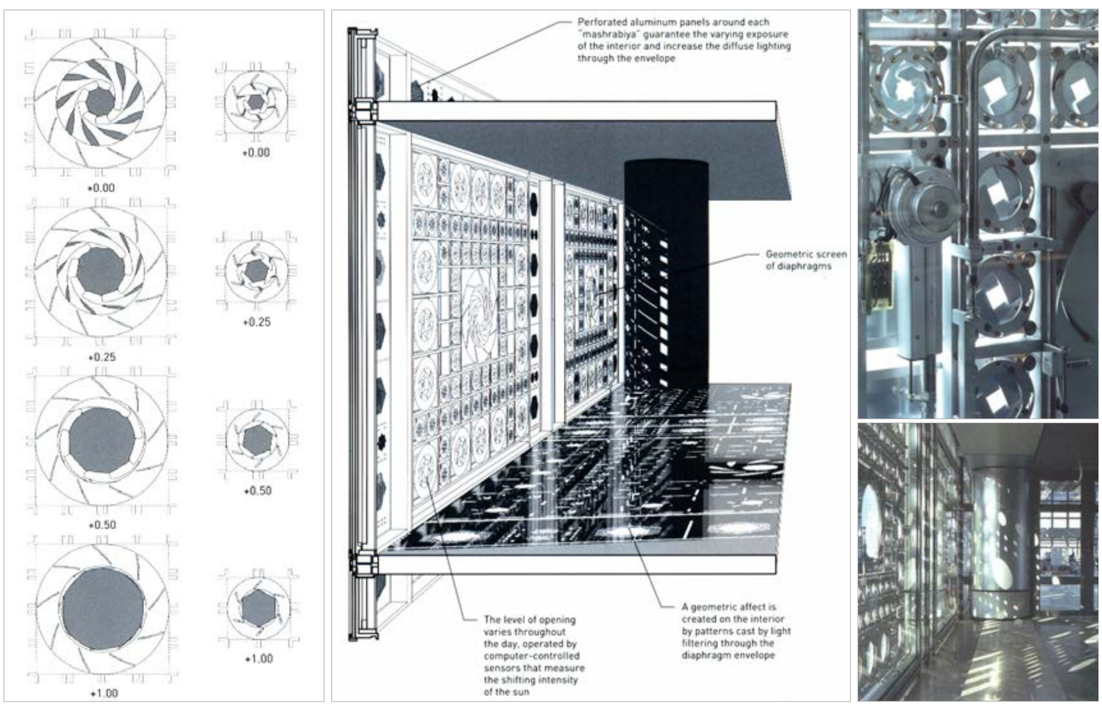


Figure 22: Kinetic Shutter panel of Institute Monde Arabe.

Six shutters are used to create an open and close behavior to respond to the daylight condition. Horizontal rotating irises use a light sensor to moderate indoor light levels.

Pivoting Systems - Horizontal/Vertical Axis-Unchanged

- **Nordic Embassies & Melbourne Council House**

Movable louvers can shade windows and control the sun radiation in summer and winter. Normally, using several louvers can have a dramatic impact on the overall architecture of a project and appearance of buildings. A well known example of such an impact is kinetic façade of Nordic Embassies[25] in Berlin that composed of many horizontal louvers (Figure 23). By using thermo-hydraulic drives, each panel is individually controlled and rotated through 90 degrees to track the movement of the sun (Moloney 2011). The significant impact of louvers on both the exterior and interior appearance of the façade can be seen in the Melbourne Council House (CH2) as well, which was built in 2006. By embedding a hydraulic system, a lot of vertical timber louvers are programmed[26] to control the closing and opening of the facades (Newman, Beatley, and Boyer 2009).

Figure 23: Nordic Embassies & Melbourne Council House

- **Royal Melbourne Institute of Technology**

It is assumed that transformable shading devices should guarantee visual and thermal comfort for the building occupant. In some cases, these devices are not well-studied in

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[25] The building is designed by Berger and Parkkinen in 1999.

[26] The whole facade is programmed by computer-control. Computer-control is used to program according to seasons for most of the facades that integrated with kinetic panels. Other buildings used this system includes Al-Bahr towers in UAE and United State Federal Building in San Francisco.

the early design stage and they are not able to reduce incoming energy and light fluxes later. For instance, the futuristic circular discs that serve as shading devices in Design Hub's facade of the Royal Melbourne Institute of Technology (RMIT) are unable to moderate environmental changes completely (Davies, 2014) (Figure 24). One of the main design flaws in these discs is to rotate only in the horizontal direction. The discs cannot cast shadows especially during the middle of the day because they are located inside metal cylinders. In addition, these circle shaped discs cannot tessellate an opaque plane. The gaps existed between the discs make 21 percent of the entire facades surface exposed to the sun during periods of the day. Ultimately, the facade cannot provide adequate protection for the building occupant from the excessive heat and light from the sun. To mitigate sun exposure and reduce discomfort, the occupants have fixed blinds in the inside. The presence of these blinds proofs the inability of this kinetic façade to provide adequate protection. (Sharaidin, 2014).

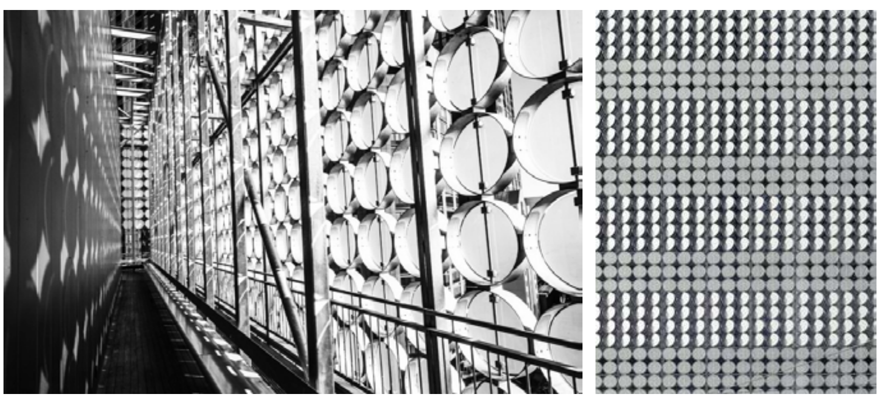


Figure 24: Royal Melbourne Institute of Technology

Folding Systems - Vertical Folding

- **Kiefer Technic Showroom**

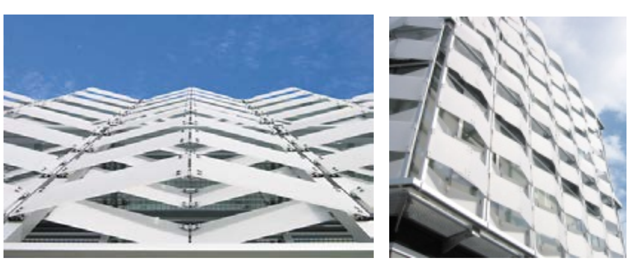
Kinetic systems that utilize folding systems can most often employ hinged systems that can cause two or more pieces to be folded upon themselves. 112 aluminum panels in the form of horizontal folding shutters have been mounted to shape an active surface in front of the Kiefer Technic showroom (Figure 25). The 56 shutters are carefully raised, lowered and folded together by separated electrical operated motors to orchestrate a harmonious visual effect in the appearance of the building envelope. These 56 motors can accelerate gradually and come to a gentle halt (Schumacher, Schaeffer, and Vogt 2010). To retract and expand to the required degree, each shutter is individually controlled by using a programmable system[27]. In this case, the façade is turning into a dynamic sculpture.

Figure 25: Kiefer Technic Showroom

Folding Systems-Horizontal Folding

- **Milsertor Service Centre**

In Milsertor Service Centre facade in Tyrol Austria, 18 different adjustable sections are fitted together to shape a folded sunscreen (Figure 26). To diffuse light to enter the interior space, the facade of the building has total of 1504 elements controlled by rods that act as two guide rails. To ensure the parallel movement of both the upper and lower gliding rods is working effectively, a motor is embedded with the system to prevent any possible snagging or twisting. Two thick white Plexiglas panels of each element are attached to one another by a hinge (Schumacher, Schaeffer, and Vogt 2010).



[27] To control the shutter, PLC-BUS system is used in this kinetic façade. PLC-BUS is a power-line communication protocol for communication between electronic devices. (http://www.plc-bus.info/)

Figure 26: Milsertor Service Centre

Folding Systems-Central (Circular) Folding

- **Al Bahar Towers**

Abu Dhabi Investment Council's headquarters[28] (2012) consists of 1,049 self-cleaning umbrella-like membrane modules[29] for the west and east side of the building (Figure 27). These individual kinetic modules create a folding and unfolding movement, which produce random surface patterns in response to the sun and local climate conditions. It is claimed the kinetic façades of these twin 29-story towers are the world's largest computerized facade built today for 150-meter high towers. (Alkhayyat 2013).

The expanding and contracting effect of this fashionable façade[30] is the result of its control systems that adopt the piston mechanism. By opening and closing a series of linear actuators once per day in response to a pre-programmed sequence, the shading devices are programmed to transform into three kinetic states, including totally closed, mid-open and fully open. Even though the facades were embedded with recent technologies[31], they still required heavy mechanical systems[32] in actuating the modules to create the kinetic pattern for the facades (Sharaidin 2014).

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[28] Al Bahar Towers

[29] Each module comprises a series of stretched PTFE (polytetrafluoroethylene) panels that have pattern of perforations with a suitable density to permit light and air to go through it (Arup, 2012).

[30] The design concept was inspired by Mangrove flower, which founded where the towers are located (Arup, 2012).

[31] For example, the entire facades are protected by a variety of sensors that will open the modules in the event of overcast conditions or high winds.

[32] Here, three main types of components are found: fixed, semi-moving parts, and moving parts. Fixed parts are supporting structure frames on the glass curtain wall, semi-moving PTFE panels, and moving parts, which are actuators.

Figure 27: Al Bahar Towers Facade, Abu Dhabi, Aedas, 2012

Sliding Systems –Vertical/Horizontal Sliding

- **The Center for Architecture**

Helio Trace Centre of Architecture facade concept was designed for a competition[33] by a team of Adaptive Building Initiative (ABI)[34], Skidmore, Owings, Merrill (SOM) and the Permasteelisa Group (Figure 28). This kinetic façade designed to foster daylight condition whereas decreasing solar heat gain impacts on building residents (Hoberman 2010a). By tracking of the sun path over the course of a day and a year, architects and field specialists of this team envisioned a configuration that enhanced the curtain wall performance regarding increasing daylight and decreasing glare, and that reduced solar heat gain by 81%.

Facade technology of Helio Trace Centre developed to be modified to different climate, sun path and processes schedules, by adapting to location attributes or orientation. It could be utilized to any reasonable non-rectangular building geometry by adjusting different curtain wall panels.

This kinetic façade system composed of a series of adaptive shading modules. Each module had a twelve metal pieces, including eight parallel and four perpendicular units. To form a continuous surface, the parallel units could expand and retract together towards the center performing a pyramid shape at the same time, however, perpendicular sheets

[33] The competition was an Open Call for Innovative Curtain Wall Design.

[34] The Adaptive Building Initiative (ABI), founded in 2008, is a joint venture between Buro Happold and Hoberman Associates.

can expanded separately. When these the system retracted, its units could disappear and hide within a façade structure. To enable light and air to go through, each module consisted of a series of slices with a suitable density and diameter of perforation holes.

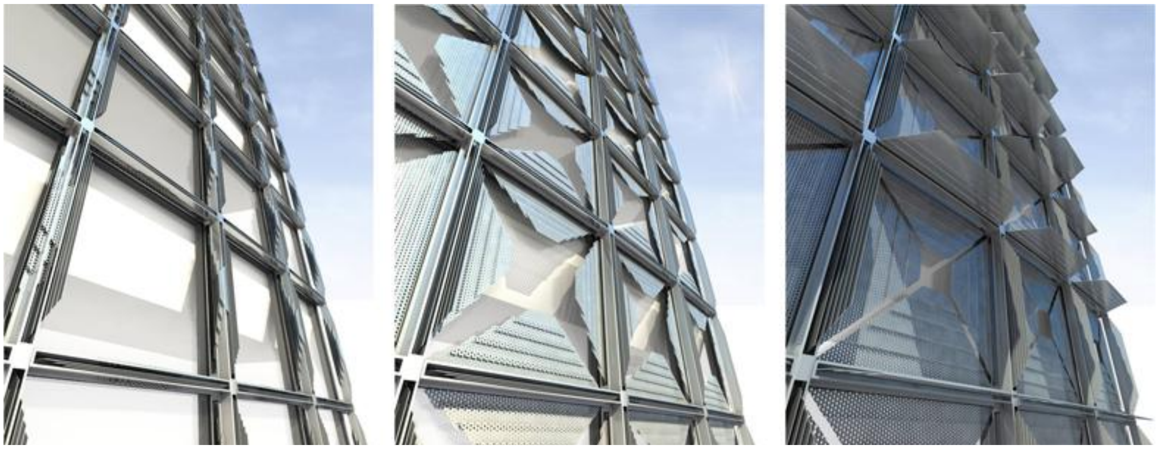

Figure 28: Helio Trace Façade System - Centre of Architecture

- **Emergent Surface**

Hoberman mainly uses the scissor like structure in most of his expandable designs to create a continually changing surface pattern and opacity. For instance, by embedding the scissor like structure in his deployable spheres[35], Hoberman can realize different scales of transformability.

Prior to Helio Trace Centre of Architecture, Hoberman Associates studied the potential of dynamically changing form and the state of the art in transformable design for several years. In 2008, Chuck Hoberman designed a wall called Emergent Surface for the Museum of Modern Art that continuously reconfigured itself with portions selectively disappearing and reappearing in terms of variable solidity and permeability (Figure 29). In one condition, the wall appeared as a solid surface with three-dimensional curvature. In another, it resolved itself into seven slender poles, running floor to ceiling. And

[35] Hoberman's sphere toys are perhaps his most well known and popular works.

between these extremes lay an infinite variety of configurations (Parkes, Poupyrev, and Ishii 2008).

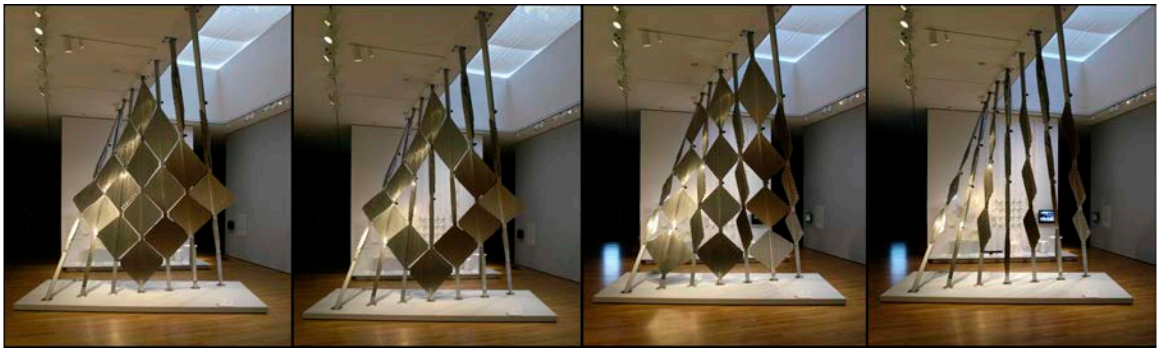

Figure 29: Emergent Surface (2008)

- **Ciudad de Justicia**

Hoberman Associates designed another sun-shading project for the Ciudad de Justicia[36] in Madrid by using similar design approach of Emergent Surface project (Figure 30). Here, a lot of horizontal hexagonal sunscreen modules were landed on a glass roof. When these modules extended, they could cover the whole triangulated roof grid. When retracted, the modules contracted autonomously and disappear into the structural profile of the roof. In this project, the self-directed movement of each module permitted a series of non-uniform arrangements from center to edge. Because of the various directions of the hexagonal modules, a custom algorithm combining historic solar gain data with real-time light-level sensing alongside a steady center-to-edge configuration created further complexities as well (Craig 2006).

[36] This project was done for Foster and Partners Co.

Figure 30: Ciudad de Justicia

- **Simons Center for Geometry & Physics**

Hoberman in Adaptive Building Initiative designed and made a modular kinetic shading system called Tessellate. The outcome of this kinetic system is a kinetic façade for the new Centre for Geometry and Physics in New York that spreads 1335 square feet with beautiful optical art illusions (Figure 31).

This modular system consists of three main planes, first and last plane are tempered glass, and the middle plane contains three components: steel frame, actuator, and Tessellate layers. Each tessellated layer can be a combination of different geometric shapes, such as hexagon, circle, square, or triangle. These layers are tied together structurally by some pivot points that serve as references for defining the movement of the whole system. By moving these pivot points, an actuator keeps revolving to maintain tessellated layers transformation and creates constantly evolving surfaces. These tessellated layers are activated by one motor. This motor is controlled by a computer processor, which programmed for several objectives (Alkhayyat 2013).

In Tessellate system, overlapping of its layers gives the kaleidoscopic visual representation of patterns aligning and then diverging into a fine, light diffusing mesh (Hoberman 2010b). As these layers align and splay; different geometrical patterns can continuously move and evolve that provides the building with the functional capability to adjusts light, sights, privacy, ventilation and airflow. The applied patterns on the tessellated layers can be designed to cover each other and block sun rays. According to ABI, patterns opacity can varies from ten to eighty five percent. Tessellate can be adjusted to track the sun and responses to light and weather conditions by using a location-based sensor.

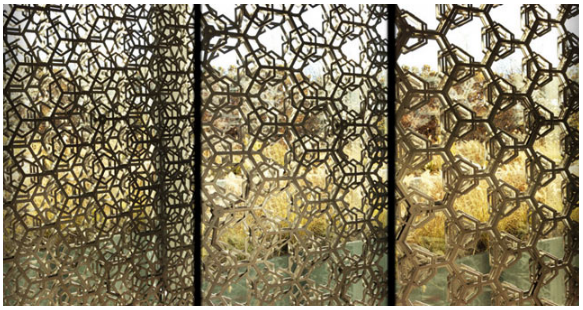

Figure 31: Simons Center for Geometry & Physics

2.5 Literature Review- Teaching Motion-related Courses in Architecture

While there is a growing demand from the professional body to exploit transformability, very few schools of architecture have taken the initiative to make their students ready for the changing needs of the profession. Among these schools, very little time is being spent on teaching motion-related courses. At best, the limited courses and subject areas in transformability are evidence of a loose arrangement of the essential aspects of motion design in isolated compartments. Consequently, the impact of these courses in the education of future architects is still impalpable.

There has been little in the way of deep research into the functional necessities, structural criteria, and technical difficulties of transformable architecture because many schools of architecture do not take a holistic approach to educating on this subject. Conversely, there is currently no comprehensive research describing how schools ultimately wrestle with the inherent complexity of transformable architecture.

Each architecture school delivers a specific curriculum, content, and type of pedagogy that influences how their students shape their respective futures. Where motion in architecture has been introduced, the majority of existing pedagogical approaches to teaching motion in architecture have shortcomings, especially in terms of the nature of transformable design education. Some motion-related courses are currently being taught in a way that does not mesh well with the overall objectives of transformable design pedagogy.

Since motion study has rarely been acknowledged as a critical component of architectural pedagogy, there are less inclusive guidelines or frameworks that articulate the design rules students should follow from conception to realization of motion in architecture. There are a few precedents that can serve as guidelines for designing transformable structures, but there are consistently fewer materials establishing a design methodology for this kind of architecture (El-Zanfaly 2011a). Most of these precedents only identify the types of motion and the respective components found in such structures, without clarifying the process of designing a change from one state to another.

Fortunately, more and more architecture students are starting to explore the potential of transformation in their projects, allowing them to design sustainable, responsive, adaptive, and intelligent buildings. However, thus far only a limited number of courses in architectural education have focused on facilitating this goal. For most students, due to a lack of sufficient knowledge and experience related to transformable design, a holistic approach to motion design is difficult to comprehend. Even with the auxiliary of CAD software and physical models, the sequence of moving parts and the tracing of their pathways is difficult to clearly foresee, and therefore difficult to visualize. Most students acquire the knowledge needed to arrive at a systematic level of analysis, formulation, and selection of motion design principles in a fragmented fashion.

2.5.1 Main Streams of Motion-based Courses

There is a diverse multitude of architecture schools; they cannot be said to represent a homogeneous set of educational approaches. Each school concentrates on the specific advances they feel should be most influential on their students. Consequently, the educational strategies associated with incorporating motion vary significantly from school to school. Up to now, there have been only a few schools offering motion-related courses. In most, motion studies are not a permanent part of the curriculum.[37]

Due to the specialization of architectural knowledge and the reality of architectural professional practice demanding a substantial portion of any curriculum, faculty, space, and budget, architecture schools must be conservative with regards to institutional change (Tzonis 2014). This is likely why motion studies have only of late been considered by a few schools of architecture.

To outline more complete motion design educational framework, this research connects together certain academic pursuits currently underway. A quick review of the existing motion-related courses presents a very difficult and often confusing structure (Table 7). The split between design-built technical courses and computational design courses has prevented motion-related courses from finding a clear position in architectural education.

Primarily, there is a lack of education in the fundamental aspects of motion design, including the vocabulary and syntax of motion language. In some cases, these aspects are discussed at a distance, and then only as an abstraction. In general, motion design principles are overlooked far too often by motion-related courses that instead focus on more conventional approaches to architecture. Since transformable architecture is emerging as a pivotal field of design, motion-related courses should emphasize the active role of building elements.

In many cases, instructors have far too little common pedagogical vision or shared task objectives, other than a desire to strive for a direction that suits their personal interest and particular skillset. In addition, educators create courses hoping that the course content will satisfy the immediate needs of the school, its students, or the image of the school propagated in the media.

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[37] For instance, the transformable studios offered by the author at Virginia Tech and Texas A&M University are not a fixed part of these schools' curricula.

Table 7. Course related to motion in different schools of architecture

Course or Studio name	Instructor(s)	Department/ University	Type	Year (s)	Country	Learning Objectives
Immersive Kinematic (Arch 724)	Simon Kim	School of Design / UPenn	course	2015	U.S.	Kinematic, material and digital discoveries
Informal Robotics / New Paradigms for Design & Construction (SCI 0647800)	Chuck Hoberman	GSD	course	2014 Fall / 2015 Fall	U.S.	Kinematics, Fabrication, Controls and Applications
Transformable Design Methods (SCI 0647600)	Chuck Hoberman	GSD	course	2012 Fall / 2013 Fall	U.S.	Transformable Design
Smart Materials (GSD 6418)	Thomas Schroepfer	GSD	course	2008 Fall	U.S.	Smart materials and Fabrication
Kinetic Architecture (VIS 0230900)	Kostas Terzidis	GSD	course	2008 Fall	U.S.	Revisiting traditional kinetic aesthetics with new technological innovations.
Environmentally Responsive Building Skins	Varun Kohli	GSD	course	2010 Fall	U.S.	Environmentally Responsive Building Skins
NEW TEXTILES	Leah Buechley	MIT Media Lab	course	2010 / 2011 / 2012	U.S.	Future of textiles
CRAFTING MATERIAL INTERFACES	Leah Buechley	MIT Media Lab	course	2011 Fall	U.S.	New (and ancient) materials are changing our understanding and experience of technology
Smart Materials (ARCH 5301)	Maria R. Perbellini	TTD (Texas Tech University)	course	2010 Fall	U.S.	Smart Materials and their applications in building envelopes, Fabrication
Shrivel and Shrink (ARCH 5110: ARCHITECTURE AS CATALYST)	Blaine Brownell	University of Minnesota	course	2014 Spring	U.S.	Biology Inspired Design
Bio-Inspired Systems in Architecture (Arch8255)	Marc Swackhamer	University of Minnesota	Studio	2012 Fall	U.S.	Bio Inspired Systems
Anti-Static: Architecture's Kinetic Systems (ARCH 6605)	Martin Miller	Cornell University	course	2014 Fall	U.S.	Implementation of advanced sensory and responsive technologies within architectural facades
COMPONENT SYSTEMS: ADVANCED	Joseph Vidich	Columbia University	course	2008 Fall	U.S.	Fabrication, Building Skin, Machine Design

FABRICATION						
Component Systems	Joseph Vidich	Columbia University	course	2008 Summer	U.S.	Production Sequence and Architectural Skin
Kinetic Architecture Design Seminar (UO ARCH 407/507)	Stephen Duff	University of Oregon	course	2013 Spring	U.S.	Architecture-in-motion Sustainability and adaptive building environments Operable mechanism for a building. Software: Solidworks/Softimage
3D Des-Kinetic Architecture (DESN 323 SU01)		Emily Carr University	Design Seminar	2016 Spring	Canada	Complete the comprehensive design of a kinetic device for a building
Performative Morphology	A. Menges, O. Krieg, T. Schwinn, L. Vasey	ICD - Universität Stuttgart	design studio	winter 2014/2015	Germany	Biology inspired design, Fabrication
Digital Matter - Intelligent Constructions	Areti Markopoulou , Alexandre Dubor, Moritz Begle	The Institute for Advanced Architecture of Catalonia (IAAC)	course	2013-2014	Spain	new techniques generating the production of non-rigid, responsive and multi-functional material and construction systems Bio inspired
Brighton Studio 09	Stefan Lengen and Kyriakos Katsaros	University of Brighton	design studio	2014-2015	UK	adaptable, responsive and or kinetic architecture
FELT_BARTLETT SUMMER SCHOOL_2013	Stefan Lengen and Kyriakos Katsaros	University College London	design studio	2013 Summer	UK	principles of interactive/responsive design (Arduino microprocessor prototyping platform)

Although the internal structures of most motion-related courses are different, an in-depth exploration of syllabi provided by various architecture schools indicates that two main streams[38] of motion-based courses tend to be offered. The first type is dedicated to exploring the field of motion design itself, as a new medium for adaptable architecture (i.e., how students can formulate motion design concepts through use of the language of motion in a building context). In response to specific environmental needs or aspirations, this first type of course considers movable elements to be characters rooted in a concrete space–time context. In this stream, students' understanding of the concepts and

[38] Additionally, each of these streams can be further divided into sub-streams.

challenges involved in motion study is epitomized by their experiences with physical and digital models. The other type of course is concerned with a specific field of activities and intended to communicate particular technical proficiencies and knowledge of environmental analysis, parametric software, digital fabrication methods, various trends, and advances in interactive technologies or smart materials through the use of movable elements. The main intent of this type of course is to investigate other constituents that – directly or indirectly – impact emerging fabrication techniques, innovative materials, interactive interfaces, or simulation software platforms. Other approaches tend to be engineering-driven endeavors and machinelike, usually taught as offshoots of technical courses. As a result, the overlaying of kinetic architecture onto a design studio culture is a somewhat technocratic solution to a series of mechanistic, cause-and-effect relations.

Motion-related courses require more sensitivity to all aspects of motion design, as well as the interaction of motion with people and their surrounding spaces. In some technology-driven courses related to motion studies, mechanical and technical endeavors limit students' capacity to invigorate the potential of motion in a built environment. In these courses, the inherent architectural possibilities of motion and kinetic aesthetics are not meaningfully revisited after new technological innovations emerge. For the most part, motion-related courses tend to foster a product-oriented mentality, evaluating motion on the basis of its performance and efficiency but rarely taking into consideration issues of human use or spatial quality.

One of the major challenges to motion pedagogy is the tension between the field of motion design itself and its technological, computational, and fabrication-related aspects. There are not only educational issues associated with this dichotomy, but also practical ones; one side fortifies the core knowledge of transformation while the other exploits motion in order to explore and experiment with different materials, technologies, and processes. In other words, some motion-related courses give priority to technological or computational approaches, and thus tend to oversimplify basic motion and neglect existing mechanisms and their initial intentions.

A mechanism is a device designed to drive a specific movement by transforming a force into a desired output. Designing the proper mechanism is very important, but students in motion-related courses tend to be ill-informed and misguided in their focus on designing mechanisms instead of motion. In the context of these courses, motion is conflated with mechanism. Rather than juxtaposing several mechanisms together, students should learn that mechanisms and motion are equally present in the design conception phase. In many cases, students attempt to design a structure or arrangement of parts, instead of determining their motion.

2.5.2 Categories of Motion-related Projects

As a core subject in architectural education, a design studio[39] is a workspace where students learn to design and explore a particular body of knowledge and set of skills. While other supporting courses contribute to design studios, the dynamic cross-pollination and cultivated serendipity of a design studio environment allows students to think about motion through hands-on lifelong learning processes and inter-relational project-based design activities. Unfortunately, some motion-related courses are inadequately associated to the design studio setting. Consequently, within existing courses, motion-based studio projects are not considered to be the key platform for generating motion, evaluating alternatives, and exploring consequences.

Motion-based courses are seldom high credit-hour classes, and educational challenges can arise when design studios attempt to incorporate movement into design. Motion-related courses usually employ four main categories of project.

In the first category, in either a long or short assignment, students are asked to familiarize themselves with existing mechanisms or design new ones to create devices that may or may not have a direct impact on a building's performance.[40] Students become practically acquainted with the principles of designing and implementing machines. These machines help students to recognize how electro-mechanical parts, mechanical components, and electronic circuits function in real life, and how these items interact with the environment. Utilizing a variety of materials and fabrication techniques (including laser-

[39] For this reason, design studios are often the targets of criticism.

[40] For instance, an under-actuated hand.

cut materials and 3D-printed parts), the applied mechanisms may integrate to provide an overarching effect, or stand alone. Popular choices of mechanisms include gears, cams, and belt drives that convert between rotary and linear motions. Here, by concentrating more on assembly drawings, fabrication plans, bills of materials, purchasing components, cutting parts, and more, the main goal is to take a chosen concept and make it into something real. In this category, students' designs can begin simply and evolve as parts are added, eventually being refined into detailed prototypes.

Creating static structures capable of becoming mobile without losing structural integrity may take months. Therefore, dealing with the challenges associated with such buildings capture students' attention and imagination. In this second category of assignment, students explore the development of transportable and demountable architecture, often in the form of temporary shelters constructed after disaster situations(De Marco-Werner 2013). These types of projects focus on the rehabilitation of devastated buildings caused by natural disasters or ravaged by war. They range from the familiar silvery capsules of Airstream trailers to ambitious living units that plug into a pre-established framework. Besides providing emergency relief, a wide variety of temporary structures such as concert and performance venues and trade fair stands make an appearance in motion-related courses. By exploring the technical aspects of design proposals, the goal is to create a temporary building that lasts long enough to be of use in a particular location and for a limited amount of time.

The third category of project explores the ever-growing range of possibilities of transformable architecture, as a new and ecologically-aware design strategy. Instead of designing mobile structures as complete buildings, students design part of buildings capable of undergoing major changes to their configuration and adapting themselves to fluctuating environments, functions, and requirements. Through expansion, unfolding, and other means, students explore a variety of ways of designing adaptable architecture. The multifaceted nature of an adaptable structure allows students to transgress the borders of the building industry, resulting in a multidisciplinary approach and addressing complex issues of sustainability. In these projects, the complexity and transience of motion connects to the practicality that transformable architecture makes possible. Thus, the design process can be developed to understand and prioritize the nature of transitory movement. This understanding provides a novel perception of the frequently moveable parts of a building, and conveys a new sense of identity to the whole building. In addition, the design process focuses on a very specific and precise means of selecting the most appropriate materials and mechanisms for achieving transformation.

In the fourth category of project, students' design concepts are interwoven with futuristic ideas – sometimes slipping past the bonds of reality – ranging from the micro-environments of wearable devices to the interior of a spacecraft, or even the macro-environment of a city. Although these breakthrough concepts suffer from a lack of technical development (De Marco-Werner 2013) and set aside many the realistic concerns of transformable architecture, students are encouraged to illustrate their concept of the future. Envisaging transformable architecture as an art of reality in no way devalues its imaginative and conceptual aspect. In this category of project, students' whimsical designs are presented in ways that seem more advanced and complex than the present reality.

The difference between the third and fourth categories bring us to the dilemma faced by many motion-based courses today: choosing between revolutionary concepts the profession does not yet dare to touch, and responding adeptly to primary environmental needs.

2.6 Background Review- Author's Kinetic Design Research Works

As mentioned in the introduction, the author has been working and researching in the field of kinetic design for more than fifteen years. The literature review of the research covers the outcome of more than a decade of experience of the author[41] in developing kinetic and adaptive design, ranging from architectural-scale structures to small products. This background review shows that the architectural attributes of the mechanism, or the ability to change in shape and pattern, are the main concerns of the author. The main body of work at this section fosters exploration of the author around one central question:

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[41] Some of these projects were collaborative research with the Art of Engineering workshop, Alireza Borhani, and PARTeE.

how can motion be suggested, depicted, or physically incorporated in the building and specifically in the building envelope? During this period of self-immersive study, the author explored new agendas for generating form through the interaction of force, geometry and motion.

Form 1999, the author was a member of the research team in the Art of Engineering Lab[42] that studied deployable systems that respond to the environment. She studied and examined responsive systems concerning the changing nature of the environment[43]. The study concluded that buildings that respond to real time circumstances result in direct benefits in reducing energy consumption and improving interior environments. Through this work a series of deployable structures were designed and modeled and the results were exhibited at the Technical Universities of Vienna and Berlin, Shahid Beheshti University and Tehran University. These collective characteristics of projects demonstrated the following:

- Change of configuration and architectural space;

- Ease of handling and transportation when the structure is collapsed (contracted) and exclusion of necessary complex and tedious constructional techniques, when the structure deploys (unfurls) into its final position;

- Temporary shelter or settlement especially in disaster prone countries; and

- Having permanent structure through the addition of the missing links or by the introduction of fixed joints or permanent coverings.

The author studied and prototyped a series of transformable Systems. This section of the literature review aims to convey the sensitivity of the author to design objects that controllably (predictably) or even uncontrollably (randomly) change their size, shape and surface. Across the breadth of various projects, the author tries to choreograph movement to reveal the forms and forces of the dynamics of unstable environments. Because of that, she lets different mediums such as wind, audience members, or technical systems animate

[42] Department of Architecture, Shahid Beheshti University

[43] The Art of Engineering Lab tries to learn from nature; not only through observation and imitation but through exploration by means of experience in the fields of materials, structures, and technologies.

the works. Indeed, a key element for the author is to make motion visible, comprehensible, and beautiful within the design process. The following is a brief overview of the author’s previous projects.

- **Deployable Geodesic Dome (based on deployable dome of Chuck Hoberman)**

A geodesic dome like structure that can fold down to a fraction of its normal size by the scissor-like action of its joints (Figure 32). This study won first place in the Second National Conference on Space Structures (2007), Tehran.

Figure 32: Deployable Geodesic Dome

- **Deployable Ceiling**

This ceiling is square in the plan (Figure 33). Model comes with the deployable covering that can fold and unfold just like a flower, based on Sergio Pellegrino's work.

Figure 33: Deployable Ceiling

- **Deployable Iris Dome**

Adopted from Hoberman's Idea, the Iris dome is a retractable roof that transforms like the iris of an eye (Figure 34). As it extends and retracts, transforming the space, while its perimeter remains essentially fixed and stable. In its extended state it forms a lamella dome whose members display a pattern of interlocking spirals.

Figure 34: Deployable Iris Dome

- **Two Expandable Spherical Cups**

These two structures are expanding dome-like structures that correspond to the most efficient folding configuration and maximum expansion conditions (Figure 35). One of these three-dimensional mechanisms is capable of expanding up to seven times its packaged size. In the first spherical cup, all the bars meet with one another once the structure contracts from a dome-like shape to a completely compact bundle. This leads to the structure that corresponds to the most efficient folding configuration and maximum expansion conditions. The cup is ideal when compact packaging is essential.

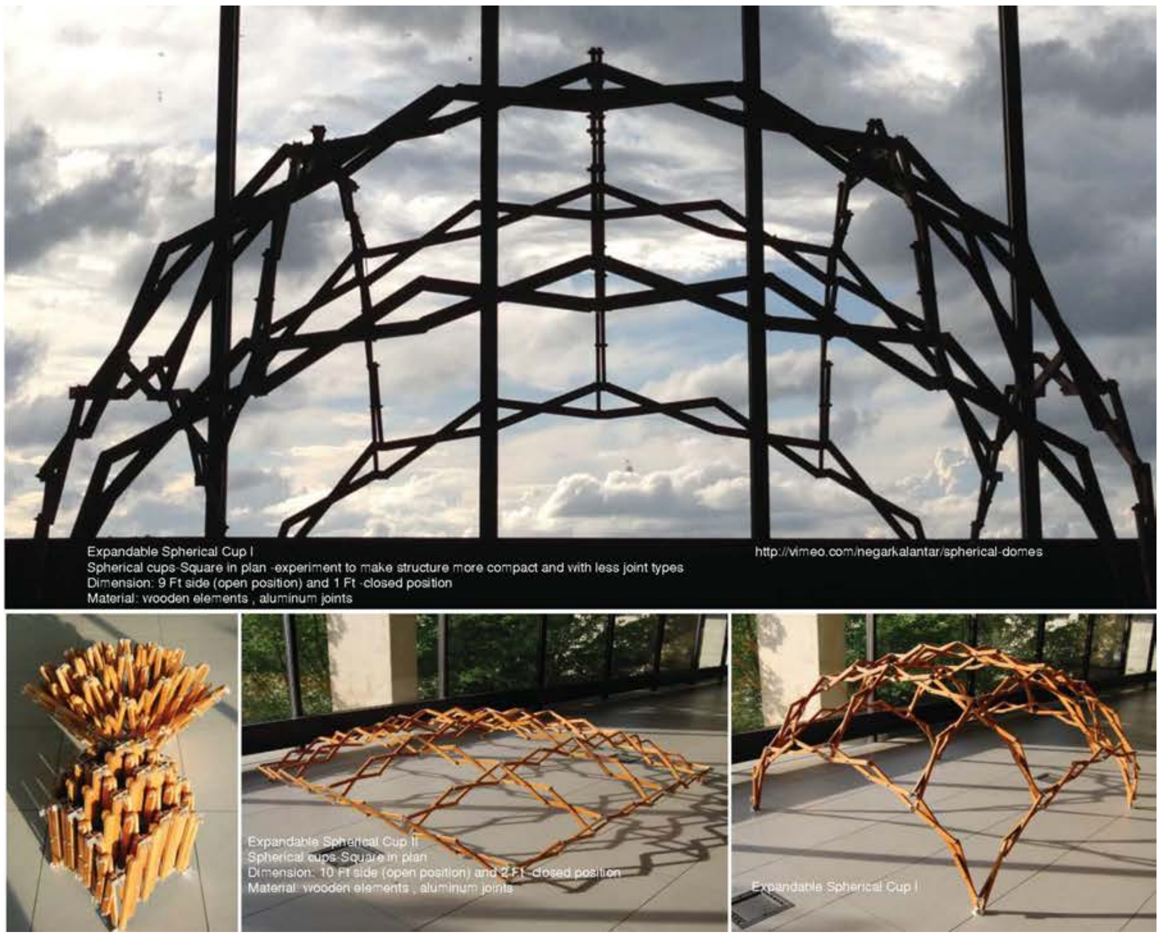

Figure 35: Two Expandable Spherical Cups

- **PARTeE: Interdisciplinary Design Laboratory**

PARTeE[44] is the name of an interdisciplinary design laboratory approach that explores the potential of prototyping, architecture, and robotics at Virginia Tech. The author was a

[44] Prototyping in Architectural Robotics for Technology enriched Education

member of PARTeE. This Lab explored computationally driven physical kinetic systems and components as they relate to building systems, environmental conditioning, and social and psychological issues. The project was commissioned by Virginia Tech's School of Visual Art's Experiential Gallery in downtown Blacksburg, Virginia. Below are two PARTeE's projects.

- **FLOWer: Agents of Responsive Mediators**

"FLOWer" examined a kinetic shading partition (Figure 36). The prototype materializes an example of the notion of a novel concept "Interactive Ornament" that evolved during the research. In FLOWer the inherent physical quality of elasticity and memory of felt along with a described geometry produced by laser cutting produces an almost unforeseeable physical emergence.

Figure 36: FLOWer- Agents of Responsive Mediators

- **a2o: A Responsive Mediator**

a2o is a responsive interface designed by PARTeE (Figure 37). These systems are understood to be singular systems, able to actively influence localized climates within a building system. The team envisioned a bottom-up design for the physical construction within a top-down computational logic. Each unit contains dedicated sensors (infrared range finder and photocell) and dedicated actuators (linear actuator, RGB LED, and piezo buzzer). Sensory data collected by each individual unit is relayed to a master controller - in this case an Arduino microprocessor- which controls a pixel of five units. The master controller would then describe an action for the individual units to perform in direct relationship to the sensory data it collected. If the master controller recognizes a specific set of data – in this case no data - it could then describe a preset task for all of the units within its pixel to perform, producing a top down response. This logic structure, described as cellular automaton, allows for the piece/part system to be expanded infinitely as each pixel within the system becomes a unit within the subsequent pixel.

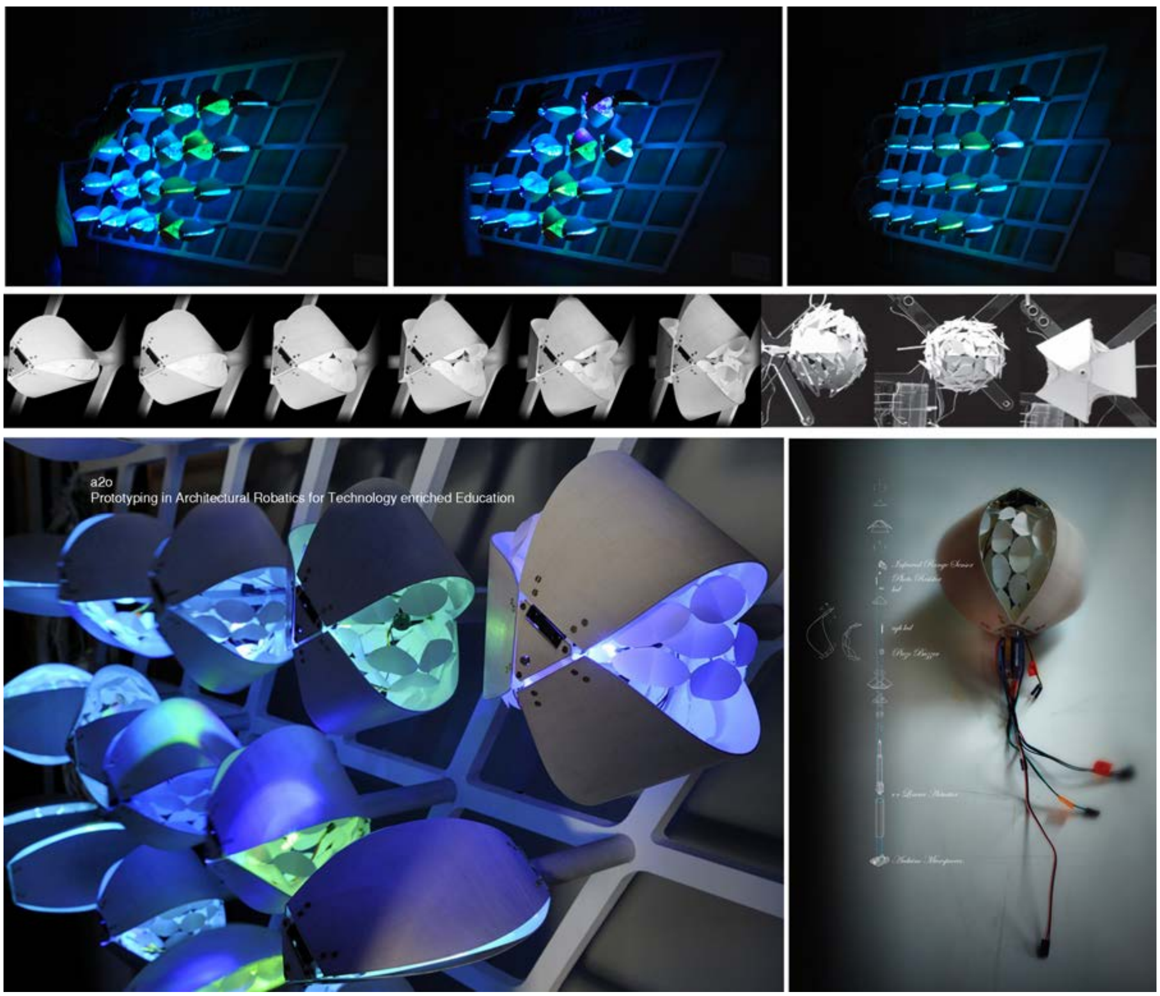

Figure 37: a2o: Agents of Responsive Mediators

- **Jet Blue Airline's fenestration**

Another project is Jet Blue Airline's fenestration[45] system, called Whispering Façade (Figure 38). This architectural-scale building enclosure incorporates both a physical transformation and a parametric design approach, and seeks to dissolve the boundary between actual and perceived motion. The project is a collaboration with the Center for Design Research and also involved extensive coordination with the international architecture firm Gensler. Whispering Façade functions as a shade for the new Jet Blue Airline arrival area in Terminal 5 of the JFK airport, blocking 90% of the sunlight and heat on the west-facing windows. A 15' tall kinetic membrane composed of thousands of wind-animated, 4-inch stainless steel spiral projections runs the entire length of the facade, shutting off the view from outside in response to the airport security requirements. The design creates a high performance enclosure system by projecting a spiral-cut section of sheet metal out of a flat surface from its larger originating body. The spring-like state of the spiral cut, caused by the agility of the material, allows Whispering Façade to undulate in the wind. Embodying the dynamic visualization through the motion of each spiral piece, Whispering Facade generates a continually changing and shimmering mosaic of light, which empowers viewers to perceive the way patterns can emerge with the passing breezes. In this way, the floor to ceiling of Whispering Façade reveals the gentle changes and normally invisible currents of air to those who are inside the building. Therefore, as a mediator between the outside and inside, Whispering Façade lets people perceive the outside world when the entire wall of the building appears to move in the wind and when the wall is resting. Whispering Façade reflects people's clothing as they pass through the space, as well as light and color from the sky based on the weather and the time of day. With elegant simplicity, Whispering Façade casts subtly moving shadows inside the building as well. By controlling the geometry of the cut path, the depth and distance of projection, and the wind speed, this design can mitigate direct light and heat in an architectural space. Graphic imagery can be embedded within the system design by leveraging amounts of open-ness and closed-ness of each spiral cut to

[45] Fenestration refers to the arrangement of windows and other openings in a building.

create pixilated images.

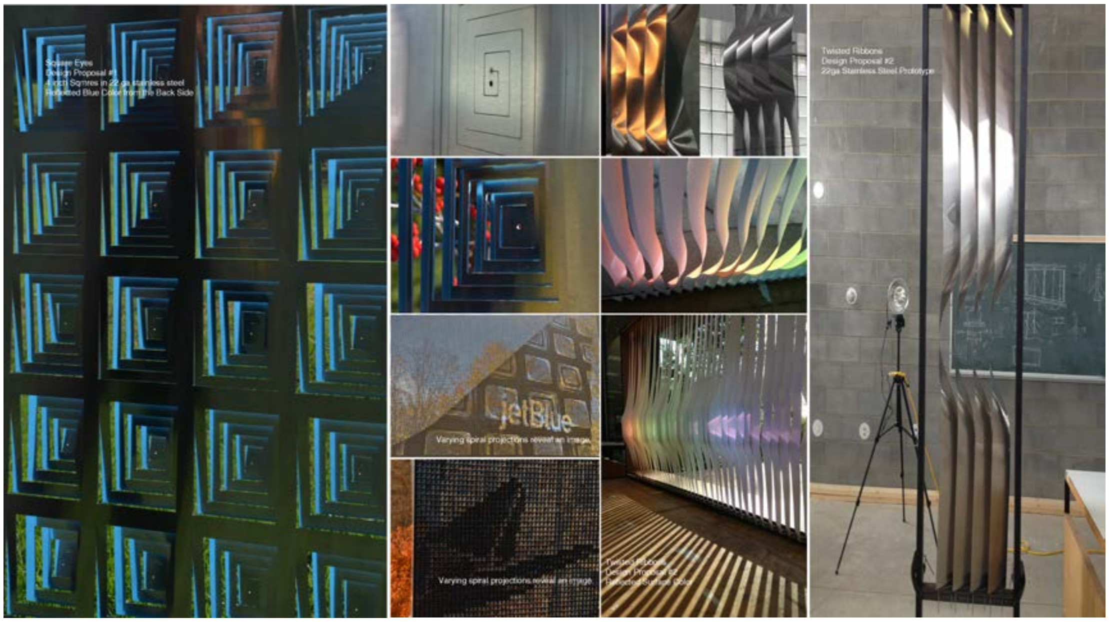

Figure 38: Jet Blue Airline's fenestration

- **L8 and Circino**

Though many objects resemble playful devices, author designed two actual hand-held toys, L8 and Circino, which both demand to be set in motion. L8 is a magnetic-kinetic toy comprised of eight L-shaped pieces which can be assembled in multiple configurations (Figure 40). Circino, produced by Naef Spiele in Switzerland, is a balance toy that is made up of seventeen semicircle-shaped wooden pieces which form a complete circle in its packaging at rest (Figure 39). In motion, Cicino's pieces can be stacked and balanced in ingenious ways. Circino has drawn her inspiration from simple but exciting laws of physics.

Figure 39: Circino, A balance toy

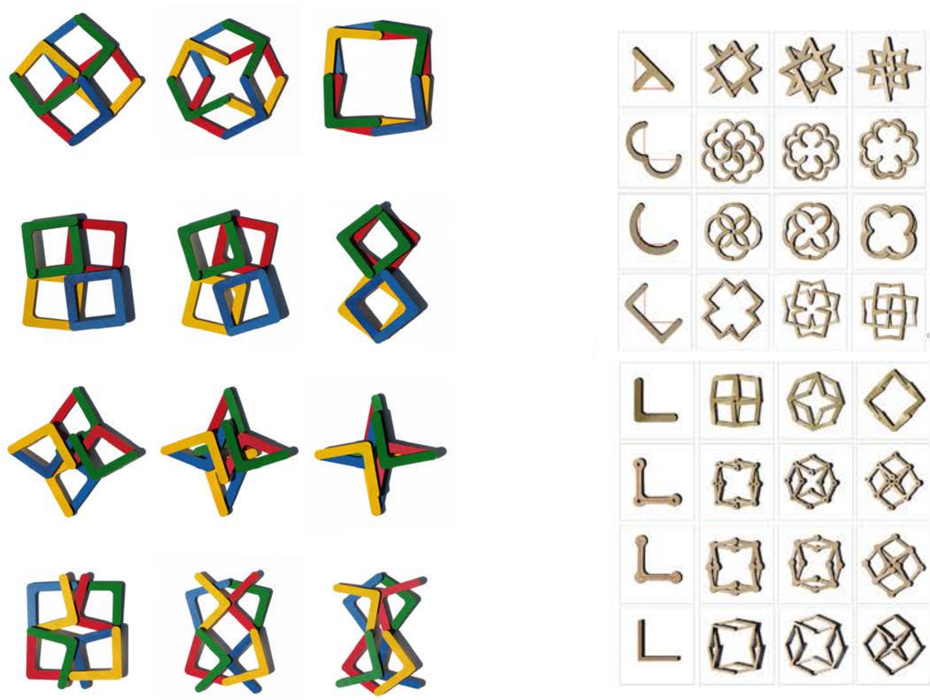

Figure 40: L8, A kinetic magnetic toy

Both toys provide a joyful experience of discovery and engagement available to the users. For instance in case of L8, when a set of motionless pieces suddenly spring to life and move, their stunning vibrancy delight the visitors. In addition, L8 is a toy designed with educational value that allows the user to play with geometry without having to know the underlying principles of geometry. Meanwhile, by tying together play, imagination and hand/eye coordination, Circino challenges one to create through play. While one adds piece by piece of Circino to employ agility, focus and consequence, they can magically configure carefully balanced compositions. The design value of these toys can inspire creative play, and the value derived by users increases when they are constantly interacting with the toys. L8 and Circino engage visitors in hands-on experiments that emphasize learning kinetic geometry through doing.

The following diagram presents the author's journey to better understand the design principles of transformable shading devices (TSS) from 2000 to 2015 (Figure 41).

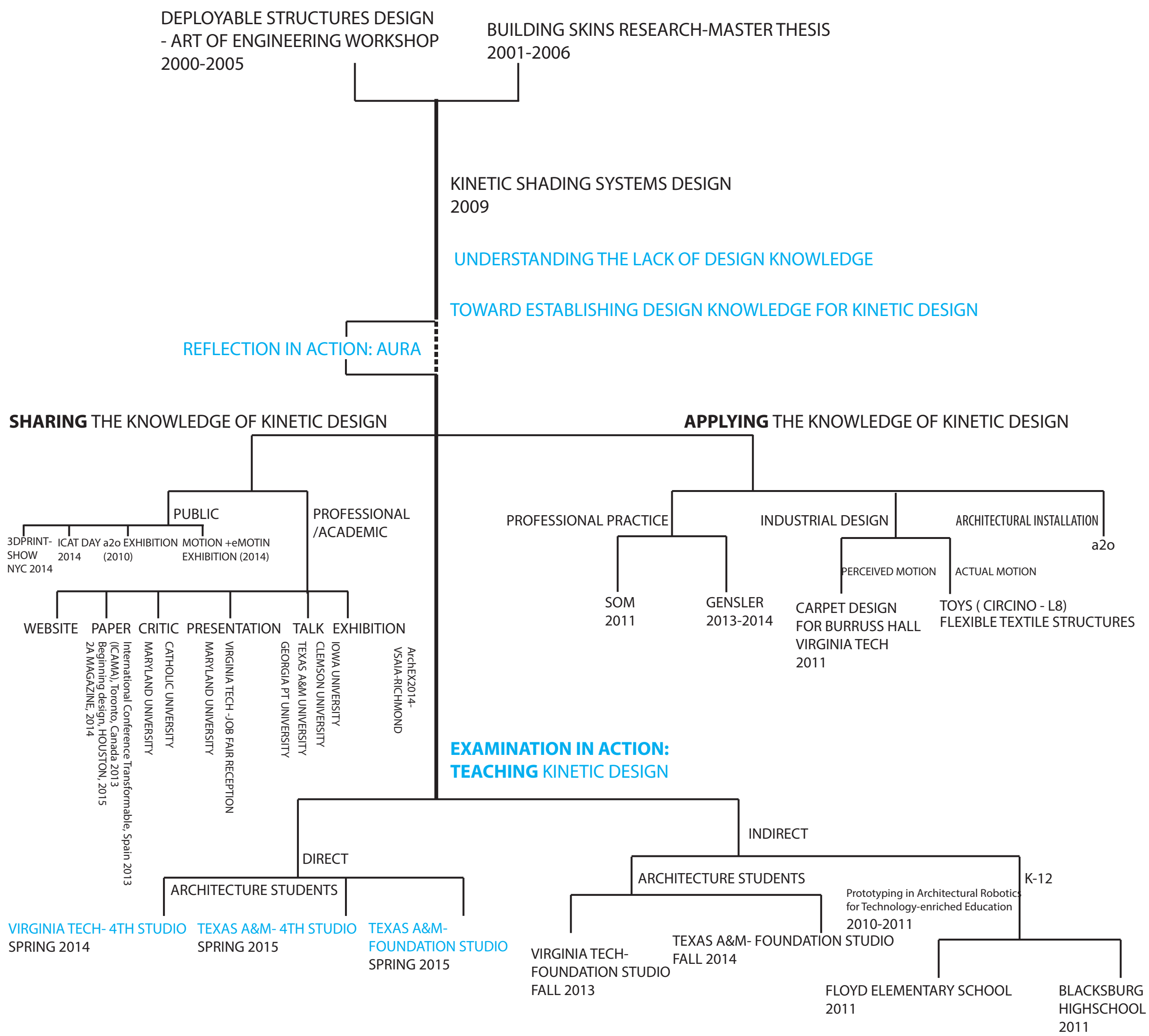

Figure 41: Author's journey (2000-2015) to understand and share the TSS Design Process

3 Chapter 3: **Research Methodology**

"Design is a way of inquiring, a way of producing knowing and knowledge; this means it is a way of researching" (Downton 2003).

This research applies a qualitative approach (Groat and Wang 2002) in using an inductive mode and the utilization of an intensive, open-ended and iterative process that simultaneously involves knowledge gathering through design, making and sharing the process. The research depends heavily on a "knowledge capturing through design" approach from design process of transformble shading system. The knowledge capturing process is developed through an immersive case study (knowing in action). The knowledge captured will be combined with the knowledge extracted from the literature in order to structure a provisional process model for design of kinetic shading systems. The findings of this self-immersive study will be evaluated in the context of two design studios in two different universities.

3.1 Design Research Strategy

Research can inform design in many ways and at many times. The design process can yield many questions that lend themselves to several forms of inquiry (Groat and Wang 2013). This study is an attempt to bridge the gap between design and research. Design and research are neither polar opposites nor equivalent domains of activity; instead, a permeable boundary and shared domains exist between the two. In the case of design, the stimulus is commonly referred to an "ill-defined problem" that cannot be understood until after the development of a designed artifact as a solution. In research, the motivation is typically framed in terms of a "question" to be answered, at least in part, by examining current or past evidence.

As Groat and Wang (2013) mention, there are many external forces driving the interest in a relating the domains of research and design or the academic environment and the profession. This requires a departure from conventional methods of scientific inquiry. Therefore, Groat and Wang proposes a new paradigm: the architect-as-cultivator.

Formation of the architect-as-cultivator is grounded on the position that the design process is a domain of research. In this view, the architect-as-cultivator has a willingness to emphasize process and interdisciplinary design.

As per Norman Denzin and Yvonna Lincoln's definition, qualitative research is multi-method in focus, involving an interpretive, naturalistic approach to its subject matter. This means that qualitative researchers study things in their natural settings, attempting to make sense of, or interpret phenomena in terms of the meanings people bring to them. Qualitative research involves the studied use and collection of a variety of empirical materials.

The above description of qualitative research characteristics goes a long way towards describing the aims and strategies of the present research. Groat and Wang (2013) provide the five key components of qualitative research:

- An emphasis on natural settings: "natural settings" is meant that the objects of inquiry are not removed from the venues in which they typically exist.

- A focus on interpretation and meaning: researchers not only ground their work in the empirical realities of their observations and interviews, but they also make clear that they, as researchers, play an important role in interpreting and making sense of that data.

-A focus on how the respondents make sense of their own circumstances: the researchers aim to present a holistic portrayal of the setting or phenomenon under study as the respondents themselves understand it.

- The use of multiple tactics.

- Significance of inductive logic: The research questions investigated through a qualitative study frequently evolve in an iterative process.

Other aspects of qualitative research include a holistic approach with prolonged contact between researcher and subjects. Also the research is open ended where the researcher is the primary measurement device. Analysis is typically through words or visual materials and writing is personal and informal.

Simultaneous Divergent and Convergent Approaches

This study is both divergent and convergent as Nigel Cross notes, "Normally, the overall aim of a design strategy will be to converge on a final, evaluated and detailed design proposal, but within the process of reaching that final design there will be times when it will be appropriate and necessary to diverge, to widen the search or to seek new ideas and starting points. The overall process is therefore convergent, but it will contain periods of deliberate divergence."

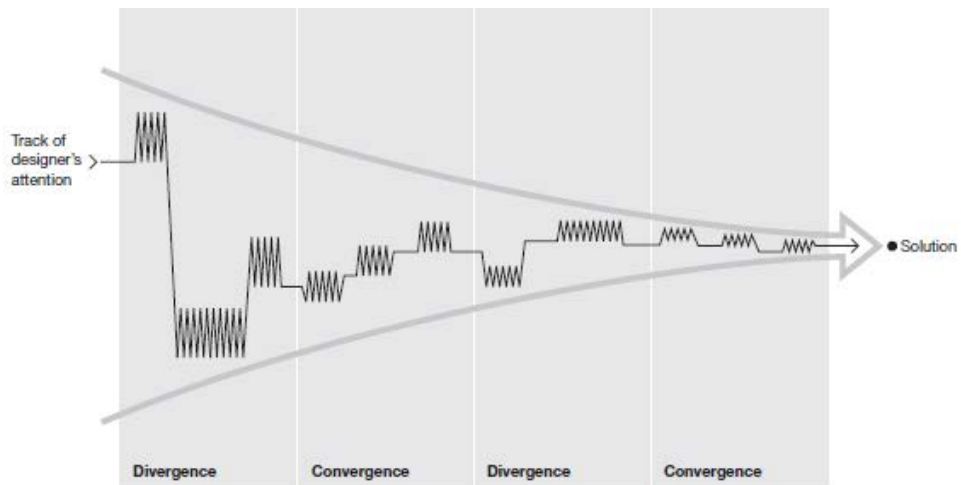

Figure 42: Banathy and Cross model for design process

Theoretical Grounding of the Research

Within the discipline of architecture, theory is a discourse that describes the practice and production of architecture and identifies challenges to it. Theory can be characterized as prescriptive, proscriptive, affirmative, or critical. Prescriptive theory offers new or revived solutions for specific problems; it functions by establishing new norms for practice. It thus promotes positive standards and sometimes even a design method (Nesbitt 1996). This research addresses prescriptive theory while it attempts to offer a new proposition in design research.

Based on Groat and Wang studies, theory can be arranged under three headings: explanatory theory, normative theory and design-polemical theory.

This study falls in the domain of design-polemical theory, that guide and assess our choices of what ought to be done. From this theoretical perspective, designers are guided in their action by “value-full” convictions of how a design problem should be addressed or solved. Designer’s approach is first to express a conviction for his or her own designs, but ultimately in the adherence of the designer’s points of view by a large audience.

In this study, theory can be applied to the outcome, which is the design of the building envelope. Since the translation form theory to formal outcomes is mostly interpretive, the design workflow proposed by this study could help to understand the designer’s decisions.

The extensive literature that is concerned with shading design has concentrated on passive design solutions or more concentrated on design constrains. Little literature can be found that examines the transformable shading system’s design process or design attributes for such systems.

The research method used in this study can impact the development of the design process. As an architect that has been involved in the research, design and making of kinetic structures for over fifteen years, the researcher believes that this work represents a shift in what research means in the field of transformable studies and what will be the expected outcomes. In this study, the researcher attempts to depart from the conventional expectation of research in architecture. Here, research and practice are more fluidly related and this study is concerned with establishing and developing an outcome that can elevate both architectural practice and scholarly research. A desire to bridge these two often-separate domains is one of the concerns of this research.

Ellison and Eatman are explicit in holding that outcomes of research need not be concepts communicated by writing or classification; they can be artifacts such as performances, exhibitions, or certainly buildings. Groat and Wang state that “making knowledge about, for or with,” suggests situated and contextual outcomes that do not necessarily promise universal applicability, can find relevance in particular application. (Groat and Wang 2013)

Because the objective of this study is to develop the process of design framework, a qualitative approach and design decision research are chosen for the research strategy.

	CURIOSITY-ORIENTED ←					→ MISSION-ORIENTED
	Theoretical Research	**Interpretative Research**	**Experimental Research**	**Survey Research**	**Simulation Research**	**Qualitative Research**	**Action Research**
Ontological assumptions	Knowledge is created by devising logical, abstract theories of some reality	Knowledge is created by developing alternative interpretations of reality in order to understand the human condition	Knowledge is created by developing and testing general theories that apply to items of interest	Knowledge is created by developing and testing general theories that apply to all social/psychological issues	Knowledge is created by improving our understanding of the behavior of complex systems through simulation	Knowledge is a socially constructed reality and cannot be generalized	Knowledge is created through the process of change; Generalized knowledge less important
Epistemological Assumptions	We know through our own reasoning capabilities	We know through our intuitive understanding combined with reasoning	We know only what we perceive through our senses (logical positivist)	We know only what we can measure and test (Logical positivist)	We learn about the world by simulating artificial worlds	We know only by developing an in depth, intimate understanding about individuals	Participants learn from trying to improve existing situations
Disciplinary base	Philosophy, mathematics	History and the Arts	Natural sciences	Social sciences	Artificial sciences	Cultural anthropology; Ethnography	Practice
Research goal(s)	Develop theory	Develop interpretative, theoretical understanding	Identify causal links; causal explanation; test theory	Causal explanation; test theory	development of insights about the behavior of complex systems	Describe situation holistically and from perspective of the participants	Focus is on developing practical results; solving real problems; set change in motion
Methodological Orientation	Logical abstraction; use of deductive logic	Both inductive and deductive	Experimental and quasi-experimental; induction; "scientific method"	Quasi-experimental; induction	Deduction to build model; induction to evaluate simulation results	Case studies; thematic/content analysis	Diagnosis; development and implementation of action plans; evaluation of action plan
Key methodological concepts	Logic	Develop critical perspective	Validity, reliability, bias; test of null hypothesis	Validity, reliability, bias, test of null hypothesis	Develop a model to simplify reality	Empathy; descriptive orientation	Empowerment; may emphasize training
Variables	Emerge during research	Emerge during research	Predetermined	Predetermined	Predetermined and emerge	Emerge during research	Emerge during research
Control or comparison group	Not relevant	Not relevant	Necessary	Usually comparison groups established in analysis	Comparisons emerge as result of simulations	Not relevant	Not relevant
Data analysis	Not relevant	Descriptive; possibly augmented with quantitative approaches	Usually parametric (correlation, t-test, ANOVA, regression)	Usually non-parametric (rank correlation, chi-square, MCA)	Varies from descriptive and quantitative to quantitative	Usually thematic or content analysis; descriptive focus	Depends on client and specifics of the situation; often used to diagnose the problem
Participant's role in research	None	Provides first hand record of event	None	None	Varies depending on definition of the artificial system	Usually as an informant	Actively participates
Researcher's role	Seeks theoretical interpretation	Seeks theoretical interpretation	Seeks to be objective	Seeks to be objective	Extrapolates behavior of simulated system to real world	Interactive; often as participant observer	Collaborates with client
Political pressures	Ignored	Often an integral part of interpretation	Controlled by research design or ignored	Controlled by research design or ignored	May be relevant depending on the definition of the artificial system	Described	Included as part of the action research context
Research report (implementation and communication)	Presentation of logical conclusions (academic focus)	Presentation of interpretation (usually academic focus)	Presentation of statistical proof (academic focus)	Presentation of statistical test and interpretation (academic focus)	Presentation of model's logic; comparison of simulation results to reality (academic or pragmatic focus)	Present holistic portrayal of participants and settings (academic or pragmatic focus)	Describes the context and outcome of the research (pragmatic focus)
Architectural examples	Design optimization approaches; mathematical theories; algorithms	Theories of architectural history and theory	Material testing	Post-occupancy evaluations, behavioral mapping	Thought experiment, gaming-simulation, mock-ups, computer simulations, cost/benefit analysis	Participant observation	Demonstration projects; advocacy planning

Table 8: Selected architectural research strategies

Qualitative Research Strategy

In this study, the strategy of qualitative research involves gaining an interpretive approach to the whole process and tries to understand how the TSS design process is structured. Here, the researcher is a main instrument of research. Therefore, by embracing a qualitative research method, the value of my narration as designer and researcher will be emphasized. From this point of view, this research is not about studying the transformable shading devices as much as it is about the lessons learned through the process of design and prototyping.

Design Decision Research Strategy

“Action research” is a term given to studies that examine a concrete situation, particularly the logic of how factors within that situation relate to each other as the process moves toward a specific experimental goal. The emphasis is on knowledge emerging from a localized setting, as opposed to abstract knowledge derived from many settings (Groat and Wang 2013).

A more focused version of action research is "design decision research"[46]. In action research, the researcher is still outside of the concrete situation as he or she examines the iterative cycles of actions taken. Design decision research embeds the researcher more into the actual process. In this approach, the "researcher" can be the various players in the design process. In this sense, "researchers" and "designers" are "one community" and not two. The researcher can be a kind of "new practitioner" that not only makes decisions but also assesses those decisions from the perspective of research (Groat and Wang 2013).

Reflective Theory

This study is influenced by the reflective theory in which the main interest is integration of theory and practice through cyclic patterns of experience and conscious application of that learning experience. The concept of experiential learning is centered around the transformation of information into knowledge and abstract theory to practical knowledge. It is important that the researcher understands the significance of experimental knowledge that has been acquired through experimentation and put them in the practice.

In the process of experimental learning, reflection of the researcher or practitioner on the action is important and critical in order to self-engage in the process. Reflection is the activity in which people recapture their experience, think about it, reconsider it and evaluate it. The main point of reflective approach is learning through experiencing, testing these general understandings on a new situation and self-regulating your learning process.

[46] This term is proposed by Jay Farbstein and Min Kantrowitz

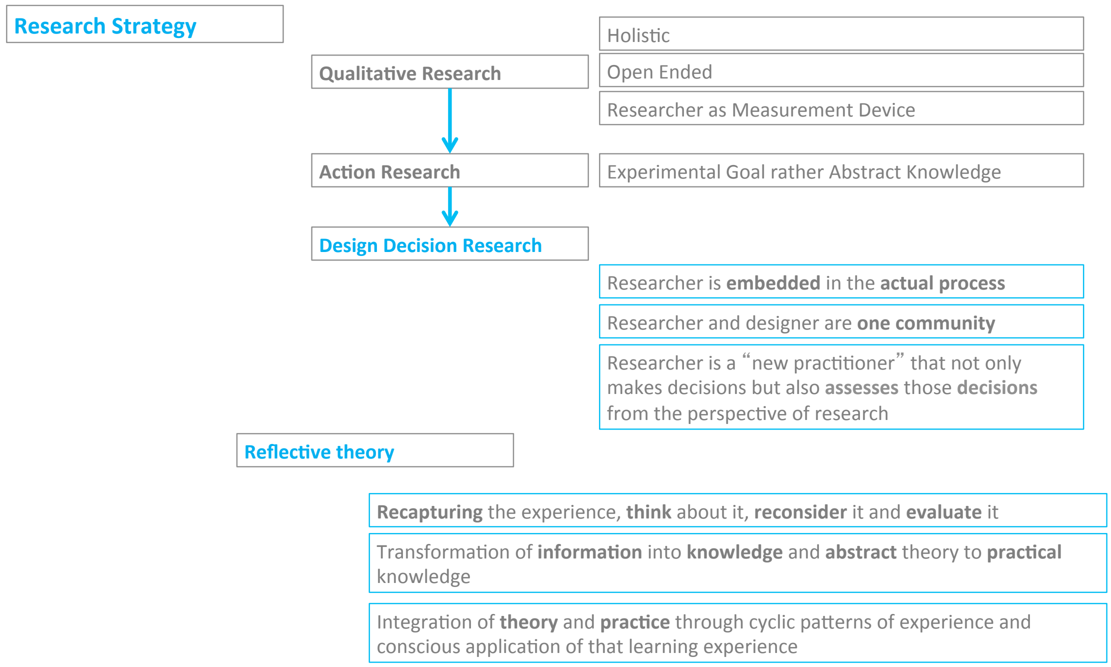

Table 9: Research strategy

3.2 Design Research Tactic

In Case Study Research, Robert K. Yin (1994) declared “empirical research advances only when it is accompanied by logical thinking, and not when treated as a mechanistic endeavor. This lesson turns out to be a basic theme of the case study method”. He defined the case study as “an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident”.

Case study is a qualitative research tactic when a holistic, in-depth investigation is needed (Feagin, Orum, & Sjoberg, 1991). Many writers have advanced definitions for qualitative case study. The Merriam (1988) definition states: "Qualitative case study can be defined as an intensive, holistic description and analysis of a single entity, phenomenon or social unit. Case studies are particularistic, descriptive and heuristic, and rely heavily on inductive reasoning in handling multiple data sources." Of these three types of case study, the descriptive approach will be used in this study. A 'descriptive case study' is one that presents a detailed account of the phenomenon under study. Lijphart (1971) described such case studies as " entirely descriptive and move in a theoretical vacuum." They are useful in presenting basic information about areas of education where little research has been done. Such case studies often involve innovative programs and practices and often form a database for future comparison and theory building (Merriam, 1998).

Descriptive means that the end product of a case study is a rich, 'thick' description of the phenomenon under study. 'Thick' description is a term from anthropology and means the complete literal description of the incident or entity being investigated (Merriam, 1988).

3.2.1 Knowing in action: Immersive Case Study

Heidegger and Spradly mention the necessity of immersive case study in regards to edification. Heidegger's pedagogy is an attempt to lead students in taking their own leap across the ontological difference. It is important that this leap not just be spoken about; it must be experienced personally as a "transformation." Heidegger uses the example of swimming to convey this pedagogical direction. "We shall never learn what "is called" swimming ... or what it "calls for", by reading a treatise on swimming. Only the leap into the river tells us what is called swimming" (Heidegger 1968, 21).Without such a leap "one is supposed to learn swimming, but only goes meandering on the riverbank, converses about the murmuring of the stream, and talks about the cities and towns the river passes"(Heidegger 1984, 7). All this talk unaccompanied by the personal experience of the leap "guarantees that the spark never flashes over to the individual student".

The self case studies included in this dissertation will be envisioned as an influential method to discover the knowledge, process and issues inherent to kinetic shading design and to refine the research questions. The self-immersive case studies will be conducted to answer the question, "What are the key knowledge exchanges within the design process of kinetic shading systems?"

Research Tactics	
Immersive Case Study	
	Researcher is embedded in the actual process, he/she is not only an observer
	Researcher make decisions and assesses those decision
	Researcher is an active participant in the research: capture, evaluate and reconsider the experience
WHY - Immersive Case Study	
	limited projects, designers and experts in the field of KSS
	The **scarcity** of available **information** about the design process of a KSS
	Limitation of access to KSS design process information (very few designers working on this topic)
	Researcher background

Table 10: Research Tactics

AURA System as an Immersive Case Study

As mentioned above, this research is intended to understand how to facilitate the design process of TSSs in practice through an immersive case study (Table 1). The full depth of the kinetic design process cannot be understood by theory alone. Therefore, for the sake of better understanding of the design process and the relationship of internal and external factors this research attempts to simulate the design process of an integrated kinetic window shading system called AURA. Through conducting the research via a project-based approach, AURA design allows the author to point out what the specific outcomes led to. Through stages of exploration, to an intervention or the sudden recall of useful information, resulted in a new direction of inquiry (Downton, 2003).

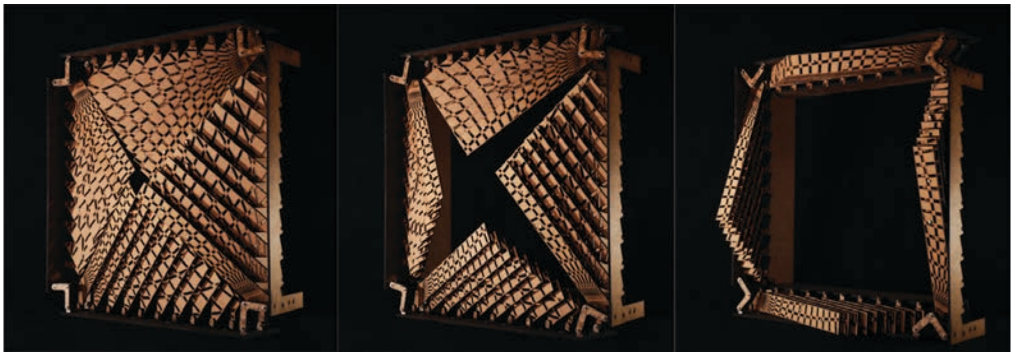

Figure 43: AURA system

The design process of AURA expands the current domain of motion design research. With a focus on the importance of the design process, this study will present a design process model from a seed idea through the fabrication phase in which motion evolves into physical models.

3.3 Evolving the Design Process Model for Transformable Shading Systems

The process of designing a TSS is not straightforward and an extensive number of factors should be considered. During design process, the given constraints and problems may be altered, but the general approach with which those problems are confronted does not. The best design strategy comes identifying and understanding the contrasts while clarifying all related problems. By setting up a preliminary workflow, it is easier to organize the given constraints and limitations to simplify the process of finding the best design solution.

This study tries to develop the design process model for the AURA, while potentially leading to framework for transformable design language. This workflow tries to frame the influential factors, problems and knowledge domains in the process of designing a TSS. This workflow helps to recognize which variables are most important in design process.

In the study of the AURA, to lessen the distinction between design and implementation, each design approach comes from thinking through how the final design can be built and each concept is assessed in terms of how technologically, functionally and aesthetically it can be fabricated.

The design process of AURA is a path to achieve knowledge about the conception and realization of TSSs. The design process of AURA creates an opening for the design process of transformable devices and inspires new avenues in the exploration of kinetic design. Thus, it can help other architects to exploit an integrated design approach to leverage kinetic shading devices.

3.3.1 Attributes of TSS Design Process Model

To understand the design process of a TSS, establishing a design process model[47] is critical. The design process model of TSS integrates information from a wide range of practical and theoretical domains to reveal patterns hidden in the design process and identify the relationships between decision related factors. This model is used to describe design methodologies and design pathways through the different stages of design. The design Process model breaks down a sequence of design phases into their component parts, such as design activities and decision nodes, to provide a context for understanding and evaluating how a specific design approach is applicable for a transformable shading project. Although the design process of each transformable shading project is concerned with creating and delivering an appropriate concept, the design model captures this process and consequently allows it to be improved. This model is beneficial for designers of transformable shading devices in the form of decision accelerants and deterrents, iterations, considerations, and rationalizations.[48]

It is important to realize that the design process model of TSS is not just presenting the flow sequences; it is also supports discovery and evaluation. This model is cyclic in the

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[47] There is wide range of models with different roles. Mendel makes taxonomy of models to describe types and roles of each model in different steps of a design process. (Mendel 2012)

[48] As Mendel explains all design process models should have those characteristics. (Mendel 2012)

sense that design team members design a transformable shading project, then prototype, execute, monitor, and evaluate in a forward-looping process. This process is a continuous improvement cycle.

The design process model of TSS is a shared representation of how design flows. Also, this model can facilitate better communication between different stakeholders involved in the design development, including users, designers, engineers, fabricators and researchers.

3.3.1.1 TSS Design Process Model Is Based on a Design-Led Perspective Approach

In general, there are two approaches toward a design research (Sanders 2008). These approaches can be derived from a research-led perspective or from a design-led perspective. A research-led approach begins with defining all the factors of the problem in order to develop a solution. A design-led approach on the other hand begins with a solution. The solution, then, is actually the starting point. More over in a design-led approach there is not a fixed or predictable answer (or right or wrong answer) to the problem and design process is a cyclic action between formation of solutions and clarification of the problem.

The cyclical nature of the TSS design process model is based on a design-led perspective approach. In this model, instead of first analyzing and then synthesizing, analysis, or understanding the problem is integrated with synthesis, or generating a solution. In the TSS design process model, by establishing a relationship between problem and solution, each solution concept is a means of helping to clarify the problem. This kind of problem is identified as an “ill-defined” problem.

3.3.1.2 TSS Design Process Model Focuses on Envision Phase

As Mendel (2012) describes, there are four steps in any design process: “discover, reframe, envision, and create”. As he explains: discover is about understanding the current situation, reframe requires a deep study of data gathered to understand the current situation, envision is about exploring potential solutions and create is about designing the future.

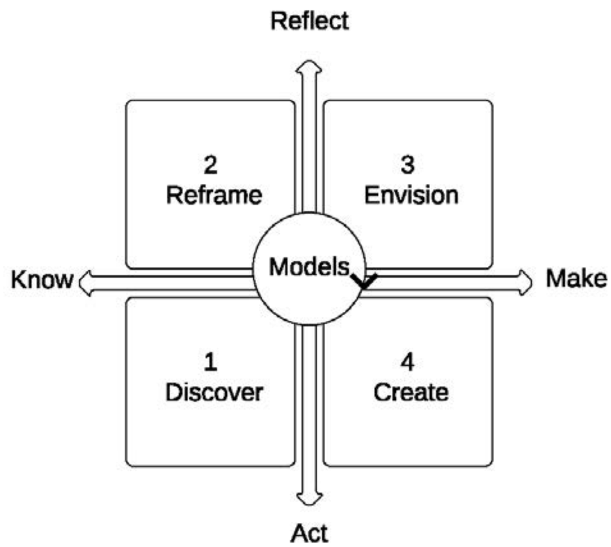

Figure 44: Taxonomy of models used in design process proposed by Mendel (2012)

This research mainly focuses on the envision phase of the design process for transformable shading devices. During the envision phase, ideas are generated, evaluated, and prioritized. This phase provides a framework in which designers can identify possibilities, explore alternatives, and conceive new realities that are grounded in research insights discovered through the process.

Base on Mendel's proposed structure, the envision phase includes the following (Mendel 2012) :

-Idea generation models: These models combine various aspects of a solution that need to be present when generating ideas.

-Prioritization frameworks: This is a platform for comparing and evaluating ideas, scenarios and concepts.

-Design conceptual models: These models are for the abstract representation of solutions.

-Roadmaps: Roadmaps provide a path toward a product or a design. Components of the roadmap are organized in a phased approach. They describe the path for moving from the current situation to the desired future. Roadmaps range from the high-level conceptual to detailed plans.

-Scenario prototypes and frameworks: Scenarios prototypes and frameworks demonstrate how an end product can be functioning for users.

-Prototypes: Prototypes are working models for exploring the tangible experiences.

3.3.1.3 TSS Design Process Model is Design-Led Perspective vs. Research-Led Perspective

Sanders (Sanders 2008) explained that there are two approaches toward a design research. These approaches can come from a research-led perspective or from a design-led perspective. The research-led perspective has the longest history and has been driven by the humanities and engineering. The design-led perspective, on the other hand, has emerged more recently. In the early 1990s there was an argument that design is either science or humanity. Some, such as Banathy, suggest that design is a way of knowing, distinct from the humanities and the sciences. Lawson (1990) notes, "Most of the maps of the design process resemble more closely the non-designer, scientific approach than of the architects: first analysis then synthesis. For the designers it seems, analysis, or understanding the problem is much more integrated with synthesis, or generating a solution."

Early models of the design process in architecture were often very similar to models of the engineering design process. A major difference is the apparently linear, sequential nature of the engineering model vs. the spiral, cyclical nature of the architecture model. Models of the engineering design process tend to emphasize the sequence of stages through which a project is expected to progress (e.g. concept embodiment-detail stages), whereas the models of architecture and industrial design emphasize the cycle of cognitive processes that the designer is required to perform (e.g. productive-deductive-inductive thinking). In emphasizing the sequence of stages that is expected to occur during project development, the engineering model is more prescriptive; in emphasizing the thought-processes that have to be employed by the designer, the architecture models are more descriptive, as follows(Figure 45).

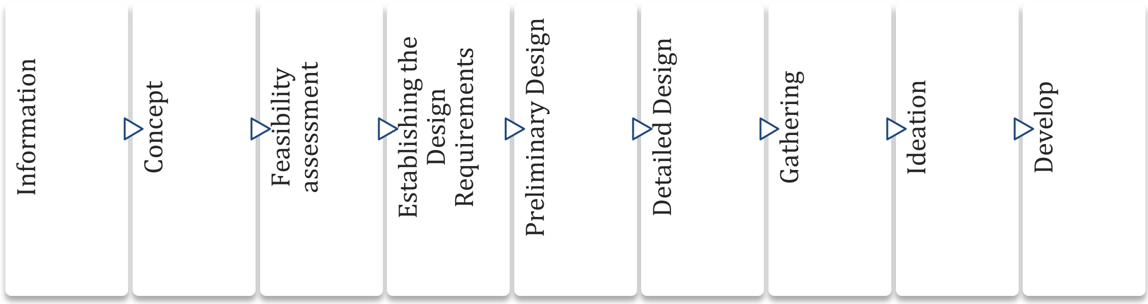

Figure 45: Linear model

Among the most important reasons for differences between the models is that the knowledge domains of the professions are different. For engineers the process is more qualitative where numerical information is often available as inputs to known procedures. For architect, on the other hand, the process is more qualitative and exploratory where knowledge is more individualized.   Architects also tend to view their design problems as inherently ill-defined problems, whereas engineers' problems are usually more well-defined (Table 11).

Such a dichotomy might arise because of differences between engineering's science-based, problem-focused education and architecture's arts-based, solution-focused education, as suggested by Lawson.

Table 11: : Comparison of characteristics of the engineering and architecture models (Cross and Roozenburg 1992).

Characteristics of the research-led perspective model	**Characteristics of the design-led perspective model**
Assumes problems are (or can be) well defined	Assumes problems are ill-defined
Systematic, expert process starts with	Opportunistic, argumentative process starts with solution-conjecture; accepts

problem-analysis; avoids preconceptions	prestructures
Linear	Cyclical
Tree-like problem structure	Lattice problem structure
Prescriptive of design behavior	Descriptive of design behavior

This Study is based on a hybrid model (Cross 2000) which integrates several aspects of different models (Figure 46).

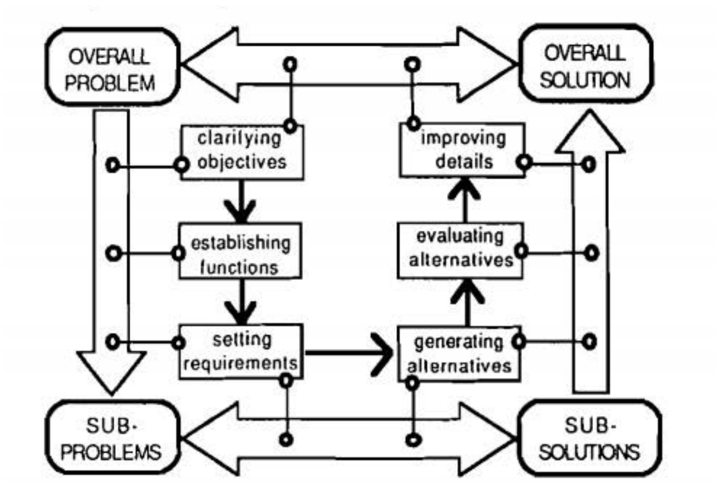

Figure 46: Cross's model of the engineering product design process (Cross and Roozenburg 1992).

3.3.1.4 A Symmetrical Relationship Is Assumed Between Problem and Solution, and Between Sub-Problems and Sub-Solutions

This study attempts to demonstrate and indicate that the relationship between problem and solution is not one directional, but that problem definition is often dependent upon solution concepts. This is an acknowledgement that making solution conjectures is often a means of helping to clarify the problem. The designer explores and develops the problem and solution iteratively. There are similar interactions between identifying sub-problems and generating sub-solutions (Figure 47).

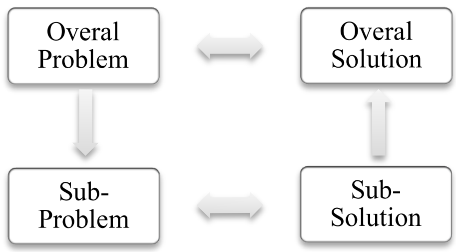

Figure 47: The symmetrical relationships of problem/sub-problems/sub solutions/ solution in design (Cross 2000).

3.3.1.5 Creative Loop Is a Part of TSS Design Process Model

There are several design methods that are intended to help stimulate creative thinking. In general, they work by trying to increase the flow of ideas, by removing the mental blocks that inhibit creativity, or broadening the search for solutions. Lawson illustrates the creative process as a five-stage model: first insight, preparation, incubation, illumination and verification. Illumination includes representing creative thought, significant innovation or novel design concepts (Figure 48).

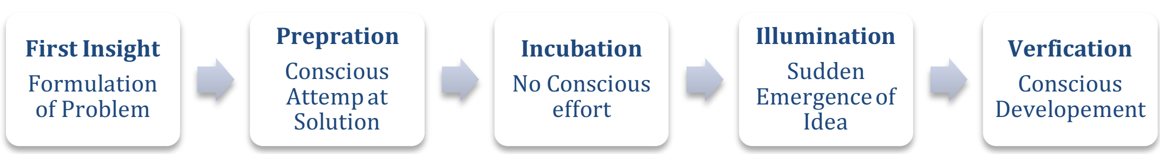

Figure 48: Bryan Lawson (1980) – Creative Process

3.3.1.6 Communication is a Critical Aspect of TSS Design Process Model

The creative process involves many conversations about goals and actions to achieve those goals. In 1963, Archer might be the first who included communication as an explicit stage in a design process model (Figure 49). Cross's model also includes communication as a final stage: conversations with co-creators and colleagues, conversations with oneself, or with fabricators or engineers. In this study, conversation is not only about verification of a design but also helps to discover, create, evolve, and make decision. Collaboration is a key element for understanding and conducting research concerning transformable shading devices. Different stakeholders and experts should be involved early in the design process. There should be a tacit understanding between the designer and these other disciplines when working on TSS.

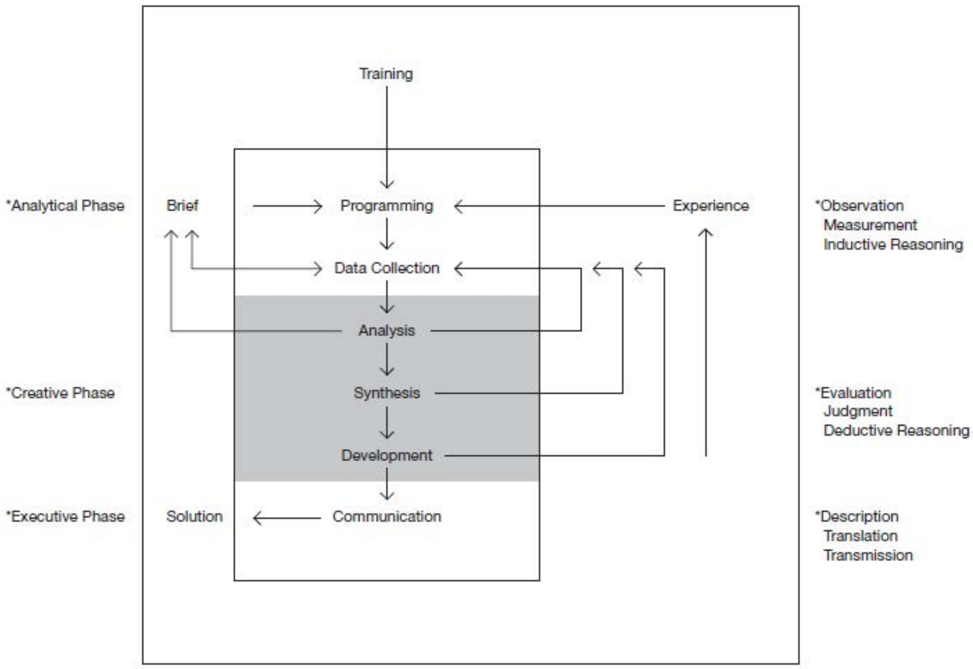

Figure 49: Basic design procedure-Bruce Archer (1963-1964) from How we design?(Dubberly 2005)

3.3.1.7 Feedback Is a Part of TSS Design Process Model and the Model Is Cyclic

Design not only follows the sequential overall process and cyclic feedback in sub-processes. It is anticipated that the developed design process model will include feedback loops for continuous improvement. Dubberly (2009) in "A Model of the Creative Process" mentions that "the creative process is not just iterative; it is also recursive. Many engineers define the design process as a recursive function: discover > define > design > develop > deploy". The Dubberly model is a cycle of three phases: Designing, Prototyping and Testing. As Alice Agogino mentions the process includes feedback loops to help "find errors faster" (Figure 50).

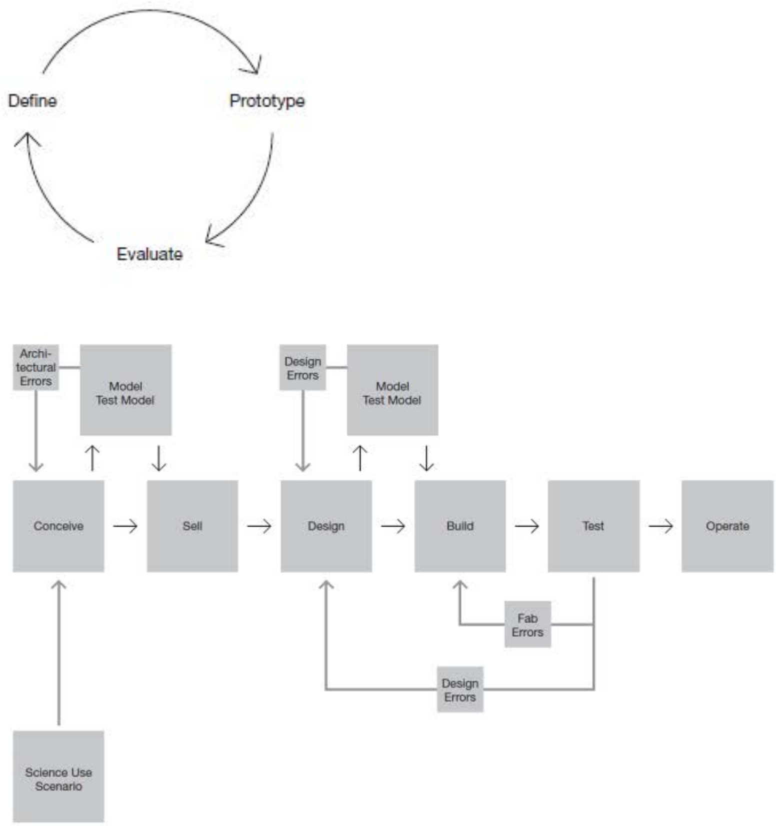

Figure 50: The third model developed by Alice Agogino for NASA's Jet Propulsion Laboratory (JPL) at California Institute of Technology.

3.3.1.8 Design Process of TSS as a Multi-disciplinary Approach

To meet the objectives for this research it must be done using an interdisciplinary approach. For example, the proposed design for the TSS and resulting environmental performance are inter dependent. However, a well-designed TSS cannot be achieved through environmental performance alone and it must consider other disciplines for fabrication, construction assembly and control. This design research seeks to synthesize technical, theoretical, and artistic aspects equally, through an immersive exploratory approach. This study seeks to integrate several fields including art, architecture and engineering into an interconnected, interdisciplinary whole.

3.3.1.9 Making is integrated in TSS Design Process Model

The design process of TSS is more closely tied to the process of making. Here, making is considered as a form of research and prototyping as a way of knowledge gathering and design thinking therefore making is integrated into the design intent. Accordingly, this study is an approach that contributes to making and hopes to situate the designer of transformable shading devices in a position that is active in relation to what will be fabricated. This study is grounded in knowledge gained through making. In this study, the required knowledge is acquired from the existing literature stated and from other researchers in addition to making a variety of transformable shading prototypes.

In TSS design process, making models is a way to visualize and evaluate the proposed concept before the manufacturing process. This approach transforms a motion concept into more tangible constructs. These reduced-scale models provide an exhaustive understanding of the outcome and help to visualize the final appearance. Prior to manufacture, the way these models perform under simulated conditions offers opportunities to better understand the way these models really work. When the budget allows, designers working in the field of kinetic design should perform extensive in-house research before the proposed design is sent out for fabrication. With more reliable input early in the design process, this could allow architects to focus on the intricacies of fabrication, installation, operation and maintenance. It is arguable that by spending more time in the design phase considering these issues, the manufacturing process could be expedited.

By integrating design and prototyping, this study intends to keep mistakes and malfunctions to a minimum. The development of a body of work occurs through the possibilities that emerge during the course of making. Prototyping can be effective for exploring alternatives and selecting the best option. The process of prototyping and model making new opens up potential territories for creative thinking related to TSS. During the process of making and testing models, there are opportunities to make unanticipated discoveries, and unanticipated issues can be resolved creatively.

In this research, prototypes are working models for exploring or demonstrating how design principles can translate into tangible experiences in a context of use ranging from small to full scale moke-up.

In this research there are three types of prototyping:

1- Concept models (digital and physical)

Primarily models for visualizing and checking the concept, developing underlying geometry.

2- Constructive (form-fit) models (digital and physical)

Models for visualization and assembly (how well parts fit together), basic motions/functions, and checking the underlying geometry and overlaying geometry.

3- Operational prototype

Operational model for testing, material, scale, dimensions, and detailing.

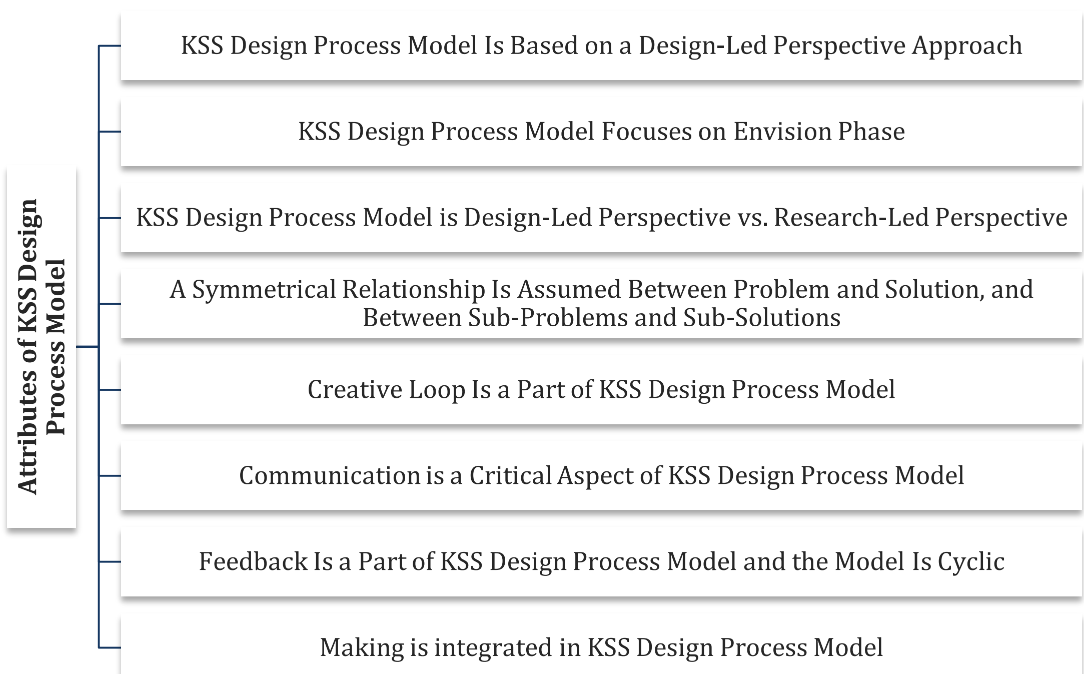

Figure 51: Attributes of TSS Provisional Design Process Model

3.4 Checking and Evaluating the Provisional Design Process Model

The process of determining the correctness of design process is an important activity. There are two validation techniques that will be used in this research: testing and peer reviewing. This checking phase can detect potential deficiency in the design process (Figure 52).

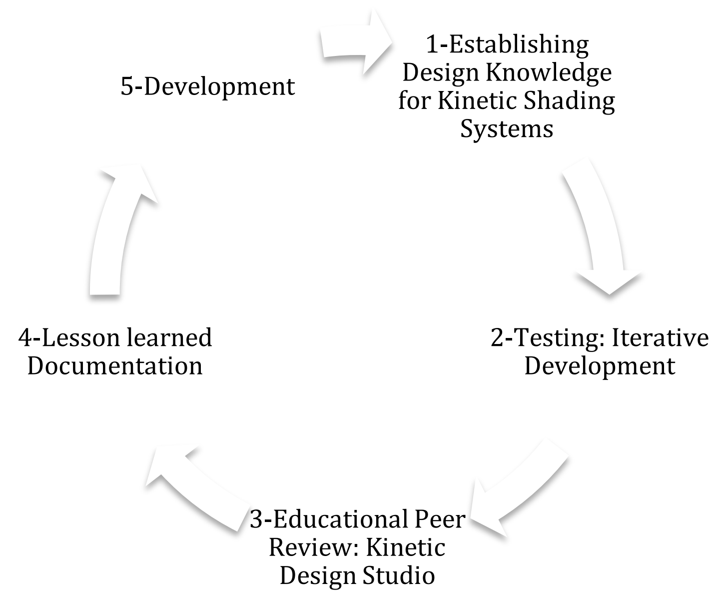

Figure 52: Cyclic process of developing TSS design process model

3.4.1 Testing: Iterative Development

Testing is an operational way to check whether a proposed model is functional. Testing will be applied by implementation of the design process model in designing a transformable shading system. Since developing a design process is an iterative process, the author will take advantage of what will be learned during implementation and iteratively enhance the evolving the design process until the acceptable model is developed.

3.4.2 Educational Peer Review: Kinetic Design Studio

After establishing the provisional design process model based on self-immersive case study, the author will design and run two design studios to test the design process model with architecture students at Virginia Tech and Texas A&M. The primary goal of the studios is to teach students the principles of transformable design. Although the verification applies throughout the development process as well, these studios specifically provide the context for checking the process and identifying the strength and weakness of the author's proposed design process model. The studios represent the direct application of the transformable design process and represent the culmination of the self - immersive design-research process established by author's model.

3.4.2.1 Participants

Participants of these design studios will be from diverse group of fourth year students of architecture from two different architecture schools in the country. These two studios will be only focus on the topic of Adaptive Thought, Design and Fabrication. During four months studio, students will receive required knowledge and skills about the field. Then, they will apply their knowledge and skills in series of design project.

In addition, the author indirectly exposes foundation students of architecture (First year studio) to the concept of transformable shading systems by giving special assignment to design adjustable shading system and transformable dwelings.

3.4.2.2 Knowledge Capturing Process in Kinetic Design Studio

Survey and Questionnaires

During the design studio on transformable design, voluntary and anonymous surveys and questionnaires will be conducted in order to establish pedagogical feedback (on first day of studio and on the last day of the studio). As a checking research instrument, the preliminary questionnaire will consist of a series of questions and prompts in order to gather information from respondents in a set format. (Leung 2001). Questions will be designed as open–ended format, which means that questions asked the respondents to formulate their own answers. At the end of the questionnaire exercise, answers will be gathered and some be coded into a response categorical scale. One of the main reasons of using this preliminary questionnaire tool is to understand the background knowledge of participants in this field and their understanding about the design process of kinetics systems. A more detailed procedure of the questionnaire and its phases will be explained in the chapter. The preliminary questionnaire will be done in the first day of studio without previous notification. This helps to gather the information without giving them the opportunity to do research and just reflect what they know.

There are few important times in the studio that author will conduct predesigned surveys.

1- Before the first day of the studio (FORM A)
2- First day of the studio (FORM B)
3- Last day of the studio (FORM B)
4- Process self-evaluation form after each design project (FORM C)

More information will be provided in chapter 5.

Author Observation

Since most of the participants of the studio do not have any background knowledge or experience in this field, the observation of their progress could evaluate the design process model. The author observes and documents the studio progress entirely and makes notes about what can be change or evolve in the design process. Documentation includes notes, images, video and conversation with students.

This will be a checking platform to evaluate the proposed design process model in different aspects:

- **Comprehensiveness**

The checking phase results provide feedback on the completeness and integrity of the provisional model and can be used to define areas of development for further design process refinement.

- **Clarity of the design process**

To ensure that other designers and professionals can understand the provisional model.

- **Checking the key knowledge exchange in the design process**

To ensure that the deign process model meets all the fundamental knowledge required to design a transformable shading system in an multidisciplinary synergies.

Involving People Outside The Design Studio At Appropriate Junctures

Receiving feedback from professionals is another checking technique that can inform the checking process. By inviting professionals and other educators to the exhibition and review sessions of students' works, authors can receive external comments. The author will document all the comments and suggestion in this phase.

Face-To-Face Interactions and Communications

The studios provide a context to discuss directly with the students in different design stage. There are some aspects of design process that are hard to be observed. Therefore face-to-face discussion could make those aspects clear. For example decision-making flow is one of those aspects. The main questions are:

What are the key decisions that they make in the design process of kinetic systems?

What knowledge and information is needed at these decision steps?

What make these key decisions different from the conventional and static design?

What knowledge they would like to gain to make these decision steps wiser?

3.5 Refine the Provisional Design Process Model based on the lessons learned through checking phase

Lesson Learned Documentation

The author tries to do well-maintained, consistent documentation in order to hold more effective design reviews and keep evolving the design knowledge. Also, the author would encourage students to record the design process in following categories:

-Concepts and Sketches
- Digital drawings and Modeling
- Prototypes
- Motion capturing (GIF[49], VIDEO)

[49] Graphics Interchange Format

In order to share the process with the larger audience and receive feedback from them, the author will design two weblogs for each studio as context that students can share their thought and progress and they can continuously monitor and evaluate their own learning processes.

Refine the Provisional Design Process Model

After establishing the design process and check it with above mentioned techniques, author will analyze the outcome of the validation phase and what learned through the process to implement them in design process. Therefore, the model can constantly change and evolve to be more comprehensive and integrated.

Author observations will refine following domains:

1- What students need to know (key knowledge including geometry of motion, material, and motion behavior and control).
2- Which skill they need to learn (key skills including software and fabrication).
3- When students need to know those knowledge and skills.
4- Which resources students need to have (material resources, mechanical resources and fabrication resources).
5- Which disciplines should collaborate with the studio (mechanic, computer science, electronic, and material).

Further explanation will be provided in the chapter six.

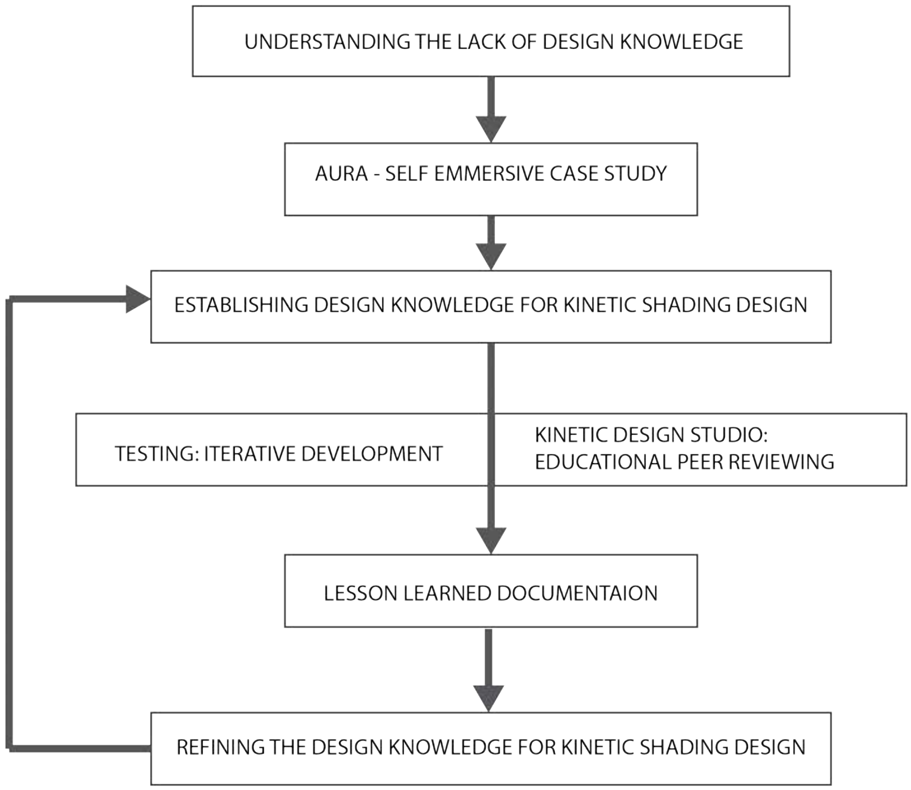

Figure 53: The proposal process for developing a provisional design process model for TSS

4 Chapter 4: **AURA:: Knowing in Action – An Immersive Case Study**

The design knowledge-capturing process for a transformable shading system that was conducted for this research had two main parts: one that operated through a self-immersive case study (i.e., AURA's design process) and one that operated through an educational peer review (i.e., a design studio). In this phase of the research, the inquiry shifted to a more active mode and the author served as an insider researcher. Based on Groat and Wang's description, the research strategy for this phase of the research was a more focused version of action research called "design-decision research." Design-decision research embeds the researcher in the actual concrete process; the "researcher" in design-decision research can be one of various players. In this sense, "researchers" and "designers" are "one community" and not two; programmers, architects, decision makers, and fabricators can all be a kind of "new practitioner" that not only makes decisions, but also assesses those decisions from a research perspective (Groat and Wang 2013).

In this chapter, an immersive case study tactic is described in order to propose a provisional model for a TSS design. This model was the outcome of an exploration of a range of kinetics, accomplished through a series of design experiments called AURA. This chapter describes the AURA design experiments and classifies the required skill and information, captured knowledge, and ultimate outcomes identified during the design process.

The motivation supporting this research was to explore the underlying parameters of the TSS design process through a series of self-immersive experiments, in order to elicit design decision strategies by capturing several variables such as knowledge, skill, and information. The ability to experiment with these underlying parameters also provided an opportunity to document them.

To briefly restate the scope of this research, the focus was on the actual physical movement of a transformable shading system. As previously mentioned, each transformable design has three fundamental design parameters:

Kinematic – Geometry of motion;

Material – Physical property; and

Behavior – time-based control of motion.

AURA's main focus is the design process of the geometry of motion; this coincides with the study of "movement itself." In order to map out the edges of motion geometry as a new design space, this Chapter frames a critical question: *What are the skills, information, and knowledge exchanges required for the design process for the geometry of motion?*

This query, as mentioned above, was pursued in this research through two knowledge-capturing processes: a self-immersive case study (the AURA design process) and an educational peer review (transformable design studios).

The literature review revealed that the main emphasis of the relevant precedent has been on the means and methods of kinetics (such as technological and engineering aspects) rather than the design process of motion. Despite this, the emphasis here was to understand the "process of designing motion." As Moloney (Moloney 2011) describes:

Kinetics shift architectural focus from the design of objects and spaces to the articulation of a process. The outcome of kinetics is not the design of the component parts, nor is it the enabling technology. The "thing" that is designed is the process that determines a multiplicity of kinetic pattern.

Therefore, this chapter focuses on the transformable shading system (TSS) as a "thing." The goal of this analysis was to understand the TSS design process through self-immersion.

4.1 Motion Study As A Design Methodology

In the field of architecture, movability can be considered as an important way to respond more actively to ambient conditions while meeting the needs of the occupants. Within contemporary architecture, it seems there is a growing interest in motion; buildings or their parts are gradually shifting from static to dynamic, but there is a shortage of design criteria to support this new domain. For Most of the existing kinetic projects, their main concern is either functional or technical and the performance or operability of the system is a priority. In functionally-and technically-orientated projects, architectural aspects of movable design are not considered alongside the other factors.

In general, most of the existing research or practices relevant to kinetic architecture do not consider motion in relation to motion itself and they do not address the comprehensive kinetic design methodology. Therefore, the existing body of literature on kinetic architecture does not provide further insight for those who want to know about motion taxonomy, compositional character, configurations of possible types, or morphology of movement.

Many architects or researchers may design and study motion but there is not yet enough evidence to completely be aware of the impacts of motion design process. Unfortunately, motion study as a design methodology is by far the least exploited by architects. To the author's mind, an architectural design method should be altered to accommodate a systemic approach towards the design process of transformable architecture.

The full depth of the motion design process cannot be understood by theory alone. Therefore, for the sake of better understanding of the design process and the relationship of internal and external factors that craft a motion composition, this research attempts to simulate the design process of an integrated dynamic window shading system called AURA.

This research is a step toward understanding how to facilitate the design process of AURA in practice. The design process of AURA expands the current domain of motion design research to the broader perspective of contemporary practices and contributes toward adding value to design criteria through motion study. With a focus on the importance of AURA's design process, this chapter presents a sequential design development of different mechanisms from a seed idea through the fabrication phase in which motion evolves into physical models. AURA is a mediator between idea and reality. Thus, through hand sketches, computer modeling and prototyping, the underlying drivers of motion formation is specifically examined.

Addressing the internal structure of the motion design process in architecture, AURA emphasizes the importance of motion language and its permissible morphologies. Design process of AURA ties directly into the language of motion formation and underlines the advantages of the language. The language of motion unveils the way that movable elements of AURA are designed and perceived.

This chapter develops the design process of AURA, potentially leading to a first-hand and comprehensive framework for motion language. Although language of motion is inherent with any motion design study, the characteristics and opportunities offered by motion language must be addressed. In order to discover the primary form generators of motion configurations, the design process of AURA is a way to understand a set of vocabularies and syntaxes that form a coherent picture of a language with infinite variety in its application.

In the design process of AURA, there is a tendency to deeply understand how an architect can orchestrate all different aspects of motion geometry. The process of making enforces the authors to be more involved in different parts of the project. The design process includes some empirical work and relies upon active experimentation with real models. All models that introduced here are fabricated by the author[50] over a period of two years to reveal the richness of motion language (Figure 54).

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[50] To develop and fabricate the AURA models, the author collaborated with Alireza Borhani, a doctoral candidate at Virginia Tech.

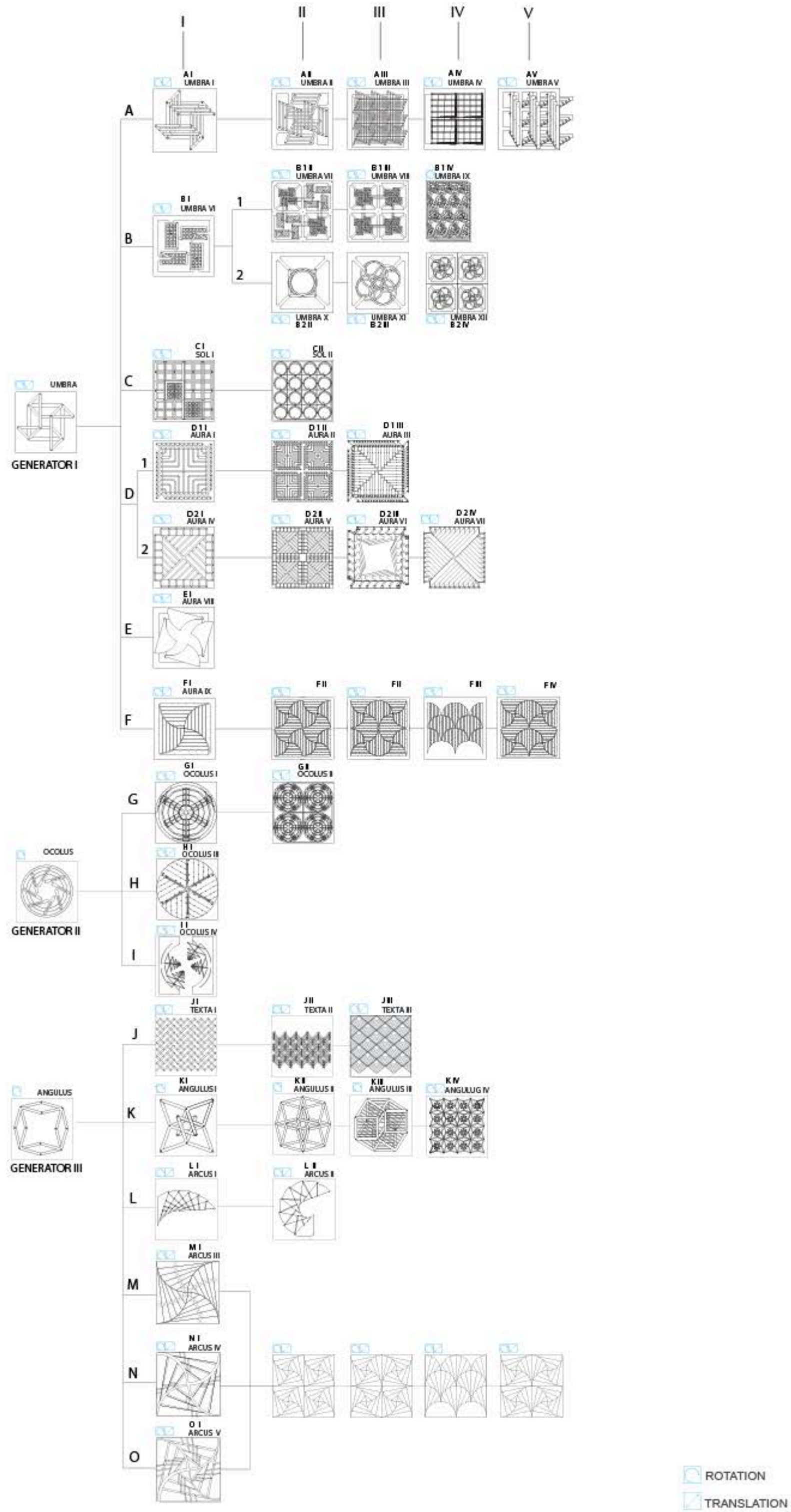

Figure 54: AURA's evolution during the self-immersive case study

4.2 Description of AURA

This section describes the TSS design process that occurred within the context of a self-immersive case study called "AURA's Design Process," the purpose of which was to develop the AURA system.

AURA, taking its name from the Latin term meaning "breeze," acts as an external or internal kinetic shading process for a building envelope. It consists of two basic parts. The first is the structural frame, and the second involves mechanisms that maintain the performance levels of the components. Each mechanism is composed of several movable wings and hinged joints. The joints allow the other parts to move freely. In AURA, all wings can change their positions with respect to one another and the structural frame. When all of the components are pushed by a constant force, a constant level of movement is achieved. The homogeneous movement of these models combines both rotation and translation. Each wing alternates between completely covered and extensively open states. When one wing moves, the other adjacent wings move simultaneously to provide the maximum amount of openness or closedness. The wings can be freely expanded to cover a large area when closed, but take up very little space when open.

By moving these wings, several shapes and configurations constantly morph into one another. Each opening and closing takes time, with each wing moving back and forth from one side of the frame to the other. By moving the wings toward the center, AURA's transparency and permeability can be adjusted to regulate the level of privacy, ventilation, and airflow. All of the wings can be closed by counter-clockwise rotation and opened by clockwise rotation. Individual linear elements that interconnect each pair of wings counterbalance the motion of all the other wings. The embodied mechanism (in the open position) can hide within the underlying structure of the building, invisible to the eye.

AURA consists of a basic modular unit fabricated out of various materials such as hardboard, aluminum, or acrylic. As a system, it can be tailored in a number of ways to suit different geometries, shapes, and sizes of buildings. AURA's module can be utilized along different scales, ranging from small windows to an entire building envelope. The module can also be applied to a broad range of existing or new buildings.

The design concept for each model was derived from geometry informed by environmental design principles. AURA, as a dynamic architectural element, offers the opportunity to optimize its configuration and perform more sensitively in response to ever-changing environmental conditions. For example, AURA can track the sun and interact with the daylight. In AURA, by repetition of a basic unit a wide variety of compositions and patterns can be generated.

Although AURA is not an intricate system in terms of geometry or mechanism, it is able to generate a wide variety of compositions and patterns by repeating a basic unit. The movement of these units can bring the whole system to life.

4.2.1 AURA as a System

Each system[51] may have several characteristics governing its structure, behavior, and interconnectivity. AURA, as a system, has a structure comprised of its own components, which are directly or indirectly related to one another, forming an integrated whole. This system behaves by fulfilling specific functions in response to its surroundings in order to control light, sight, and airflow. Similar to other systems, AURA's components are connected by their structural and behavioral relationships.

AURA is delineated by the general elements common to every system such as input, output, process, control, and feedback. AURA involves the capturing of various inputs such as intense direct sunlight, solar heat, and airflow that enter a space. A major intention of AURA is to produce several outputs such as shade and diffused lighting that provide occupants the maximum possible visual and thermal comfort. In this system, the inputs are transformed into outputs through the execution of a series of actions and processes (including the preclusion of direct lighting and cultivation of indirect lighting) in order to take advantage of reflection and refraction. AURA controls the patterns in which inputs are received from the outside and delivers them to the outside to fulfill its intended purpose. Control in a dynamic system such as AURA is accomplished

[51] http://en.wikipedia.org/wiki/System

through proper feedback. Through the feedback process, AURA exhibits certain characteristics that are contingent upon the inputs and outputs.

Although, AURA, as a transformable shading system, necessitates a full immersion in and focus on the performative dimensions of a shading system, it departs from common assumptions about the performance of such systems. AURA strives to clarify that while there is still a dominance of performance criteria in the evaluation of design decisions (Scheer 2014), performance or behavior is not the only criteria for its acceptability and effectiveness. Hence, AURA is concerned with far more than being just a functional machine with predefined utility values. As a system, AURA provides both a critical approach to and a conceptual framework for understanding the application of TSS to the built environment.

4.2.2 AURA in the Era of Simulation

Besides the opportunities presented by simulation software, for many students and professionals in the field of sustainability, performative and operational values are mistakenly and overwhelmingly considered to be central to the notion of architectural practice. For instance, due to the ambiguity of many of the terms used to understand the relationships among design ideation, visualization, and simulation, many shading devices are no longer judged according to the spatial quality of the resulting design, but rather by the application of specific functional or operational utilities.

In some cases, simulation, as a medium for reflecting reality, is achieved at the cost of refusing intrinsic[52] knowledge about that reality. John Dewey's concerns about thought process bear special relevance in today's rapidly evolving field of computer simulation programs, an area which is quickly overtaking the building industry(Dewey 1997). If we agree with Dewey that wisdom is often lost for the sake of knowledge and knowledge is hidden by data[53], then we should call for caution when

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[52] Intrinsic knowledge is not imparted to us in crystallized form, and therefore it is opaque to our rational thinking (e.g., our knowledge of how to walk without falling down). Intrinsic knowledge is what students know without even realizing that they know it.

[53] Dewey argues that "learning is not wisdom [and] information does not guarantee good judgment".

displacing wisdom through data; the result could easily be the misuse of simulation tools and the accomplishment solely of performative economic outcomes.

The design process of AURA does not give up valuable performance simulation methods in exchange for inadequate and inaccurate experimental tools. Rather, the design process is an attempt to make a case for simulation as an interface between several design approaches and the work itself. During this design process, simulation software is an active binding agent in the links between imagination, drawing, and evaluation. AURA's design process is to absorb how the need for a simulation to fulfill a requirement beyond a simple desire for simulation is far more potent than simulation for its own sake. In the design process of AURA, simulation, as an excellent tool to facilitate a better design, is not a substitute for design thinking, but rather a certification of some approaches acceptance over others.

4.2.3 AURA's Value

Three primary concerns have emerged with regards to AURA as a transformable mediator; the first is the humanistic value. This issue relates to maintaining inhabitants' desired light and thermal comfort levels while still providing an interface between the ever-changing environment outside and the more habitual climate preferences of the building's users. The second concern focuses on the efficiency and performance of AURA's adaptive system as it responds to multiple environmental factors. The third concern addresses the aesthetic status, visual quality, and appearance of AURA's final composition, which can assist the shading system and its companion building to become more connected to its cultural and social context.

To enhance the relationship between the natural and man-made environments, AURA enables the mediation of synergies between objects and the environment, humans and objects, and humans and the environment.

AURA has three levels of value:

– AURA as an object, serving as a Transformable Shading System;

– AURA beyond an object, serving as a space generator; and

– AURA as an immersive case study for understanding the design process of motion itself.

4.2.4 AURA as a Transformable Shading System

At its foundation, AURA is concerned with two domains associated with transformable boundaries, one physical and the other meta-physical. Both domains merge in the experience of the observer as the system transforms its appearance in response to changes in the ambient environment. The physical transformation of AURA relates to the movement of the system from open to closed in response to stimulation from the external environment, analogous to the opening and closing of the iris of an eye. As outdoor temperatures and cloud cover change, and the sun moves throughout the day and throughout the seasons, the system can respond to reduce heating and cooling loads and control glare while maximizing the benefits of daylight. In this way AURA is a high performance system that contributes to resource conservation and the sustainability of buildings while supporting high quality indoor environments.

Born out of a combination of necessity and foresight. AURA as a transformable shading system undertakes the followings:

- As a versatile architectural element, AURA offers opportunity to create an integrated envelope design that can achieve design excellence in conjunction with high functional performance. AURA reduces energy usage, enhances comfort and increases the flexibility of the built environments.
- AURA controls its permeability, varying smoothly between a completely covered and a largely open state.
- By shifting multiple layers, AURA continuously reconfigures itself and modulates between opaque and transparent states. In this way, AURA can preserve transparency where desired.
- By expanding functionality of movement, AURA intelligently controls transmitted light and solar gain and regulates ventilation and airflow.

- AURA as a system with modular units can be tailored to match different building design and requirements. AURA can be customized to various geometries, shape and size of building facade.
- AURA can visually disappear into a building's underlying structure when retracted.

AURA is well-suited to applications for different applications such as:

- Façades, roofs and awnings (Different vertical and horizontal positions).
- Exterior and interior spaces.
- Freestanding structural or non-structural divider (partitions).

4.2.5 AURA as a Space Generator, Beyond a Transformable Shading System

The second domain of inquiry for AURA is the meta-physical. The AURA is a beautiful system that evokes a perceptual response of the viewer. This perceptual response occupies the meta-physical space between the object (AURA) and the cognitive processing of mental stimulation. The mental stimulation is the result of experiencing the interaction of the AURA with environmental variables including light level, solar intensity, sun position and outdoor air temperature. The understanding of this transformative boundary between the object and perception is key to the design and implementation of AURA. By understanding this meta-physical boundary through its design, AURA has the potential to teach the viewer about geometry, the daily and seasonal rhythms of the environment and sun, as well as the role of technology in advanced control of building systems. From a phenomenological theoretical position that recognizes that meaning given to architectural spaces and building systems is the result of sensory stimulation and the mental processing of that stimuli, AURA becomes a transformative boundary that provokes one's perceptual response toward either self-awareness or an understanding of one's place within a larger external world. For example, as AURA automatically adjusts to dynamic outdoor conditions, the observer may become aware that those adjustments are being made to satisfy their personally space requirements. On the other hand, recognizing that the system is adjusting to the dynamic outdoor conditions stimulates a cognitive response of awareness of one's place

in a larger environment. The design of AURA seeks to understand and take advantage of this boundary between the object (AURA) and perceptual response.
AURA is designed to be more than what it is. By going beyond an object that serves the daily needs of people, AURA ties itself with the existential qualities of its surrounding. For instance, when AURA changes its status from fully closed to fully open, the magic moment of surprise and delight uncovers the true essence of its dynamic construction in the presence of light. In this case, by pushing the boundaries of its core competencies to reveal the initial qualities of its immediate environments, AURA's design process desires to grant transformable shading devices the capacity of generating space. To shift the focus from designing a transformable object to designing the experience of a constant change from one status to another one, the design process of AURA tackles the followings:

- The relation of whole to part: AURA as a whole is greater than the sum of its part.
- Process of learning: AURA can teach us about its surrounding environment in terms of variable solidity and permeability- AURA leverages contextual and environmental inputs to make an interaction between mind and body.
- Experiential learning through making meaning from direct experience.
- Mediating between mind and matter: Based on AURA's adaptability to environmental conditions and humans in the creation of space, AURA serves as a mediator between physical and mental space.
- Gaining consciousness through a mediator: AURA helps us to be aware of our own presence and the world of inside and outside.

Architecture can be seen as a dynamic responsiveness to a variety of intricate relationships among form, space, structure, materiality, and the senses. These relationships are not static, but rather are dynamic and ever-changing entities. The now-ubiquitous current research dedicated to adaptable architecture pays less attention to the potential of active communication between responsive building components and their social, cultural, and historical contexts. From this perspective, transformable architecture, as an emerging mode of inhabiting and constructing our built environment, requires a long period of spatial, practical, technical, and even cultural preparation.

AURA, as a proposition for transformable architecture, can be considered as an effective means of generating new forms of sensual, spatial, and cultural interaction with surroundings. As Frampton declares, “architecture's potential is to deliver authentic meanings in what we see, touch and smell” (Frampton 2001). As an expressive element in a building envelope, AURA’s underlying geometry and overlaid patterns can provide layers of meaning to the places we inhabit. Exploring this potential of AURA within spatial design offers an opportunity to establish a more malleable architectural approach that also has the potential to adapt in function to its immediate environment.

As a new medium of study, design, and communication with the environment, the primary concern with AURA’s design process is creating a more participatory dialogue between the inside and the outside. By modulating light and sight through a variety of means, communication with outside spaces and objects become mediated through AURA.

AURA examines the behavior of wind and light in relation
to different architectural spaces. The conception of AURA is derived from our nature as sensorial beings; it provides a multi-sensory approach that may incorporate visual, auditory, and interactive aspects. By allowing us to see the world outside, AURA tends to engage us with the sky and the rest of the surrounding world. As a device through which we might see, AURA is not just a joy to the eye but also awakens one’s senses simultaneously and instantaneously.

Light has a significant impact on our experience of life. As James Carpenter explains: “not so much in the sense that light allows us to see the world outside ourselves, but in its capacity to accumulate information along its journey to the eye (Schielke)”. AURA aims to provide new prospects for reinforcing the vital relationships among light, space, occupants, and architecture. Through a perpetually dynamic play with light intensity, AURA has the power to deeply shape, direct, enliven, and differentiate facets of the temporal nature of space. As a multifaceted light mediator, AURA is the means by which light is revealed in a very vivid form to generate spatial depth. In this way, architecture can be characterized by the way AURA allows light to enter the space. Through counterbalancing the light exposure, AURA calls for us to think about a presence of light that goes far beyond its practical advantages.

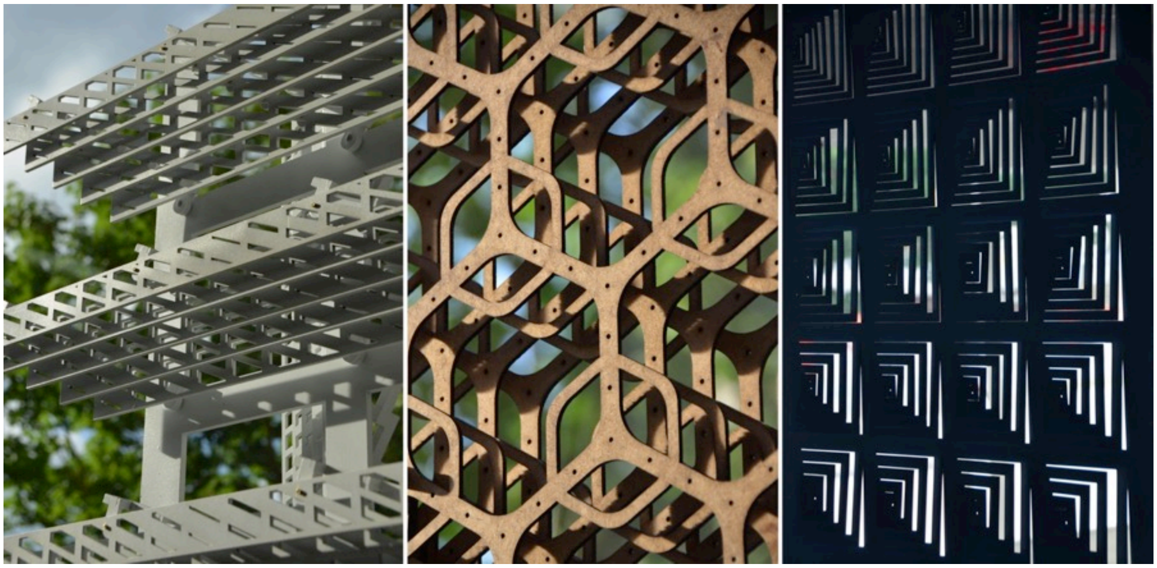

Figure 55: AURA- light mediator

AURA defines how and when the light will be cast in the desired direction. In this case, AURA is capable of deepening our understanding of what light is. Additionally, by making light tangible, AURA, as a component of a constructed environment, positions itself to provide an awareness of our physical presence (Figure 55).

Our different senses constantly scan the physical world. As environments around us change, so does our dependency on our various senses. Pallasmaa urges a return to the senses as a means of arriving at a more embodied existence (Pallasmaa 2005). By explaining how we are rooted to place and space when our senses work to navigate our world, Pallasmaa addresses the importance of light and shadow as it relates to the feel of the temperature on one's skin, along with smells and sounds[54].

As a vehicle for changing our visual, acoustic, and thermal environments, AURA can position itself as an opportune medium for enabling sensory appreciation when employed

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[54] Pallasmaa argues: "We behold, touch, listen and measure the world with our entire bodily existence and the experiential world is organized and articulated around the center of the body." See: Pallasmaa. J., Holl, S., Perez-Gomez, A. (2007), Questions of Perception: Phenomenology of Architecture. William K Stout Pub.

to communicate with and sense the environment around it. In the AURA design process, sensory response is a critical design factor. AURA is not a static entity, but rather is enmeshed within a set of dynamic environmental interactions. As a result, it offers alternative ways of understanding spatial experience and provides an awareness of our physical presence.

By increasing a person's emotional bond to a space and overall sense of “insideness”, AURA tends to create place as a humanized space (Tuan 2001). The ultimate goal in AURA’s design process is to treat sound and heat as the equals of sight and light in order to create a greater connection between our rootedness in the places we inhabit and our perceptual experience. In this case, AURA can respond “to a desire for an eloquent place to dwell (Perez-Gomez 2008)”.

AURA’s design process is to embrace the processes of creation, utilization, and perception in architecture. As Merleau-Ponty (2008) claims about the coexistence of space and things which help us to perceive the world, AURA can be a touchstone for comprehending how the perception of a light mediator and the space around it can be warped by experience.

4.2.6 Aura as an Immersive Case Study for Understanding the Design Process of Motion Itself

In addition to the understanding of AURA as an object that serves to provide shade and its meta-physical response to the environmentally stimulated transformations of the object, this research mainly explored a third domain, that of process. Through the development and demonstration of AURA, a goal is to capture a design process that can be effectively customizable and sharable. To meet this goal, the process of designing AURA must include consideration for the processes of fabrication, assembly and manufacture. For this, the designer of AURA must be a responsive mediator with knowledge of properties of materials, fabrication, assembly and manufacture. The understanding of these knowledge exchanges is necessary for AURA to be a high performance yet cost effective system. In addition, advanced technologies such as digital modeling software and digital fabrication through using computer numerical control machines, all can support advanced manufacturing and mass customization. But for this, the designer of AURA must consider how these technologies might inform the design. Therefore, this research is not only concerned with the object/space itself but with the process of making the object/space. Through a process of prototyping, and participant reflection and interpretation, this research sees to document and understand the process of designing while meeting the performance and production goals for AURA.

4.3 The Language of Motion as AURA's Form-Finding Process

The language of motion is about some of the general guidelines that formed the core principles of motion formation. The language of motion formation is indicative of an important shift from manipulation of movable compositions to motion study as a design process. Within the design process informed by the language of motion, a designer explores new agendas for generating form through the interaction of force, geometry and motion. The main proposition of this research is that motion language offers a possibility for designers to study motion in terms of motion itself. In other words, this language ultimately is about the regulations for discovering potential forms of motion, rather than the forms themselves.

In the language of motion, the final form is not determined beforehand. The motion language is a way to address the border between form-finding and form-giving processes; this language exclusively indicates a system for finding form. The form-finding process is about forms and shapes which motion objects or compositions could take. The process of finding form narrows down the number of potential ideas according to principles of motion language. Through this process, it becomes possible to predict the accepted configuration of motion. In this manner, a singular form is not the end result of this system; the main focus is on the process by which a series of forms might be created.

The language of motion has two main parts. The first part deals with the formation analysis, and the second part with the formation synthesis. The language of motion seeks to discover many linguistic aspects that could be used in design. This language proposes a framework for understanding the particular design variables that influence motion compositions. Therefore, it is an inquiry into the “vocabulary” and “syntax” of the motion language.

The design process of AURA is the result of having asked the following question: In order to propose a method for designing a set of motion compositions, what might be the language of motion and its permissible vocabulary (the basic movement) and syntax (the systems for their use)?

The vocabulary and syntax of motion language describes the physics of motion. Motion language contains components of formation (as vocabulary) and rules of their combination (as syntax) to generate the language. Hence, the current study tries to formulate and classify a set of basic vocabulary and syntax of motion in relation to its morphology and analyse the possible types by kind and status (Figure 56).

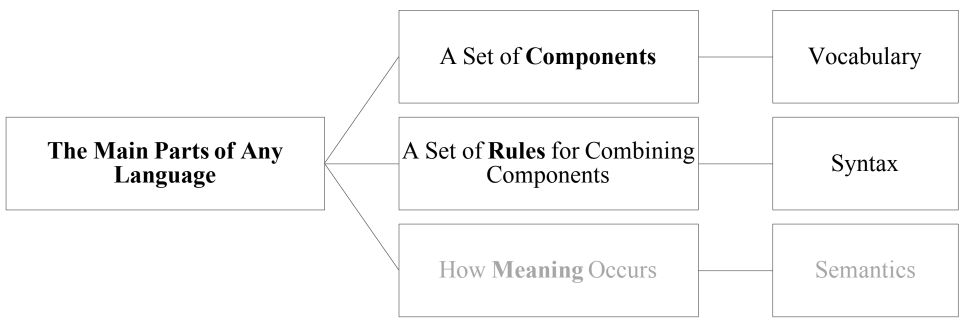

Figure 56: An example of the language of motion and its permissible vocabulary and syntax.

Motion language tends to explain what a vocabulary of movement is and how combinations of those patterns could form more complex movement. Here, vocabulary means a range of primary motion forms (basic movement); Translation, Rotation and Scaling are the three main terms of motion language. These few and simple geometric transformations are combined and generate more comprehensive vocabulary (composite movement), such as a Twist, Roll, Spring or Yaw (Moloney 2011). By recombining these vocabularies, a great range of movement is produced (Figure 57).

Syntax of motion language is defined by canons or rules that show why some compositions can or cannot be actualized. It clarifies the way that the relative connectivity and integration of different variables are put together to form a motion composition. Syntax is the main device for revealing the order of motion language.

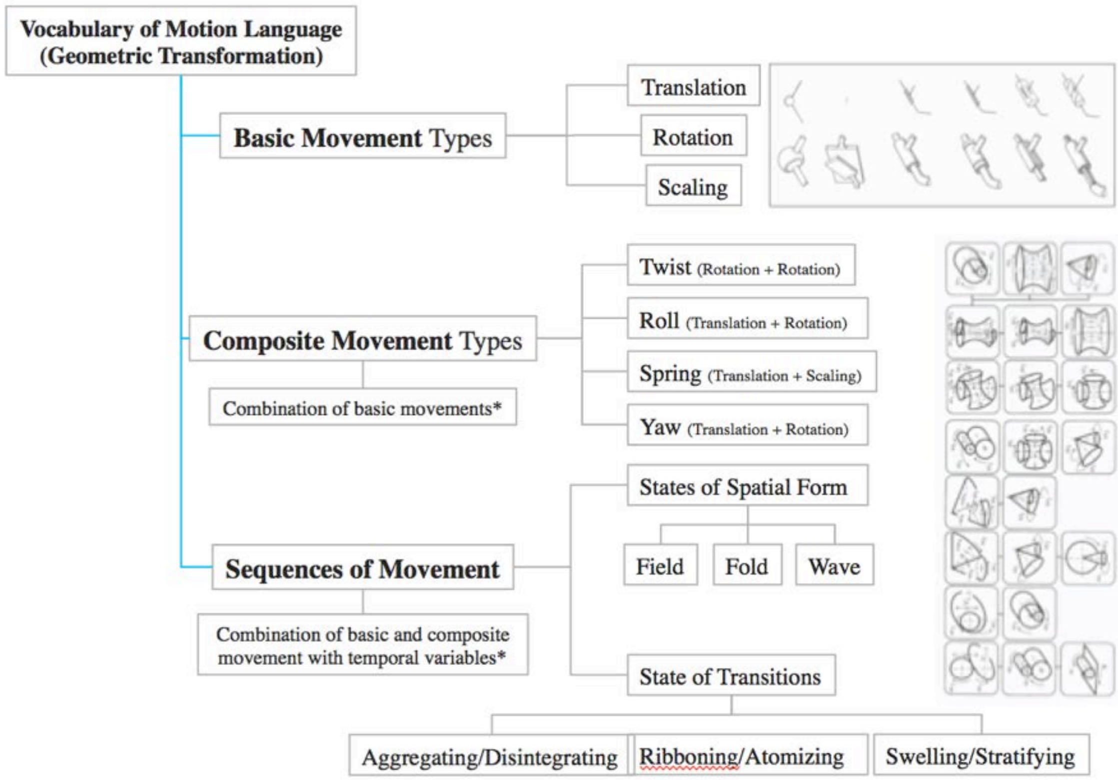

Figure 57: In the language of motion, vocabulary means a range of primary basic motion forms. For instance, by using rigid materials, the processes of translation, rotation, and scaling become the three basic vocabularies of motion language. These few and simple geometric transformations, when combined, generate a more comprehensive vocabulary (as composite movement), such as twists, rolls, or springs (Moloney 2011).

4.3.1 The Syntax of Motion Language

The main sub-syntaxes in language of motion can be developed through four dominant threads. First: transformation of geometry, second: transformation of connectivity, third: transformation of materiality, and forth: transformation of behaviour. According to the allowed values, these sub-syntaxes are the result of using new variables that generate new or known motion compositions. Among the above-mentioned sub-syntaxes that serve as canon for designing physical shapes with motion, transformation of geometry is the prevailing one and language of motion is based largely on this type of transformation. Transformation of connectivity and Transformation of behaviour have been employed to some extent. However, Transformation of materiality has received less attention. A transformable design can be composed from one syntax or several sub-syntaxes together.

Transformation of geometry; underlying and overlying geometry:

Before discussing the movement typology, it is necessary to define kinematics and kinetics. The main focus of this research is on rigid body mechanics. Rigid body mechanics can be broken down into two branches: statics and dynamics. Statics include systems that are not accelerating (i.e., that have zero acceleration). The second branch of rigid body mechanics is dynamics, which refers to systems that are accelerating. Dynamics can be further broken down into two additional areas: kinematics and kinetics. Kinematics refers to the geometry of motion without consideration of the causes of motion. Kinetics is the study of the causes of motion. Therefore, kinetics is the study of forces.

Motion has a strong bond with geometry because motion is the spatial transformation of one geometric configuration to another. Although the study of geometry of pure motion without reference to force or mass often called kinematic has been recognized across many disciplines, it is not introduced in architecture as a fundamental part of geometric thinking. For developing deep conceptual understandings of kinematics, and its underlying design principles, there is an extensive undertaking of the study of the movements in the ways design thinking translates into the built environment. The favoured movements of the parts together and separately can support the development of these understandings. By finding a path that converts an abstract concept of motion as an input into a tangible and meaningful mechanism to act responsively as an output, the goal is to move beyond developing sophisticated machines by just combining intricate mechanical components such as cranks, cams, and linkages. Comparing to more complex and machine like mechanism, it is preferred to deal with non-complex and simple movements based on geometry.

In any kinetic design process, there is two design efforts: to generate an underlying geometry and to design an overlaid configuration. The underlying geometry of any kinetic structure is described as the geometric constraints of motion. Here, the geometry of pure motion is studied without reference to force or mass. A transformation of underlying geometry of motion outlines the relationships between elements, arrangement of them, and the final layout of motion composition regardless of some values such as the dimensions or shapes of elements. By manipulating position of the endpoints and shifting the location of connectors where the elements intersect, a new set of motion composition can be constructed.

In spite of maintaining geometrical relationships between various elements of a motion composition, a transformation in the geometry of each element causes a specific sub-syntax of motion language called transformation of overlying geometry. Overlying geometry is a secondary issue, as compared to the underlying geometry. Transformation of overlying geometry is the result of manipulating the applicable ranges of values for different variables. By modifying element proportions, adding additional elements, or altering the shape of elements by another given shapes, the composition has a familiar structure but with a different appearance to generate another design. In addition, the overlying geometry could be derived from degree of permeability, environmental, technical and economic considerations, or cultural and aesthetic references.

Transformation of connectivity:

By replacing the type of joints between elements, control means, and changing the freedom degrees of joints, different motion composition can be accomplished to satisfy diverse design goals.

Transformation of materiality:

This sub-syntax deals with physical qualities of elements in a motion composition. Transformation of materiality is the result of working within material properties such as friction and expansion to bring something new into existence. Based on the type of materials, different kind of movements can be accomplished. For instance, rigid materials can cause the basic movement (such as rotation, translation, and scaling) or composite movement. In addition, by using deformable materials the following movements are available: stretch, roll, bend, shear, flutter, and gather.

Transformation of behaviour:

This sub-syntax examines the means/methods of control and direct/indirect modes of operation.

4.3.2 Motion Language in AURA's Design Process

As mentioned above, the syntax of motion language involves an investigation into various terms that influence the motion of objects such as transformation of geometry, transformation of connectivity, transformation of materiality, and transformation of behaviour. In the design process of AURA, the language of motion in general and the characteristics of its syntax with regards to transformation of geometry in particular were studied. In other words, AURA's design process specifically explores motion geometry as integral to syntax.

For AURA, in addition to being named as a motion composition[55], it is also described as a grouping of movable elements according to the primary generators of motion and their ordering principles. The design process of AURA is based on the generative capability of the language of motion. This design process is a case for analysing general patterns of motion language and includes the specific studies to describe the vocabulary and syntax of its formation. Therefore, by using the vocabulary and syntax of movement, a series of exclusive motion compositions are generated through the design process. These different motion compositions provide an opportunity to examine what the language offers to the design process of AURA and how motion is implemented in physical models. The design process of AURA acknowledges the presence of motion language from small scale (every detail and joint) to large scale (the whole structure).

The variety of configurations and designs presented in the diagram are derived from three simple motion forms as vocabulary: Translation, Rotation and Scaling. Combinations of these three simple movements end up creating not only a variety of mechanisms but also dynamically and geometrically rich shading devices. Underlying geometry of each design serves as syntax and makes that design unique. This syntax is used as a tool for inquiry and can generate a potential number of design possibilities. The vocabulary and syntax of AURA reveals the potential of motion language and identifies relevant design parameters that could strengthen the structure of the design process.

[55] Here, motion composition is defined as the relative movement of parts in time and space.

4.3.3 The Transformation of Geometry: An AURA Case Study

AURA is a system of movable elements combined according to the rules of congruence transformation. Here, congruence transformations are assumed to be linear; all lengths and angles occurring on movable elements are preserved.

AURA, as a dynamic window-shading system, is bound by geometric constraints. This study attempted to utilize the principles of motion geometry when conducting an AURA design process. This process relied on the application of motion geometry to shading devices through designing, making, and analysing.

The design process of AURA tends to examine the influence of motion geometry upon dynamic shading devices and how motion geometry can be oriented toward the practical domain of design for shaping a better environment. Of course, implementation of motion geometry is no guarantee for designing an acceptable shading system and it is important to address the principles that govern such design. No matter what the final form is, the underlying geometry of each kinetic shading device resides in the space between the performance and fabrication limits. This underlying geometry is constrained to suit different given environmental, technical and economical considerations.

The value of motion geometry is mostly undeveloped within the fixed shading systems. In the design process of AURA, motion geometry is put into play to open up the design possibilities of operable shading devices. Through the application of motion geometry, this design research exists beyond the narrow uses of geometry in ordinary motorized sun shades and sun screens.

Motion geometry creates a spatial relationship among all the various components. The design process of AURA is dominated by the mode of geometric patterning in two and three dimensions. In AURA, all motion takes place in either two- or three- dimensional space.

Since motion geometry is capable of tailoring and expanding itself, an architect might shape the language of motion to fit whatever specific circumstances he or she is confronted with. Sometimes there is a shift between the primary design concept and the completed model. In this case, the final model is an extension of adapting the preliminary concept modified by geometry. The final design is achieved through the course of many iterative stages of development. Motion geometry leaves room for further improvement and it is a tool for testing variations and decision-making.

Through participation in thinking about the way motion geometry is applied, the design process of AURA enhances two parallel design approaches: to analyse the range of motion for a given joint and to synthesize a number of joints for an applicable range of movement. In both approaches the analysis of underlying motion geometry of mechanisms is a goal.

4.3.4 AURA's Underlying Geometry and Overlaid Patterns

One of the most influential syntaxes of motion language is the configuration of geometric transformation. Motion geometry concerns relative position or spatial relationship of different components. Motion geometry classifies the possible motion configurations and evaluates their potential in motion language establishment. Therefore, a designer of transformable composition must have an understanding of geometric principles related to mechanism design and how they could be effectively applied.

Motion has a strong bond with geometry because motion is the spatial transformation of one geometric configuration to another. The underlying geometry of any kinetic structure is described as the geometry of motion and it is a fundamental part of geometric thinking and concepts of motion. Motion geometry traces the positions of different components and reveals the relationship between movements of them.

It is challenging to adopt internalized logics of motion geometry as syntax without doing remarkable research on the ground. Motion geometry impacts the design process every step of the way. The design process of AURA is a path toward revealing the importance of motion geometry for the author through her insights and experiences.

Motion is an integral part of AURA. Therefore, motion geometry is used to understand the kinetic behaviours of AURA's components and to address "how" these components move and change their space dimensions. In this way, motion geometry articulates the fundamental aspects that need to be considered in AURA's formation process. But of course, motion geometry does not deal with issues of “what” and “why” in regards to movement.

In addition to the knowledge that is mediated between conceptualization and realization, AURA throws light on how a mechanism is geometrically realized as a kinetic shading system. One of the main contributions of AURA’s design process is to identify the underlying motion geometry of the proposed design. Finding the underlying geometry of each concept is one of the most important tasks throughout the design process, and a relatively difficult one to perceive. Study of motion geometry provides an accurate insight into the complexity of motion and facilitates the analysis of movement.

The design process of AURA requires a comprehensive understanding of motion geometry as syntax of motion language. In AURA, the element of movement in combination with geometric rules is the essence of each design, and the main design inspiration comes from a combination of geometry and movement. Here, geometry and movement are so closely related that the development of one is the development of the other. In this regard, the major objective in the design study of AURA is to articulate geometry as an exclusive syntax and study of the geometric relationship of motion compositions. Through a series of design experiments, AURA demonstrates the attempt to comprehensively explore the most important potentials and opportunities that motion geometry can offer to the design process.

For the analysis of the general characteristics of motion geometry in the design process of AURA, this study is accompanied by examples of well-studied models. These models are employed to conduct an inductive inquiry. After the required modifications, each model is employed to illustrate the rationale behind the underlying geometry of each mechanism. Although there is an appreciation of how well these models fit with the general principles of motion geometry, the given underlying geometry in some cases is not quite changeable because of the applied motion. While there are limited type of mechanisms employed in AURA, the underlying geometry used in these models is rather regulated.

The underlying geometry reveals the inherent beauty of motion (Figure 58). In the design process of AURA, any underlying geometry (geometric relationship between components) is overlaid with additional designs, mainly symmetric or asymmetric patterns.

Motion geometry is open-ended and consists of infinite sets of compositions from a finite set of basic features and rules. In the design process of AURA, each model is a laboratory that allows understanding and testing of this matter. AURA is created based on the generative capability of geometry. Therefore, in its design process, the underlying geometry can be used many times, without ever using it the same way twice. Here, motion geometry is the design research tool used to recognize and visualize the possible motion compositions. A deep knowledge of motion geometry helps one find solutions that may not be commonplace. Furthermore, the author has been convinced that the underlying geometry of each model helps bridge the early form-finding studies to the fabrication phase.

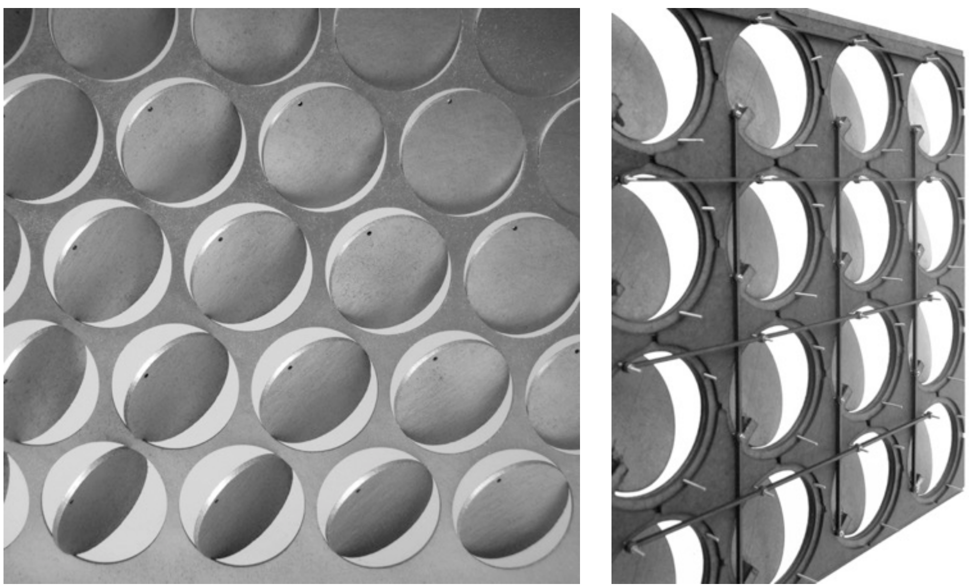

Figure 58: Sol II: the overlying geometry (left image), the underlying geometry (right image) is the grid systems on the back of the model. In this case, by observing the overlaying geometry, it is hard to predict the underlying geometry.

4.4 AURA Typology

The AURA transformable shading system is an adaptive building envelope component that controls solar heat-gain and glare. AURA, as a shading system, offers different designs composed of geometrical screens. These screens can move and create dynamic architectural elements that regulate light quantity and quality. As the elements move and overlap, the results are an intriguing and delicate visual display of patterns.

AURA's design is based on motion-geometric rules that result in a visually stunning appearance, and movements in response to changing outdoor conditions. Because of its geometry, the system is scalable and adaptable to both new and existing buildings.

The embedded geometry of the screens is simple, but can provide complex patterns. While kinetic designs can enhance the environmental performance of architectural facades, kinetics can provide functional ornamentation and cultural reference.

The approach taken in this research was to begin with a basic motion design. After going through the early design process, three motion generators were developed and named UMBRA, OCOLUS, and ANGULUS. Through the creation of these generators, more than fifty different design concepts were developed.

By finding a path that converts the abstract concept of motion as an input into a tangible and meaningful mechanism that acts responsively as an output, the various concepts developed during the AURA self-immersive case study were not sophisticated machines constructed from intricate mechanical components such as cranks and cams. Instead of more complex and machine-like mechanisms, the AURA design process dealt with non-complex and simple movable parts based on geometry.

During AURA's design process, more than fifty different design concepts were developed; all were the result of a continuous search to develop a basic concept. In this dissertation, the entire AURA design process was categorized as a single immersive case study: a "Simultaneous Divergent and Convergent Design Thinking Approach". Here, the design strategy was superior to the design experience, a concentrated expression of the designer's thinking.

AURA designs are the result of deconstructing the design problem and reconstructing and extracting design knowledge in a continuous design process. As previously mentioned, design problems are always *ill-structured* (Cross, 2006). Therefore, problem-solving strategies are difficult to unify because the problems are not clearly defined. *Divergent* and *convergent* processes are the best tactics for capturing and framing an *ill-structured* problem. In this research, more than 50 different design concepts were created to diverge from the ideation process and facilitate selection, in order to converge upon the best design. Based on Dubberly's description, AURA's design process can be characterized as a *decomposing* and *recombining* process (Dubberly, 2004).

AURA's design process is based on Banathy, Cross, and Pugh's models where iteration is the essence of repetitive *divergence*, *convergence*, *analysis,* and *synthesis* (Banathy, 1996). Cross argued that the design process is always convergent (Cross, 2008), but in that process, there are proper and necessary diverging steps to take to expand the designer's thoughts (Figure 59). The Pugh model (Pugh, 1991) illustrates a gradual development in the concept generation and evaluation process, which is an iterative process of convergence and divergence that gradually reduces the solution to get better design results (Figure 60). After evaluating the above-mentioned models, one can conclude that AURA's design process should be considered structured.

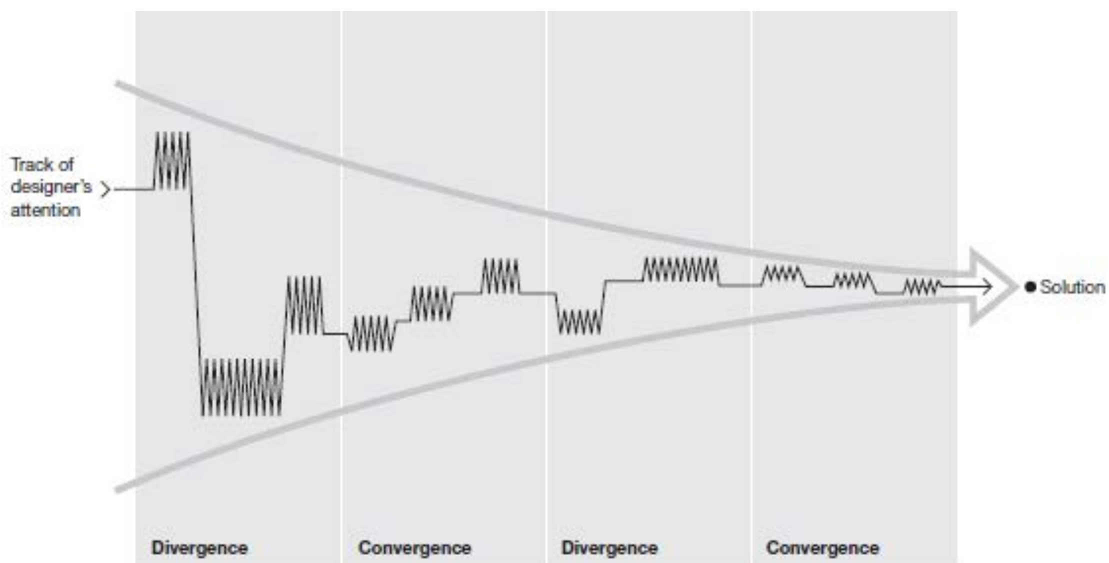

Figure 59.: Banathy and Cross's model for the design process

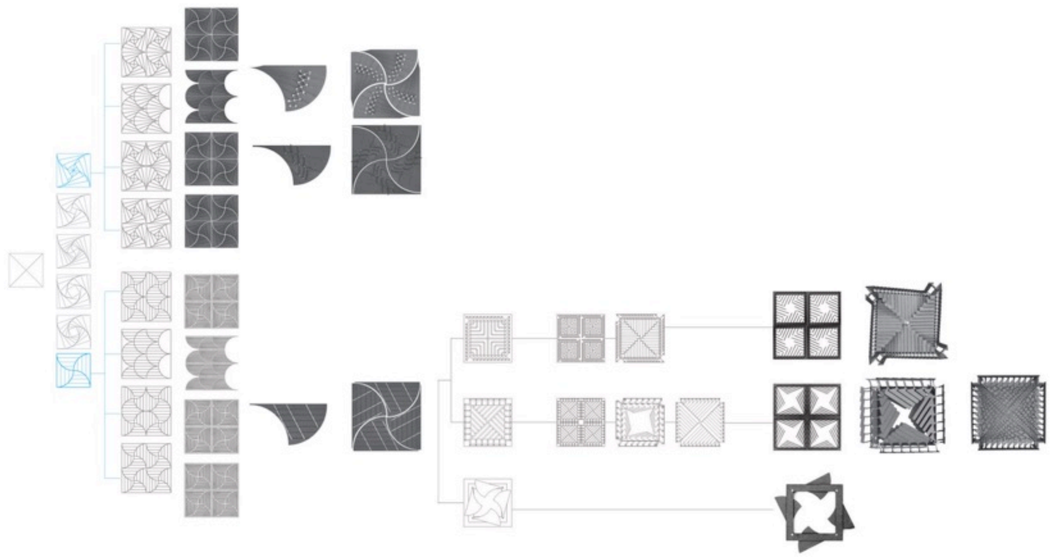

Figure 60: Design diagram of the simultaneous divergent and convergent design thinking approach used in AURA's design process.

The development of a series of iterations of models is presented in the design diagram (see Figure 54). This diagram is a way of discovering and comparing the linguistic aspects of the AURA series; it exposes the orderings principle of motion language. By drawing parallels and comparisons between these models, the design diagram articulates the vocabulary and syntax behind them that are applicable from one model to another.

AURA's mode of geometric design is relatively well documented by the design diagram (see Figure 54), which serves as a tool to better visualize a wide range of design variations. The design diagram represents the different kinetic models explored by the author; it is a graphical representation of the hierarchical structure, and indicates the progression of each model from a basic motion concept to a developed working system. Thus, through this diagram, motion geometry can be seen as one of the main drivers of all of these models. It categorizes different AURA model series, based on their underlying geometry and overlaid configuration. Most of these models are similar iterative variations of an underlying geometry, overlaid by different configurations. The underlying geometry makes a contribution to an overall sense of unity among all the models.

4.4.1 AURA's Motion Generators

In AURA's design process, the loop between concept development, construction of the conceptual models, and evaluation continues until an acceptable motion generator that has enough potential to be a TSS emerges. A basic knowledge of environmental design, fabrication, and structure help designers to evaluate the motion generators and select the one with enough potential to be turned into a successful shading system. Once a motion generator is developed and its general behavior established, designers begin developing variations of the parametric models to help architects progressively change their design variables and implement complex assemblies, while keeping the geometric relationships among the various links and joints.

In the self-immersive case study, three generators were developed: UMBRA, OCOLUS, and ANGULUS. Here, the term "generator" refers to the underlying geometries of these three basic designs.

4.4.1.1 Generator I: UMBRA

The UMBRA assembly was comprised of four perpendicular L-shaped links and four straight links supported by a frame. The straight links moved parallel to one another in two different directions and to their frame surface during retraction, allowing them to be completely stacked next to one another when retracted (Figure 61). The four L-shaped links had three pivots joints, one pivot connection to the frame, and two pivot connections to the straight links. Each straight link could be extended to create a wing. Thus, the assembly had four simple wings that performed together.

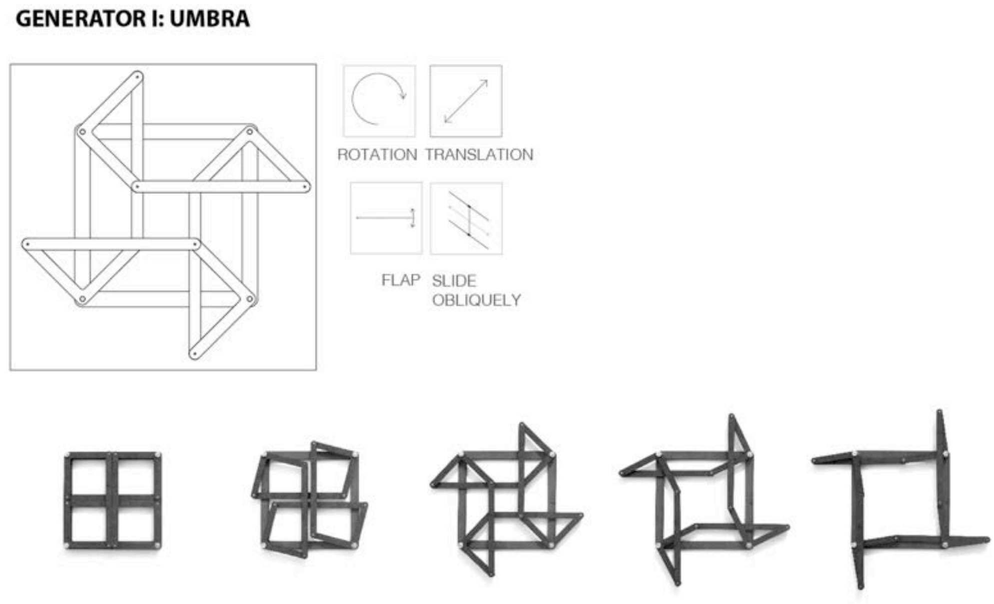

Figure 61: The plan view of the UMBRA assembly

Table 12: UMBRA Assembly's Specifications

Design name: UMBRA	**Strength of the concept:** UMBRA can control its permeability, varying between completely covered and largely open states. The boundary of the design does not change during the transformation; therefore, it can easily be applied to geometrically-shaped windows.	**Type of motion:** Compound motion (Combination of rotation and translation) **Type of rotation:** Four L-shaped links change their orientations in space by rotating about the rotational axis outside the object's centroidal axis. **Number of links:** 8 **Number of joints:** 8 **Number of points of connection:** 4 **Boundary of design:** Fixed

4.4.1.2 Generator II: OCULUS

The OCULUS assembly was comprised of one main ring superimposed between two guide rings. The mechanism worked like a diaphragm. There were several blades (or arms) connected to the main ring (Figure 9). The number of blades could be varied, depending upon the preferred quality and quantity of the light entering the aperture. The overlaying geometry of the system (including the length, width, outline, and profile of each blade) provided different characteristics, creating a variety of environmental, functional, and visual effects.

Figure 62: The plan view of the OCULUS assembly

Table 13: OCULUS assembly's specifications

Design name: OCULUS	**Strength of the concept:** OCULUS can control its permeability, varying between completely covered and largely open states. The boundary of the design does not change during the transformation; therefore, it can easily be applied to geometrically-shaped windows.	**Type of motion:** Rotation **Type of rotation:** The blades change their orientation in space by rotating about the rotational axis outside the links' centroidal axis. **Number of links:** Varied (in this case, 8) **Number of joints:** Varied (in this case, 8) **Number of points of connection:** Varied (in this case, 8) **Boundary of design:** Fixed

4.4.1.3 GENERATOR III: ANGULUS

The ANGULUS assembly was comprised of eight perpendicular L-shaped links. The links moved parallel to the building's surface. The eight L-shaped links had three pivot joints. The assembly had four simple wings that performed together. ANGULUS had a changeable boundary that made it difficult to connect to the reference frame without using tracks and hardware sets (Figure 63).

Figure 63: The plan view of ANGULUS's assembly.

Table 14: ANGULUS assembly's specifications

Design name: ANGULUS	**Strength of concept:** ANGULUS consists of only one type of linkage. **Weakness of concept:** The boundary of the design changes during the transformation; therefore, it is hard to embed the design in a window frame with a fixed border.	**Type of motion:** Rotation **Type of rotation:** The object changes its orientation in space by rotating around a single centroidal axis. **Number of links:** Varied (in this case, 8) **Number of joints:** Varied (in this case, 12) **Number of points of connection:** One point. Having more points of connection locks the system. **Boundary of design:** Changeable

4.5 Typology of Movement

Designing movement is the intention of AURA's design process; therefore, the transition between the two start and end states are important, and the sequence of changes of state during the opening and closing process offers many design opportunities. It is not common in architecture to have a design situation in which the sequence of movements is not the primary focus, but rather it is the start and end states that are important (Schumacher, Schaeffer, and Vogt 2010). Transformable shading systems are one of the few design possibilities in architecture in which a designer can focus on the design and sequencing of movement.

In general, movement can be categorized in two typologies:

the product of changes to the position or orientation of rigid pieces, and

what occurs from transformations within the materials.

In AURA's design process, the focus is on the movement of rigid materials; the motion occurs in the joint sections. The rigid bodies transfer their force to the joints, and the joints change the direction and/or orientation of the components. Movement for rigid materials is the ability objects have to move around a space. The main kinds of movement (Schumacher, Schaeffer, and Vogt 2010) of rigid materials include:

Changes to a position in space: the rigid material has a linear movement along one plane, and its position moves parallel or perpendicular to the coordinate axes. This type of change is known as translation.

Changes to an orientation or direction in space: this is a circular movement in space. The axis of rotation can be in the center of the object (or element), or it can be outside of the object's center.

Changes to an orientation and position in space: when a rigid object changes its orientation and position at the same time, it experiences compound movement. Folding, scaling (aperture opening), and scissor structures are included in this category. Most of AURA's designs include compound movement.

In the second typology, deformation occurs inside materials and in different forms, including stretching, rolling, bending, shearing, gathering, pleating, and fluttering. Deformable materials are available in different spatial forms, such as linear, planer, and volumetric. These types of materials can keep their overall formal consistency during force application; they have the ability to return to their original form after releasing the force or with reversed force. This category of materials was not explored during the AURA design process conducted for this research; however, in the two design studios that were offered during the spring semesters of 2014 and 2015, a few students explored deformation with their materials (Figure 64).

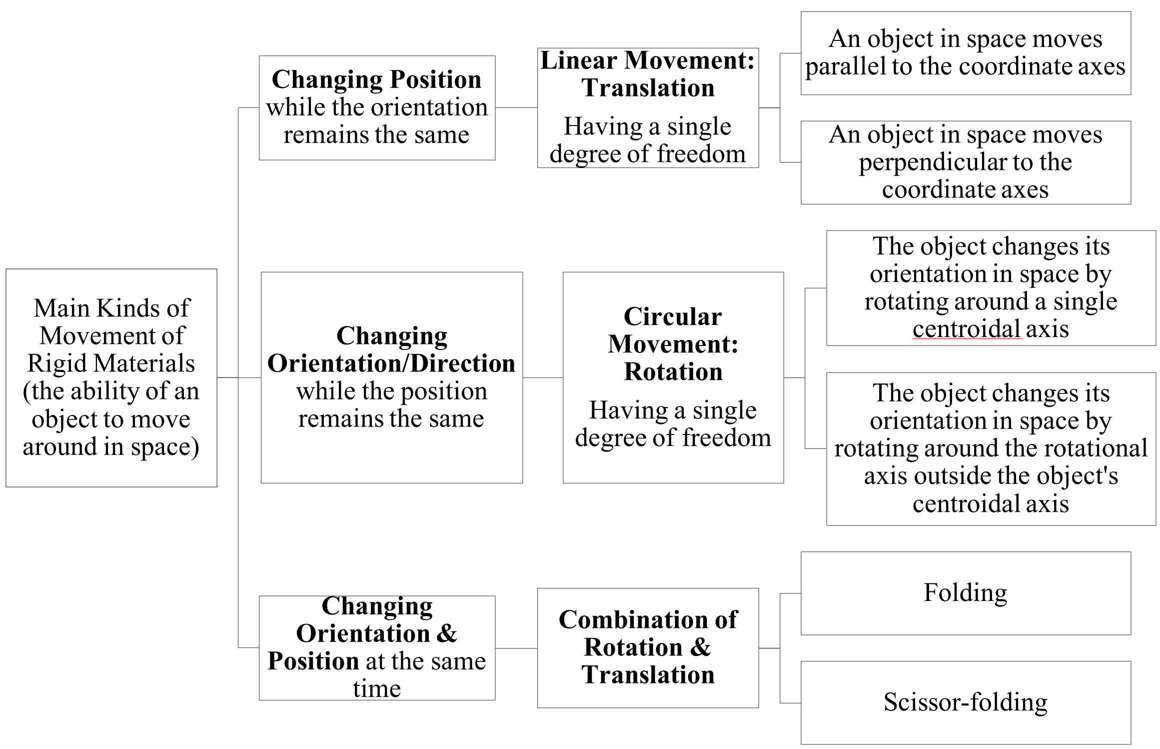

Figure 64: Typology of movement in rigid materials.

To properly understand AURA's design process, several terms in kinematics must be defined (Vinogradov 2000).

1. Degree of Freedom (DOF) or mobility: The number of independent ways by which the object can be assembled. If the DOF of a line assembly is positive, the assembly is a kinetic mechanism. If the DOF is zero, the assembly is a static structure.
2. Link or linkage: A link is a rigid body that possesses at least two nodes; these nodes serve as points of attachment to other links.
3. Joint: A joint is a connection between two or more links that allows some motion or potential motion between the connected links. The following are possible types of joints:

- Lower pair: The two members forming a lower pair joint have an area of contact between the two mating surfaces. Therefore, the contact stress is smaller than the higher pair joints. Examples of lower pair joints include (Norton 2012) (Figure 65):
    - Revolute/Hinge Joint, 1 DoF
    - Prismatic/Slider Joint, 1 DoF
    - Screw/Helical Joint, 1 DoF
    - Cylindrical Joint, 2 DoF
    - Spherical/Ball Joint, 3 DoF
    - Planar Joint, 3 DoF

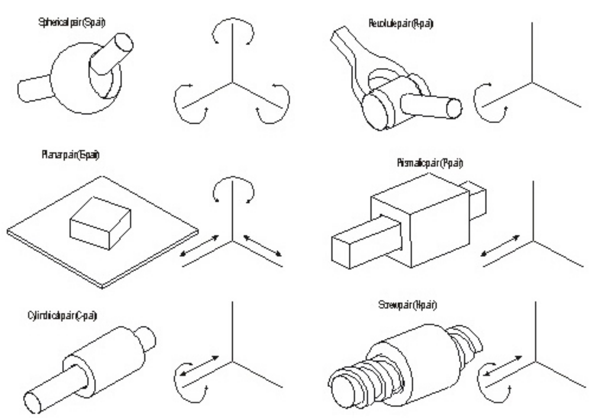

Figure 65: There are six lower-order kinematic pairs: spherical, planar, cylindrical, revolute, prismatic, and screw(Vinogradov 2000).

- Higher pair: The contact between the two members of a higher pair has either a point or line geometry. The contact stress for a higher pair joint is large because of the very small contact area. If there is pure rolling contact between the members, then at any point in time the contact point or line is at rest. There is no relative sliding between the contact surfaces, and thus friction and wear will be negligible. Examples of higher pair joints include:

- Cylindrical roller, 1 DoF
- Cam pair, 2 DoF

4. Compound joints: Lower pair and/or higher pair joints are combined as per the design requirements in order to obtain compound joints. Examples of compound joints include ball or roller bearings and universal hook joints.
5. Point of connection (point of ground): An assemblage of links and joints becomes a mechanism when at least one link has been grounded or attached to the frame of reference.
6. Ground: Fixed points with respect to the reference frame.
7. Boundary of design: The assemblage can have fixed or changeable boundaries during movement. If the assemblage can maintain its original boundary during motion, it will attach more easily to the frame of reference.

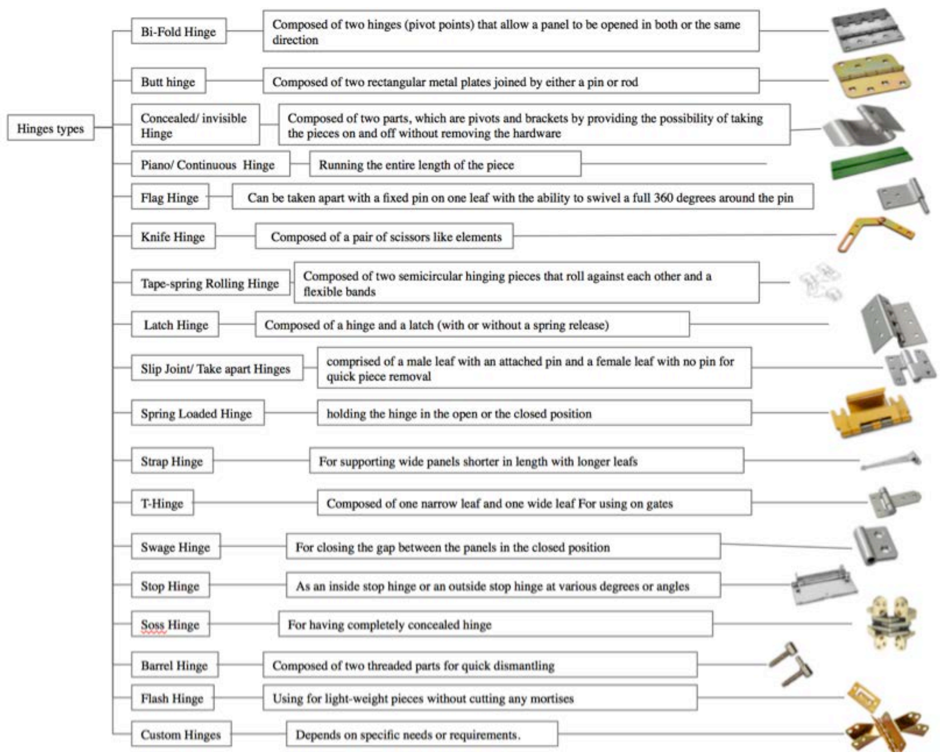

Figure 66: Typology of hinges.

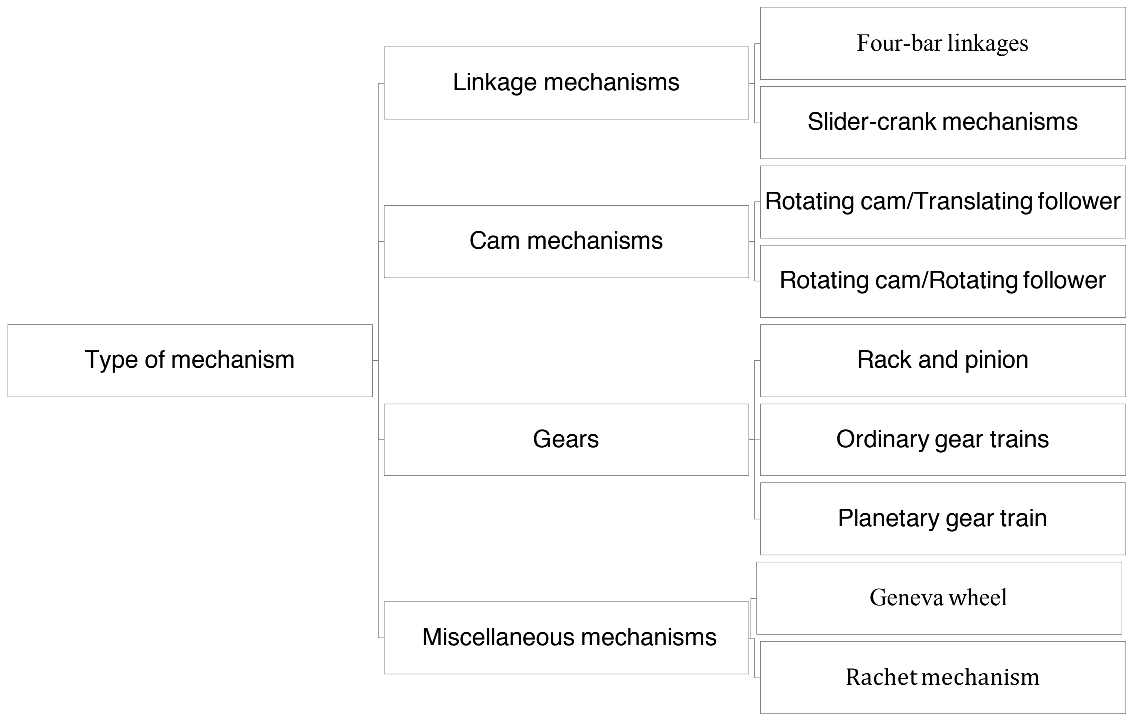

Figure 67: General types of mechanisms.[56]

A cam is a rotating or sliding piece in a mechanical linkage used especially in transforming rotary motion into linear motion, or vice versa (Figure 67 and Figure 68).

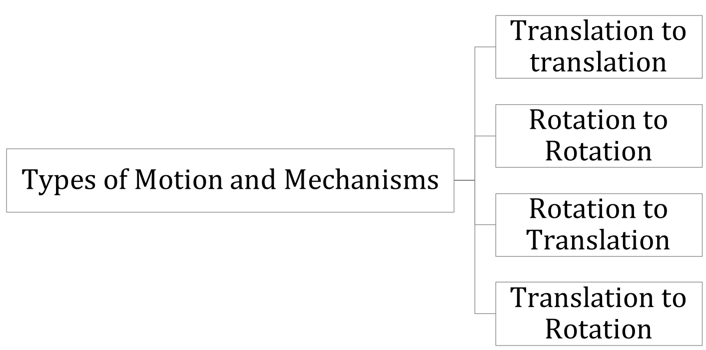

Figure 68: Motion transformation typology.

[56] http://www.cs.cmu.edu/~rapidproto/mechanisms/examples.html#HDR1.1.1

4.6 Control System: Mediation Between Data (Reason for Movement) and Motion

One of the main questions in the TSS design process is: *What are the key variables of the control system that may affect the formation of a concept?* We can categorize TSS controls based on various variables. These key control variables include:

Level of control;

Direct, semi, or indirect control;

Reflexivity (the degree to which the control system is open to reconfiguration) (Moloney 2011);

Speed of interaction;

Centralized or decentralized (individually controlled or simultaneously controlled); and

Passive and active control.

There are three main types of control systems. First, there are systems that directly react to data. For example, wind, humidity, and temperature can all cause movement in the TSS (Figure 69). Therefore, the pattern is a result of the data and speed of reaction of the TSS components. These systems mostly react to one source of data, and are hardly controlled by others (prescribe-responsive).

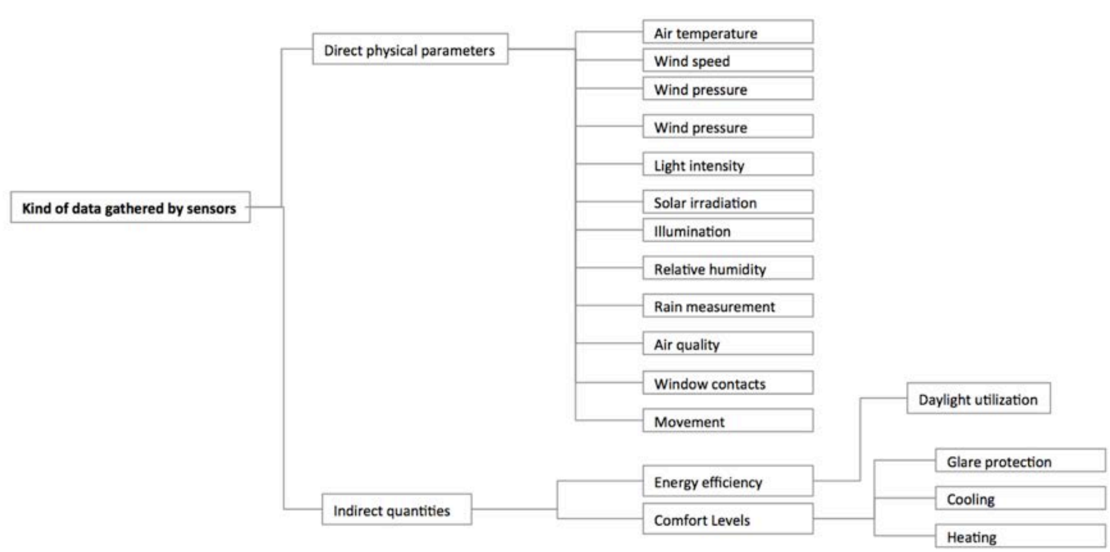

Figure 69: The different types of data collected by sensors.

Second, there are systems that are fully controlled that indirectly react to data. Data (the reason for movement) collected by sensors are processed by computer; then, TSS systems react to the instruction. In this category, the reaction can be moderated by the other (interactive) variables. Third are systems in between direct and indirect control systems (Figure 70).

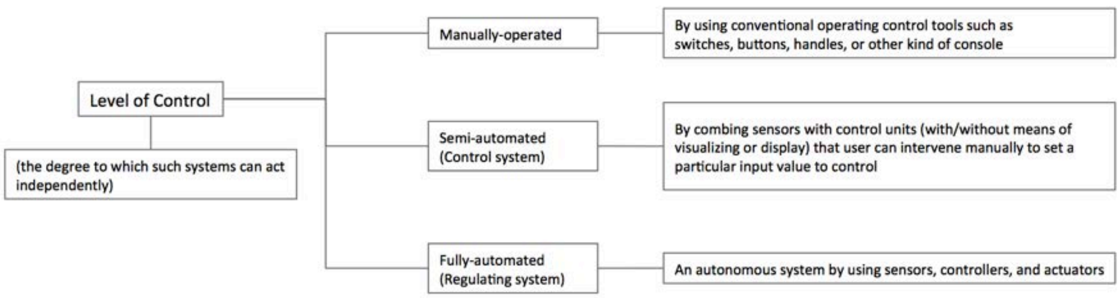

Figure 70:A TSS can be controlled with different levels of independence.

The designs for all of AURA's models have the potential to be partially or fully controlled. However, the focus of this research was on the geometry of motion; as such, the control aspects were not fully explored.

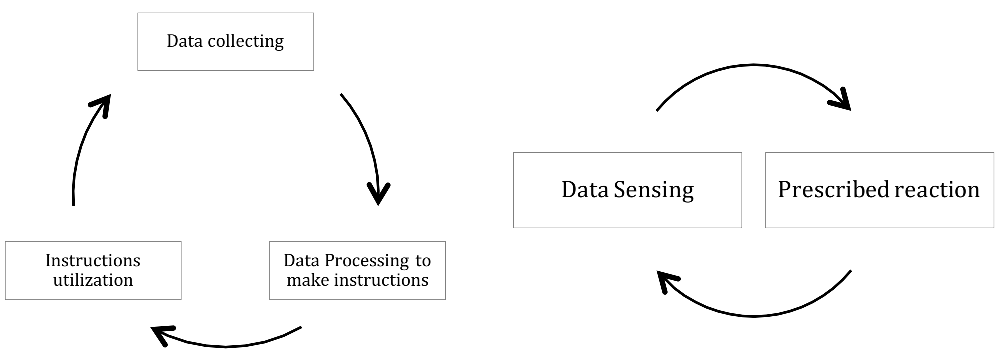

Figure 71: Comparison of the interaction process (left) to the prescribed responding process (right).

Transformable shading systems can be interactive or prescribed to be responsive. An interactive system distinguishes itself from a prescribed responsive system by its ability to create real-time personalized reactions to changes. In these systems, the data are absorbed, processed, and transformed to deliver newly curated instructions. In prescribed responsive systems, the data initiate a reaction instruction previously defined and embedded once it is in the system (Figure 71, Figure 72 and Figure 73).

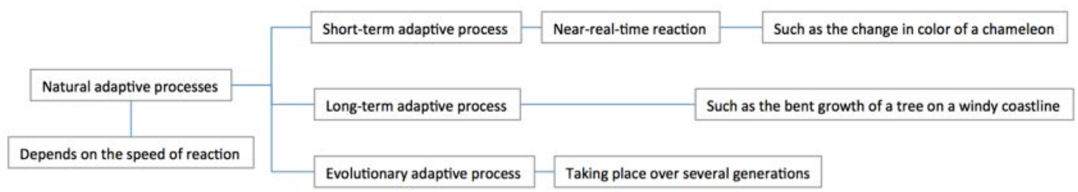

Figure 72: The adaptation speed is varied.

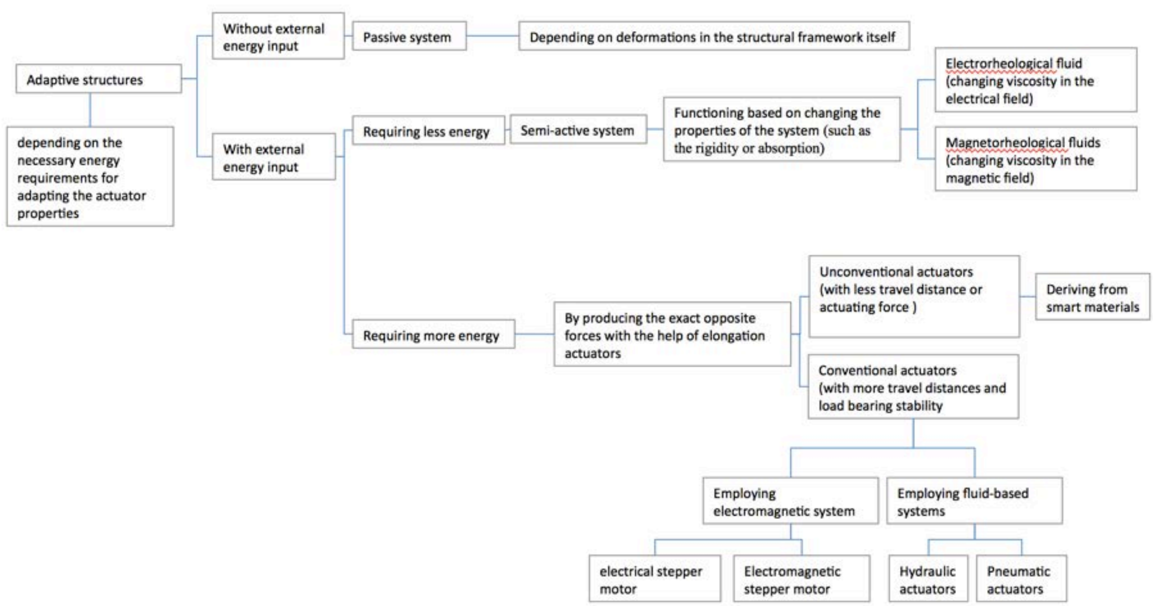

Figure 73: Most of the adaptive structures need external energy input to adapt themselves to the environment.

4.7 Evolution of the AURA Design Process

AURA's design process discloses much about motion design methodology, especially since the relevant body of literature lacks adequate examples of the challenges that architects face when designing motion compositions. Monitoring AURA's design process for this research was an attempt to study the ways in which transformability might lead to a design methodology. Thus, this chapter presents the findings of the in-depth analysis of AURA's design process.

As mentioned above, kinetic systems can be defined as one of three geometric transformations and their compounds, together with movement that is based on material deformation (such as elasticity). AURA's designs are restricted to two transformation types: measures of either translation or rotation, or a combination of the two. Between those two, AURA offers a finely graduated range of compounds. AURA's parameter ranges exclude scaling and material-based transformations. In other words, AURA's design is based on simple geometric transformations rather than material transformations. Accordingly, AURA consists of rigid components that provide only kinetically-based translations, rotations, or compounds.

If we separate AURA's design process into the under and overlying geometry phases, then the main question becomes: *Which design variables affect AURA's design process during each phase?* These design variables can be categorized into one of three aspects:

1- Knowledge;
2- Skill; or
3- Information and data.

Environmental control data and cultural references are the primary types of information affecting the TSS design process. Traditionally, environmental control is a dominant factor in designing shading systems. However, other factors such as cultural references, economics, fabrication processes, materiality, and durability are other issues that can directly affect the design. Kinetic patterns provide opportunities for shading systems to react to different variables as they occur in different scenarios. For example, to control light, a TSS can be adjusted based on the position of the sun. However, in different scenarios (such as when providing a view or privacy, screening adjacent urban or natural contexts, kinetic patternmaking on a façade, or insulation of the building), the ultimate design proposed for the TSS must be adjusted differently.

In this research, the inputs essential to support AURA's design and decision making process were constantly captured. These aspects will be discussed below.

4.7.1 Different Approaches to AURA's Design Process

Generally, there are three approaches to developing AURA's design process map, which include:

1. The bottom-up approach,
2. The top-down approach, and
3. An integration of the bottom-up and top-down approaches (i.e., a mixed complementarity approach).

Although the first two approaches appear to be radically different, they share a common goal of developing a transformable shading system. The AURA design process is a hybrid method of bottom-up and top-down approaches.

1. In the AURA design process, the first tactic is based on the bottom-up approach. A bottom-up design involves the piecing together of systems in order to give rise to more complex systems, thus making the original systems sub-systems of the emergent system. This method is based on developing the motion geometry of generators (their underlying geometries), and then devising patterns to overlay the geometry of the generators. The overall appearance is a consequence of the design process; it is not predefined. For example, In the AURA design process, UMBRA I, II, III, IV, and V are all designs based on the bottom-up approach (Figure 75).
2. The second approach is based on designing a general concept for the desired opening or closing status of the TSS, and then concentrating on designing the relevant geometries of a motion composition that can support that preferred status or appearance. In this case, the general appearance is predefined. The top-down approach begins with a general design concept and moves to a specific kinetic

system. Basically, in this method the TSS begins with a general idea of how the shading system may kinetically perform. Then, a designer investigates how to purpose a transformable system that can deliver that idea. The designer designs different motion geometries and tests their motion performance to satisfy a predefined condition. In the top-down design approach, an overview of a system is formulated that specifies but does not detail any components (Figure 76). In AURA's top-down design process, there is also another method. This approach is to design a static-based shading system, and then investigate how to apply the appropriate mechanisms to the static concepts. In this case, a kinetic design system definitely has its own design constrains that may change the basic conception of a static concept. A good example of this approach is TEXTA (Figure 74).

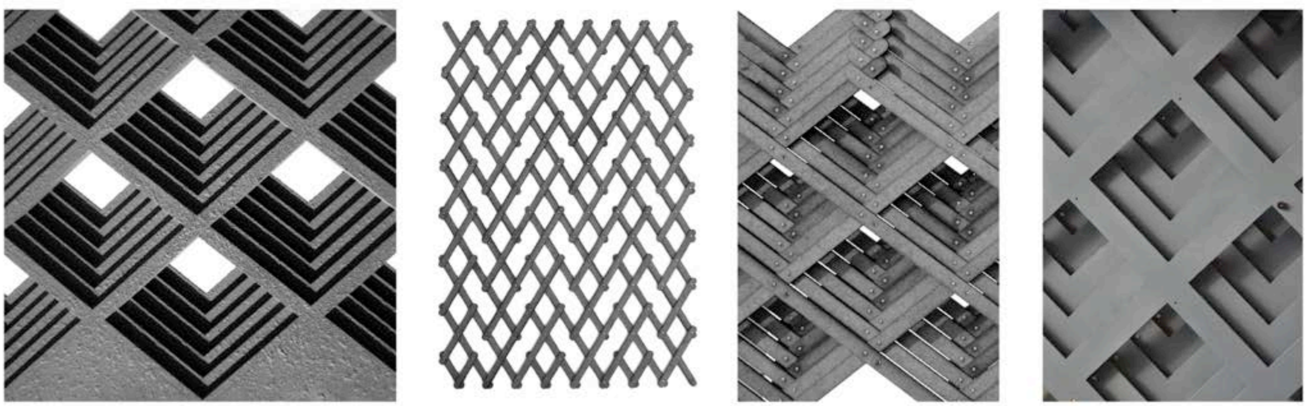

Figure 74: A static geometric concept that resulted in transformable geometric concepts.

3. The third approach in the AURA design process is to integrate the bottom-up and top-down approaches, and offer a mixed complementarity approach. Once expertise is developed in the TSS design process, a hybrid system can be developed. In this approach, the basic concept of the geometry of motion, a TSS framework, and the appearance of a system are all cultivated simultaneously and evolve together. The integrated model is advanced, requiring designers to be more experienced and knowledgeable about the entire design process. The AURA VII

design process exemplifies this integration approach (Figure 77, Figure *78* and Figure 79).

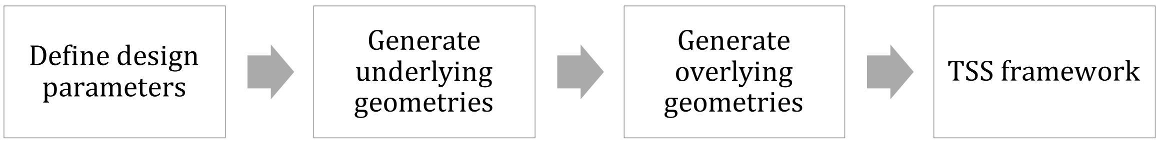

Figure 75: The bottom-up design approach in the AURA design process.

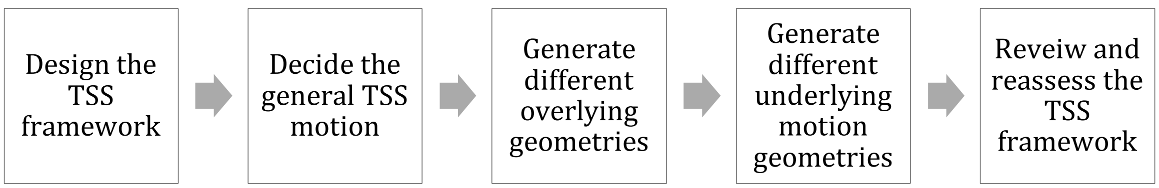

Figure 76: The top-down design approach in the AURA design process.

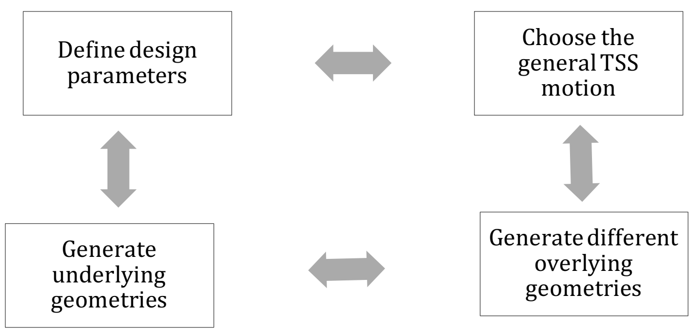

Figure 77: Integrating the bottom-up and the top-down approaches (a mixed complementarity approach).

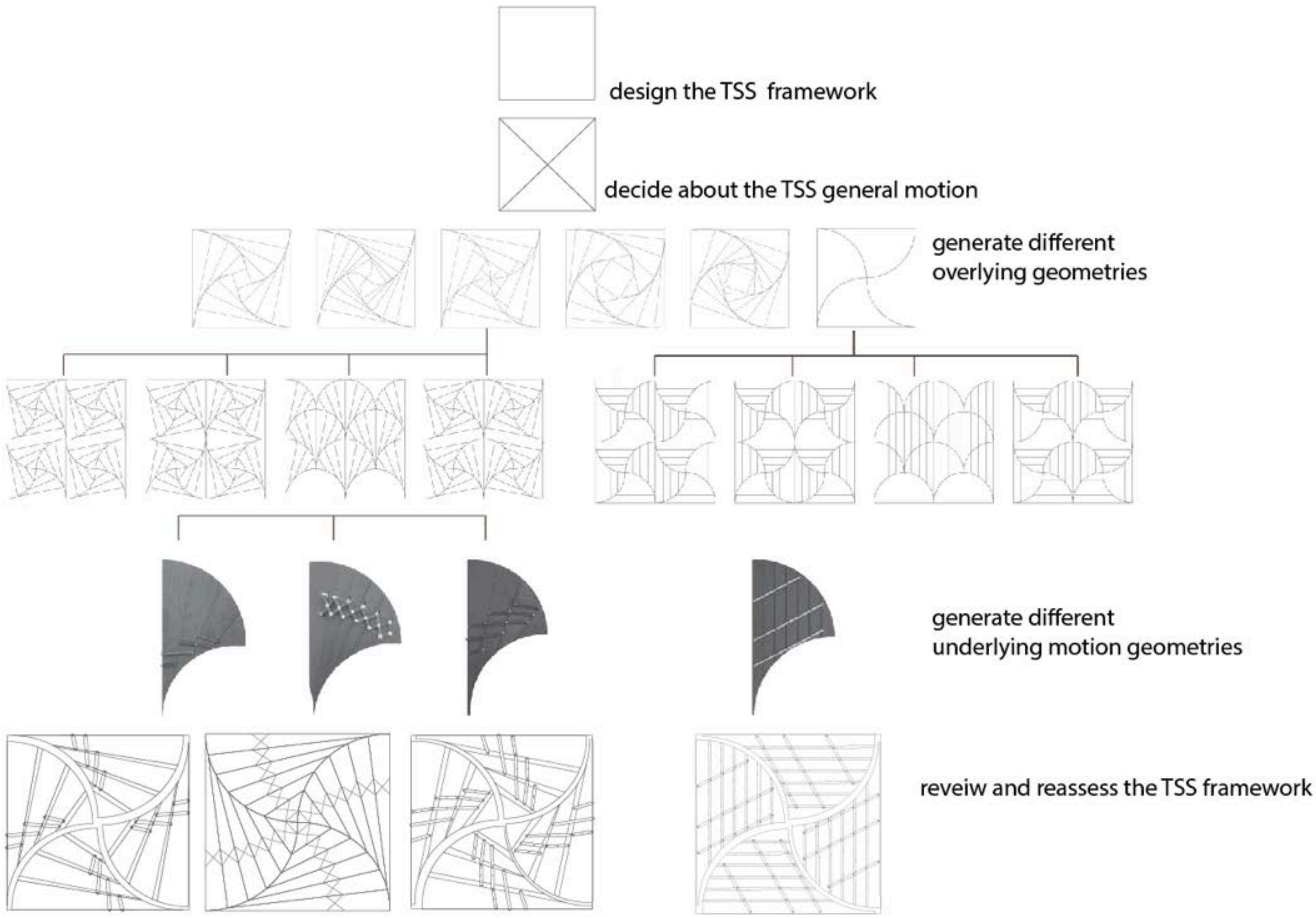

Figure *78:* his chart presents an integrated approach to designing a TSS.

Figure 79: Arcus V is the result of an integrated approach to designing of a TSS.

4.8 Main Lessons Learned from AURA's Design Process

The eleven main lessons learned regarding AURA's design process will be discussed below. These principles were the most critical that were observed and absorbed during the self-immersion process.

4.8.1 The Essential Loop Process of Designing and Making in the Early Design Stage

In AURA's design process, making and prototyping is a way of thinking. Making is integrated into the design intent, and prototyping is considered a methodology for knowledge gathering and design thinking. The AURA design approach employs a long tradition of using physical models to create, evaluate, and refine design ideas. Moreover, making physical models in the early design stage of AURA's design process is an efficient way of revealing possible problems. Creating iterations of models and prototypes, ranging from small to full-scale mockups and across material ranges, is fundamental to this type of design research.

There are three types of prototyping that were considered during the AURA design process conducted for this research:

- Concepts models,
- Constructive models, and
- Operational prototypes.

Concepts models are not usually used for presentations, but rather to facilitate communication between designers and their designs. In the AURA design process conducted for this research, concept models were primarily used to envision and check the underlying geometry. These simple models were not concerned with materiality, scale, or detailing. Here, the focusing task was the visualization of the geometry of motion. Mostly, the links were simple, straight elements between connection joints. Since the main purpose of the concept models was to check the underlying geometries, precision was important to the TSS design process. Any possible imprecision could have caused the model's motion performance to fail. If the model lacked exactness and accuracy, it would not fully communicate the main reasons for failure or confirm the applied underlying geometry.

In order to minimize a model's unwanted inexactness and have more control over the fabrication variables during the early design stage, most of the physical concept models were made with laser-cut pieces. Although these early laser-cut models offered unique design opportunities and resolved certain limitations associated with the use of analog tools, they were made simply with flat-sheet materials of a limited thicknesses. With the accessible laser cutter that the author used for this research, it was possible to cut up to 1/4″ thickness nonmetallic materials such as acrylic, wood, or plywood; this could be extended up to a 1/2" thickness under very special conditions.

Making three-dimensional movable designs from flat pieces involved several constraints, such as available brackets, screws, tabs, slots, and glues. In addition, it was challenging to work with thin pieces of a width that was the same or less than the material thickness. Such pieces could warp from the heat generated during the cutting process. Cutting tiny pieces (for instance, spacers between links) was also a challenge. During the cutting process, the flat material sat on a grid; there was always a chance that the smaller cut pieces might fall down. Regardless of the limitations of the laser cutter, in most cases it was an effective tool for checking the pure geometry of motion (Figure 80).

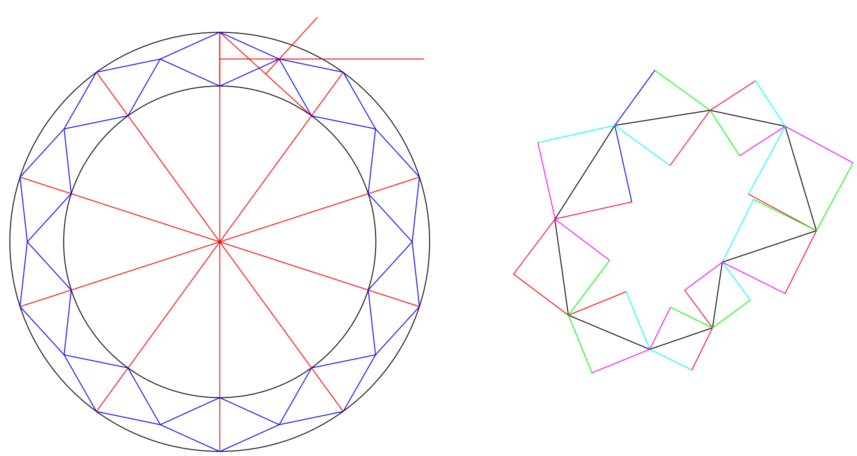

Figure 80: Linear and two-dimensional drawings.

In this research, constructive models were made during the conceptual design and design development phases in order to visualize how the parts might fit together, and to make design decisions regarding dimensions and thicknesses. Most importantly, constructive models were used to inform the researcher regarding the possible overlaid pattern of each model, based on several variables such as environmental factors, fabrication methods, structural and mechanical properties, and issues related to service and maintenance (Table 15). In the AURA design process, the digital and physical modeling progressed simultaneously because there were limitations involved in both.

Operational prototypes in the TSS design process are functional models used to simultaneously test for materials, scale, precision, tolerance, detailing, and fabrication issues. After implementing all aspects of the design, environmental, and structural concerns and progressively changing the variables, the designer should move on to developing the operational prototypes. Before fabricating the operational model, a complete and detailed digital model should be developed. All issues with regards to fabrication, materials, shipping, storage, assembly, and future maintenance must be considered in order to finalize the development of the design model. If this stage is completed properly, the TSS design will be well-developed for production.

Table 15: Different types of model in different stages of design process

Prototyping and modeling	**Concept models (digital and physical)** Primarily models for visualizing and checking the concept and developing the underlying geometry	**Constructive (form-fit) models (digital and physical)** Models for visualization and assembly (how well parts fit together), basic motions/functions, and checking the under and overlying geometries	**Operational prototype** Functional model for testing the materials, scale, actuation, dimensions, and detailing
Design stages	Early design, Conceptual design	Conceptual design, Design development	Design for fabrication

4.8.2 Essential Interaction Between Physical and Digital Modeling

Physical prototyping is key to understanding the limits and overall behavior of a TSS. During the AURA design process conducted for this research, digital and physical modeling allowed the author to conduct more informed and better design analyses of the TSS during the early design stage. Here, the physical model was a vehicle for brainstorming, studying, optimizing, and evaluating the design, as well as for providing feedback, gathering knowledge, and making decisions. In this research, prototyping was not only a representation tool, but also a way of knowing and engaging in design thinking.

In traditional architecture education, a model is made to scale to represent a simplified form of a concept; models are not meant to be functioning prototypes, but rather three-dimensional representation of ideas (Zarzycki 2013). However, in the TSS design process, even primary conceptual models are meant to function, though with less detail. In the TSS design process, conceptual models are closer to engineering models, which serve as a validation device for ideas.

The constant back-and-forth between physical and digital models is essential if the designer is to benefit from both strategies. Although it takes place early in the design process, this interaction is necessary to designing a kinetic system that can be mechanically functional. In later stages, partially detailed models can be made and remade until the design becomes properly developed. After the design-development phase is completed, a constructive model should be fabricated. This model should be an exact geometric reproduction of the real system, built to scale (if possible), and satisfying the few restrictions imposed by the design parameters such as the underlying geometry and overlaid pattern, scale, tolerance, spacers (according to the material thicknesses), operational system, and basic light performance.

Based on how a TSS concept originates, the design process may begin with a simple exploratory physical model or basic CAD drawing, and then continue on to other stages. Mostly, in this exploratory phase a loop should exist between basic physical and digital models, continuing until an acceptable underlying geometry with the potential for creating a quality shading system is generated. In this research, this loop was called the underlying geometry generation loop. Sometimes, the process may begin with an existing mechanism (inspired by the designs of other designers or some conventional system existing in the market, such as louvers), and then extend into a novel form of movement by continuing the underlying geometry generation loop.

During the AURA design process conducted for this research, the author enjoyed the advantages of both physical and digital modeling. However, there were stages in the design process during which one or the other could not be of help. On the one hand, developing a design outside a computational framework revealed a lower level of overall design resolution and quality. On the other hand, the author reached a point in which digital modeling on affordable architectural software platforms could no longer advance the designer's knowledge of materials, fabrication, and assembly (Figure 81).

Using physical models during the AURA design process will help designers:
- Better comprehend and track kinetic movements;
- Understand the underlying geometry;
- Design the overlaid patterns;
- Be more informative;
- Better understand the materials' properties;
- Better indicate the overall assembly behavior of the shading system;
- Give valuable first-hand feedback about the materials' resistances and the levels of friction within the joints;
- Provide tactile feedback that helps advance the design; and
- Communicate the design intent and receive feedback from peers and fabricators.

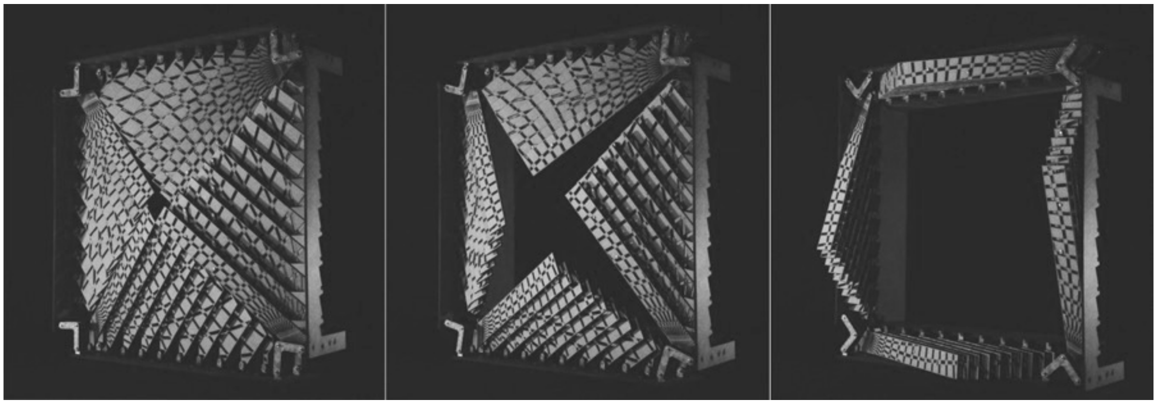

Figure 81: Physical model of AURA VII.

However, the AURA design process conducted for this research also benefitted from using digital models (Figure 82, Figure 83, Figure 84 and Figure 85). Such models assisted the researcher in:

- Delivering a high level of precision;
- Designing and resolving the underlying geometry with sufficient precision;
- Providing a platform to run performance simulations;
- Clarifying the kinetic assemblies through abstract diagramming;
- Engaging in better problem solving and design revision;
- More easily revising and refining the design;
- Running more cost-effective and efficient design, modeling, and analyzing processes;
- Simply sharing and receiving feedback;
- Embedding the TSS in the entire building system; and
- Rendering to evaluate the TSS's quality of space.

It is necessary to mention that in most architectural software packages, there is a lack of understanding of material properties, physical behavior, and motion simulation.

Figure 82: Rendering to evaluate AURA quality of space.

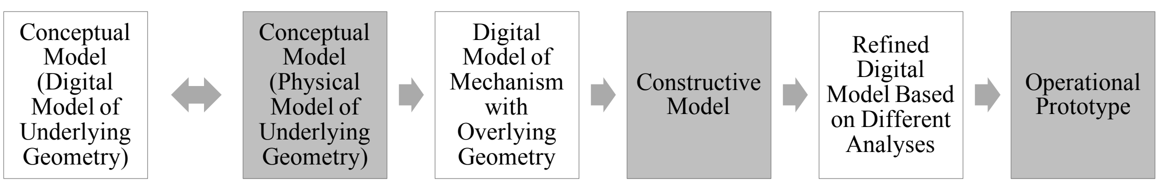

Figure 83: Interaction between physical and digital modeling.

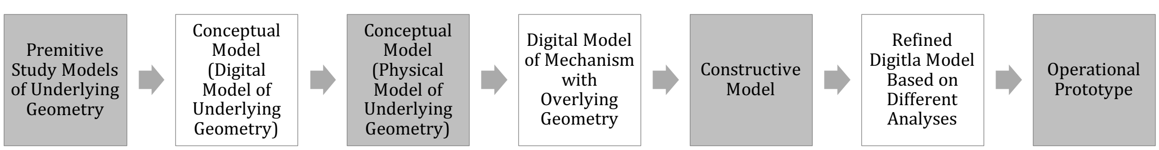

Figure 84: Interaction between physical and digital modeling (Type 2).

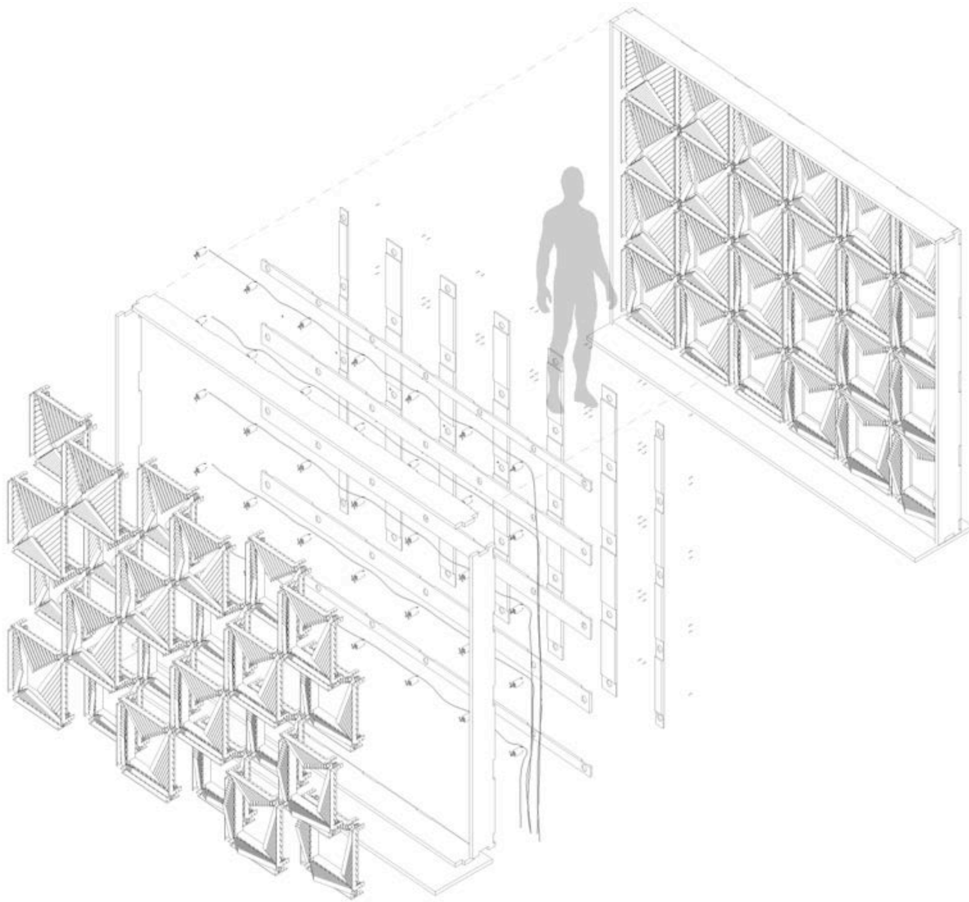

Figure 85. Digital model of AURA VII.

After designing the underlying geometry of a proposed TSS concept, a designer should explore its possible overlaid patterns. Physical models serve as a suitable design platform for checking how the underlying geometry and overlaid patterns may work together to make a shading system.

During the AURA design process, the author made different primary physical models based on the proposed underlying geometry. These models helped the researcher to be sure of the mechanical performance and precision of the dimensions. To study the possibilities offered by different overlaid patterns, various designs were applied over the existing linkages of the primary models. This process helped the researcher to understand the size and movement clearance of the proposed overlaid patterns. Some difficulties with motion design are related to imagining how different pieces might be connected to avoid any possible collision with other parts. The parts of the hardware (such as screws) that connect pieces together and the spaces between those parts are both critical for minimizing collisions. In this research, having primary models with attached parts representing overlaid patterns facilitated the process of understanding and exploring. The models helped the author to easily change the sizes of the overlaying designs, for instance by cutting new pieces of paper or trimming them. The location of the attached parts was easily changed by reattaching them with tape or other means (Figure 86).

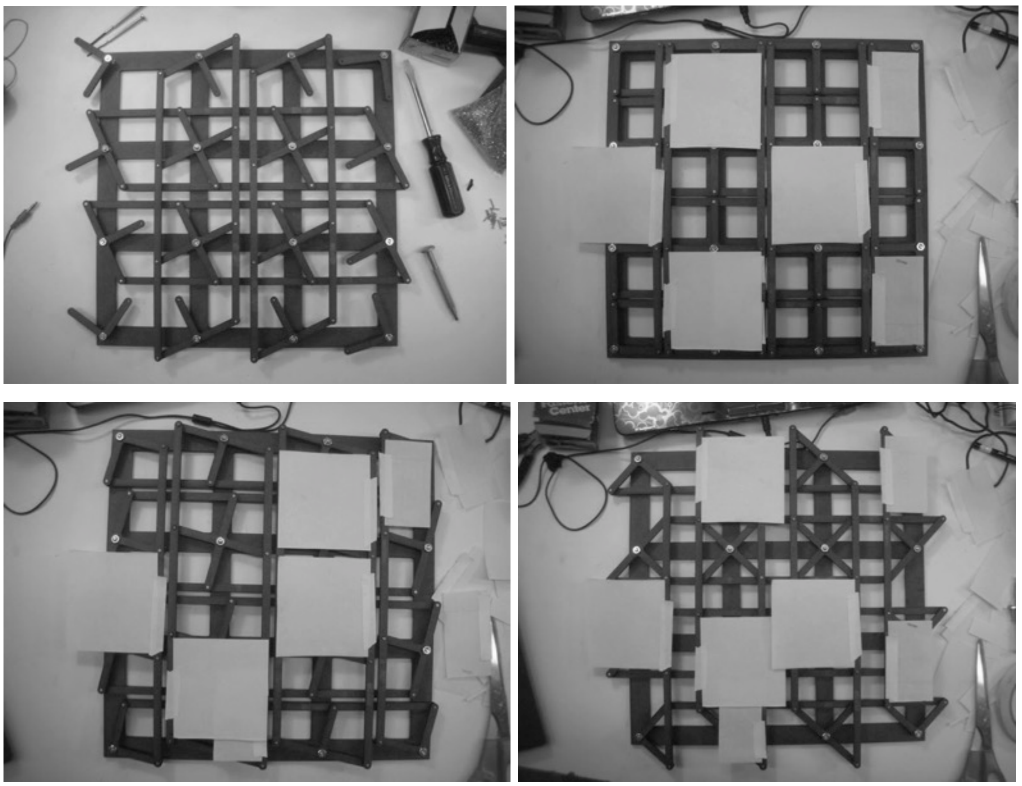

Figure 86: Exploring the possible overlaying geometries by cutting and placing pieces of paper on different linkages.

Also, with architecture-based software such as AutoCad and Rhino that do not offer motion simulation capabilities in their basic packages, it is easier to study motion geometry by drawing 2D drawings of a proposed design from the top or bottom view. One of the main problems with using 2D CAD drawings to study the motion geometry of a TSS design is the lack of depth. In 2D drawings, material thicknesses cannot be reflected in the file, and all linkages and joints must be designed in two dimensions. With the primary model of this research, it was easier to play with physical models and spacers and change the layers of the linkages to explore the motion paths and different possibilities (Figure 87 and Figure 88).

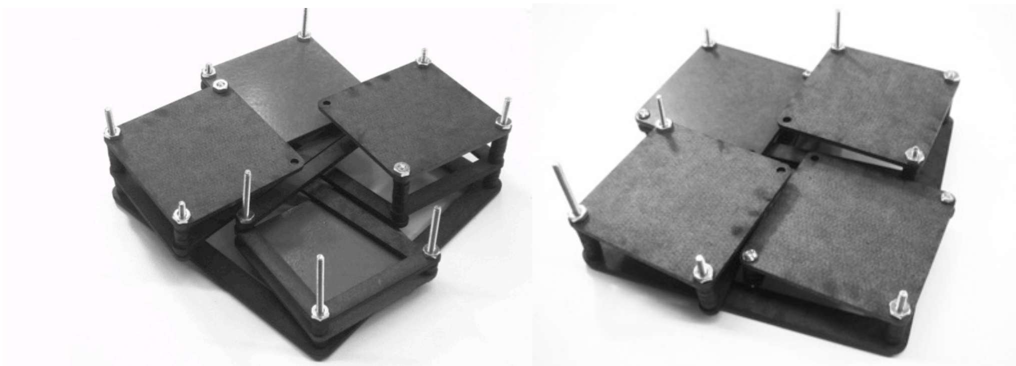

Figure 87: Linkages could be rearranged with different numbers of spacers to explore different compositions and motion paths.

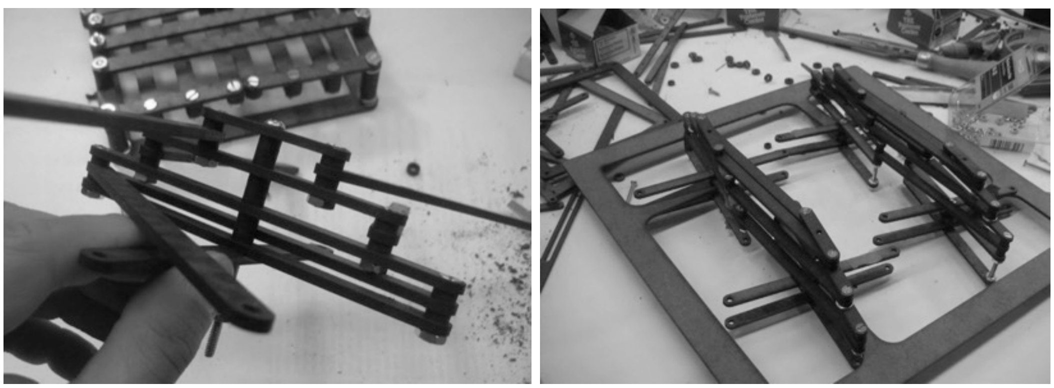

Figure 88: In UMBRA II, to provide a motion path for the linkages, spacers had to be inserted between the layers.

4.8.3 Essential Nature of Working with Different Modeling and Environmental Software

Digital modeling benefits the TSS design process in a number of ways. Many would consider the architect Greg Lynn to be a pioneer of computer-aided design. At the Canadian Centre for Architecture, he curated an exhibition on the fast-disappearing legacy of those who had gone before him (Rajagopal 2013). He referenced Chuck Hoberman as one of the earliest designers to engage with digital tools. Lynn stated that transformable design reveals what digital technology has to offer, and in this respect, Hoberman had both an agenda and a vision. Lynn claimed that digital technology wasn't simply a tool that one could use, with no consequences; it was a new fundamental concept. He continued on to say that Hoberman "was the most extreme. He refused to have some specialist do that stuff; he just learned programming himself."

Experts in modeling and digital design should be considered full members of the design team. Modeling is not simply the representation of an idea, nor a neutral tool. One of the earliest research questions faced in the TSS design process is how to find a series of compatible software. A good transformable design relies on a digital modeling tool that can address the following:

- Design: To design 3D models in a relatively easy, fast, and accurate manner and to check the geometry of motion in 2D and 3D, the software should provide a model with sufficient precision.
- Simulation: The software should perform motion simulations of complex and integrated designs.
- Validation: The software should analyze dynamic lighting performance and other environmental criteria.
- Communication: The software should provide a platform that all members of the design team can use to review and evaluate the design.
- Justification: The software should redesign a part or entirety of the proposed concept, based on the outcome of the process.
- Production: The software should provide accurate design files for fabrication and assembly.

To determine the kinematics and dynamics of the new transformable design before making physical prototypes of buildings, designers must know how to simulate and analyze their concepts. During the AURA design process conducted for this research, different types of CAD modeling software were explored in order to learn the most convenient. To digitally test the motion of a proposed concept, the author tried several different software packages, including: SolidWorks, Rhino+ grasshopper, AutoCad, NX Unigraphics, Creo, 3D max, Maya, and Max (MSP, Jitter, Gen, Cyclops).

Solidworks, NX Unigraphics, and Creo are excellent for producing accurate mechanical drawings for industrial designers and mechanical engineers. These software packages all generate digital models that can be modified with predefined parametric values such as width, length, and height. These parametric and feature-based CAD systems allow designers to go back to each time interval, according to the feature design tree, in order to edit and craft the model to properly fit their needs.

Solidworks, NX Unigraphics, and Creo use a relatively similar work environment to create and simulate moveable models. By offering integrated motion simulation and assembly stress analysis environments, these digital tools offer designers the opportunity to design components and define mates in the assembly, and animate the model in order to review how the components of the transformable design are able to move. For example, in Solidworks, motion simulation can provide a "complete and quantitative [set of] information about the kinematics—including position, velocity, and acceleration, and the dynamics— including joint reactions, inertial forces, and power requirements, of all the components of a moving mechanism."[57] By identifying high-stress areas and the environmental impact of the components, NX Unigraphics can advise designers to remove unwanted components and optimize the strength, weight, or size of different parts of their design.

Running dynamic simulation tests can help a designer see how dynamic components will function under real-world conditions (such as friction). Although in some case studies it became clear that making physical models and testing the actual geometry would be faster (at least in the early design stages), there is still a strong need for TSS digital modeling to deliver a high level of precision at the end of the design process. The complexity of learning new software (such as Solidworks, NX Unigraphics, and Creo) in the mechanical field and the availability of these packages to beginner designers and architects provided the author of this research with strong motivation to search for another set of software that could help novice motion designers in the early design stage.

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[57] http://www.solidworks.com/sw/images/content/Training/SIM_Motion_UnderstandingMotion_WP_ENG.pdf

Rhinoceros, as a NURB-based software, is an easy-to-learn piece of CAD software simple enough for any novice user. This platform is "used in processes of computer-aided design (CAD), computer-aided manufacturing (CAM), rapid prototyping, 3D printing and reverse engineering in industries including architecture, industrial design (e.g., automotive design, watercraft design), product design (e.g., jewelry design) as well as for multimedia and graphic design."[58] Rhino is a simple piece of CAD software that can be used to generate complex surfaces and deliver robust 3D design capabilities. In Rhino, a designer can control points that specify the shapes of curves in order to make complex forms.

Since Rhinoceros offers a high level of compatibility with other software[59]and supports two scripting languages, it can be considered one of the main 3D computer software modeling packages for TSS. Also, it supports a wide range of plug-ins[60] that the TSS design process requires, such as Grasshopper, DIVA, RhinoWorks, and RhinoCAM.

To present an integrated project design and collaborative team environment, efficient communication across the various design teams is critical. Unfortunately, the coordination of design and fabrication documents is not a feature that Rhino provides. To read the model, all team members must have Rhino installed. The lack of a free Rhino model viewer for use as a communication tool[61] makes it difficult to receive efficient feedback and comments from other third-party partners. In addition, Rhino is not able to accommodate the different aspects required by the TSS design process, such as scheduling, material take off, and tendering.

Although Solidworks, NX Unigraphics, and Creo are very useful platforms for testing the mechanical aspects of a TSS design, they do not easily work with environmental analysis

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[58] http://www.novedge.com/products/2217

[59] It supports over 30 CAD file formats for importing and exporting.

[60] In computing, a plug-in is a software component that adds a specific feature to an existing software application.

[61] For example, Solidworks offers a free 3D modeling viewer called eDrawing that is even available on the iPhone and iPad.

software (such as Ecotect or Radiance) that allow designers at the earliest stages of conceptual design to simulate environmental performance.

Almost all of the currently available environmental analysis tools are unable to support dynamic models of transformable design; therefore, designers should simulate their design model at different stages of motion and analyze them separately, in order to understand the light performance of the transformable design model in movement. AURA's design process is a searching procedure that can be used to find the best dynamic light analysis tool (or plug-in).

During the AURA design process engaged in for this research, the author worked with Diva-for-Rhino[62] and DASSIM as the generative modeling program for use with Grasshopper. By using DIVA as a highly optimized daylighting and energy-modeling plug-in for Rhino, the author was able to conduct a series of environmental performance evaluations in order to check the thermal simulation, daylight, and annual and individual time step-glare analyses.

4.8.3.1 Overlaid Pattern Design: Function-Preserving Editing

When developing a TSS design concept, a designer may want to modify the environmental performances, aesthetic aspects, or structural behaviors of her design while leaving the motion geometry of the transformable device intact. For example, to control the level of penetration of a TSS by providing more or less coverage, the designer may desire to play with the shape of the linkages to maintain the environmental requirements and satisfy aspects of aesthetics.

Navigating the space of physical motion for a given linkage is difficult without the aid of a parametric software package that provides immediate feedback. In the AURA design process conducted for this research, due to the aid that Solidworks provided, modifying the design and editing the entire process was less challenging. Solidworks helped the author to quickly check the course of movement in the assembly.

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[62] http://diva4rhino.com

Besides checking different parts' courses of movement, exploring different constraints of a particular fabrication method, and evaluating methods of assembly and the structural behavior of particular components, mechanically-based software such as SolidWorks and NX Unigraphics were not able to recognize the critical characteristics of a TSS design. While editing the linkages and joints, the designer should use another piece of environmental software to constantly check the functionality and performance of the shading devices.

Comparing and working with different software packages during the AURA design process conducted for this research illustrated to the author that none could serve as a comprehensive design tools for a TSS design. To facilitate the TSS design process, it is necessity to develop an inclusive software platform that would assist a designer in simultaneously developing the different aspects of transformable shading devices.

However, there often are new software packages developed for other disciplines, such as Link Edit by the Disney research group, that may be very helpful to the TSS design process. In their paper "LinkEdit: Interactive Linkage Editing using Symbolic Kinematics," the authors' stated: "Indeed, editing the shape or motion is a difficult task since inadvertent tampering with the inter-joint distances is bound to end in dysfunction of the mechanism. By contrast, our system makes function-preserving edits easy and intuitive."[63]

With software developments of this kind, the TSS design process should become more interactive. Given a working TSS design as an input, the designer can now make targeted edits to the shape or motion of selected parts while preserving others (e.g., functionally important aspects).

4.8.3.2 TSS as a Live Parametric Design

In parametric design, a designer uses parametric design software to find the best static composition that optimizes both performance and elegance. Mostly, the designer defines the primary variables, and those variables determine the final form. None of static forms

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[63] http://www.disneyresearch.com/publication/linkedit/

in the parametric software are a result of all of the possible design parameters. Even with the best process for recognizing and applying variables, the final form is defined through the optimization of limited and predefined variables.

TSS design is similar to parametric design, in that the designer animates a transformable design to generate a range of outcomes. However, in the TSS design process there is no final form. In a TSS, the parametric characteristics stay with the object throughout its life; there is no freezing moment that solidifies the various parameters (as there is in a static composition).

If we consider the TSS design process to be a live parametric design, the designer must define not only a range of kinematic designs as inputs (based on the different generators of the underlying geometries of motion), but also the final overlaid patterns of the shading devices as outputs (based on environmental, fabrication, and maintenance constraints).

4.8.4 Essential Nature of Environmental Design Knowledge

There are two main types of transformable façades: adaptable and media. Adaptable façades are responsive skins that adapt to changing environmental conditions and levels of user occupancy. Media façades, by contrast, are driven by an interest in the recasting of architectural surfaces as zones of interactivity, with the potential to engage users with public art works or embed socio-cultural information (Moloney 2009).

Transformable shading systems fall within the category of adaptive facades in that they provide a building with a level of adaptability to environmental changes. Therefore, environmental design knowledge is a fundamental knowledge that initiates the TSS design process and influences most design decisions.

Transformable Shading Systems introduce a new way of controlling the environment. Hoberman states that:

> "adaptive systems combine the best of existing strategies: low energy use and control over building environments. For instance, a building's energy requirements can be considerably lowered if its design can adapt to diurnal fluctuations in temperature. An adaptive system that is modulated to control the volume and direction of heat flow in

response to external and internal conditions can enhance comfort and energy performance."[64]

As discussed in the introduction to this research, the use of TSS as an environmental mediator is controlled by three major control variables – solar thermal, daylighting, and ventilation – although in the AURA design process, daylighting is the primary environmental factor.

In AURA's conceptual design process, environmental design knowledge plays a critical role. For example, environmental considerations are the basic evaluation criteria (besides the kinematic aspect of the motion geometry) for evaluating the validity of a proposed concept for a transformable shading device. To finalize a proposed concept, environmental performance data dramatically influence the decision making process.

As a part of the AURA design development process conducted for this research, to generate different overlaid patterns on an overlying geometry, the author had to make choices regarding design variables such as scale, permeability, size, depth, orientation, and position that were related to the main façade. These variables would significantly influence the environmental performance of the TSS.

4.8.4.1 Essential Daylight Simulation Knowledge

A TSS provides more flexibility to the user with regards to adjusting the system to meet different requirements. Givoni claims that:

> "operable shading devices can admit all of the solar radiation when this is desirable, as it is in winter. Therefore, they are inherently more effective than the fixed shading. Operable external shading devices can reduce solar heat gain through windows and other glazed areas down to about 10 to 15% of the radiation impinging on the wall." [65]

In AURA design, daylighting can be controlled by various overlaying geometrical designs. By changing the size, scale, and depth of the elements of a particular design in an AURA motion generator, the daylighting performance of the system can vary

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[64] Hoberman, C. & Schwitter. (2008). Adaptive structures: Building for performance and sustainability. Design Intelligence.

[65] Givoni, B. (1994). Passive and low energy cooling of buildings. New York: John Wiley.

dramatically. However, the intent of the TSS system is to mediate, enhance, or deny solar radiation penetration into the space by adjusting the transformability of the system (Figure 89).

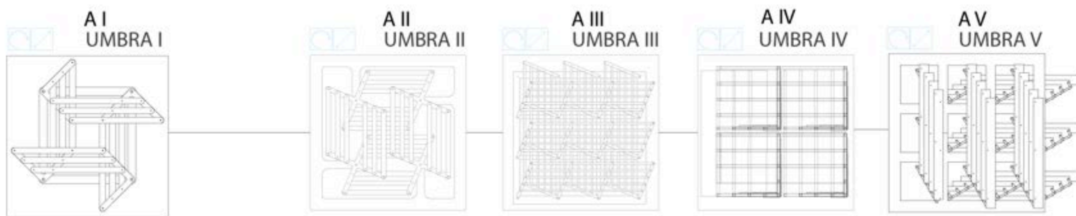

Figure 89: Different overlaid patterns are developed based on the underlying geometry of UMBRA as a motion generator. Each overlaid pattern can offer different light conditions for insiders.

The vitalizing effect of daylight can to a large degree be attributed to its seasonal and locally-specific dynamics.(Schumacher, Schaeffer, and Vogt 2010). A functional principle of AURA is the ability to shield against direct sunshine. In its closed status, AURA transmits only a small portion of daylight. Small changes in the position of AURA's wings can have a significant effect on the level of indoor illumination. Channeling a portion of the direct sunlight into the interior creates a dynamic indoor illumination.

AURA fulfills two main functions: solar protection and daylight provision. By adjusting the wings according to the position of the sun, AURA controls the degree of light transmittance and distribution. By tilting each fin at a slight angle, each wing can reflect a portion of the direct sunlight into the depth of the room. By using reflective material on AURA's inside layer, direct sunlight can be reflected back towards its source. Therefore, the wings protect against steep incident sunlight while directing lower sunlight deep into the room.

By preventing direct sunlight from shining through, AURA actively contributes to light provision. AURA, as an adaptable system, can provide a stable level of indoor illumination under changeable skies. According to the angle of the fins, AURA is able to deflect direct daylight. Distribution of the deflected light across the ceiling can illuminate the room.

AURA Daylight Simulations

The AURA VII concept was determined to be the final design. In order to study the effectiveness of the AURA VII, numerous computer simulations were analyzed and compared; the benefits of each system's daylighting performance were also quantified. The entire design process is discussed below (Figure 90).

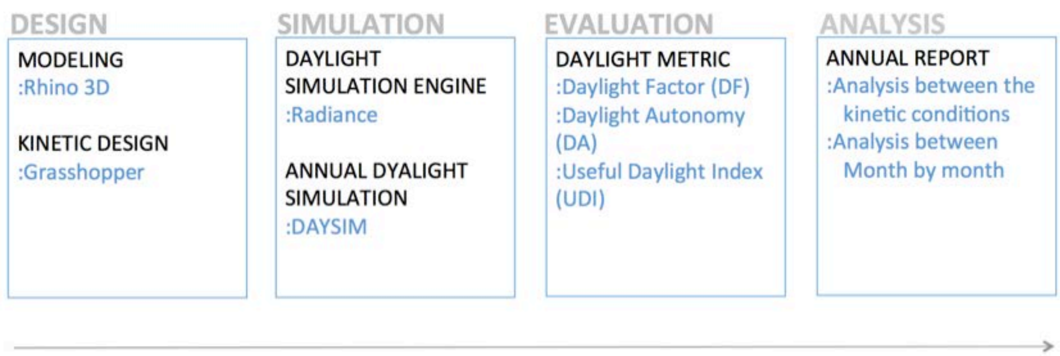

Figure 90: AURA VII simulation procedure.

Test Case Criteria: AURA VII

A deep open-plan office layout was selected with curtain-wall windows; it consisted of a 23'-0" x 23'-0" interior space with windows on the south side. The windows were placed to a full height of 11.5'-0", and ran the entire width of the façade.[66] The glass panes were of double-pane construction; the glass had an 80% visible light transmissivity.

AURA VII had two main kinetic schemes (Figure 91):

SCHEME1 (wiper rotation): The larger opening in the center allowed all fins to rotate from the closed position (45 degrees) to the fully open position (0 or 90 degrees) (Figure 92).

SCHEME2 (screw rotation): The larger gap between the fins allowed all fins to turn from the closed position (almost 30 degrees) to the fully open position (90 degrees) (Figure 93).

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[66] To increase the efficiency of sun control at the perimeter of the kinetic modules, a supplementary static system (2-foot horizontal and vertical fins) was considered.

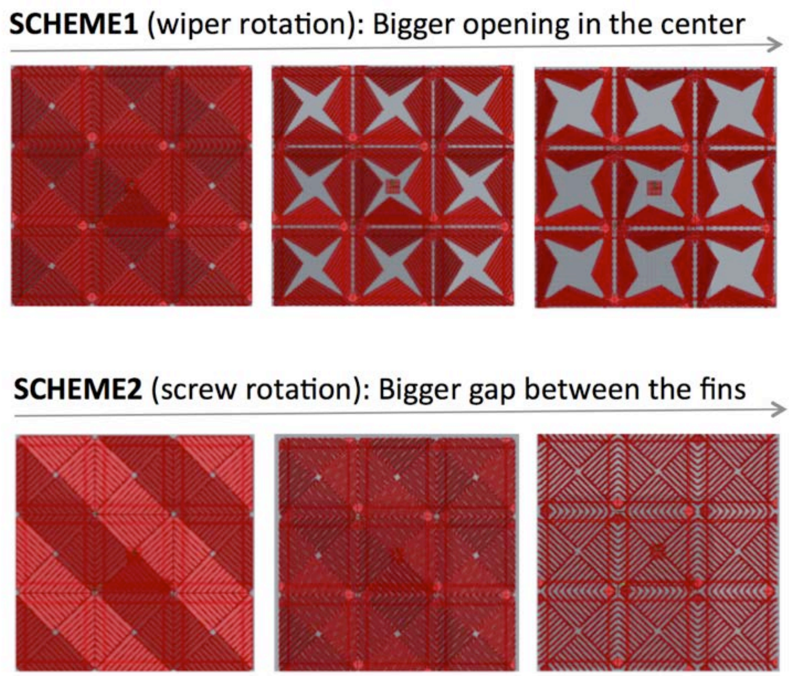

Figure 91: AURA VII had two main kinetic schemes

Of the many potential kinetic settings for the AURA VII, twelve settings were selected for this study. Each fin hinged at the frame side, allowing it to rotate from vertical (90 degrees) to horizontal (almost 30 degrees). The wiper system was an underlying structure connecting all of the fins together from the back, allowing them to rotate to the side of the frame (Figure 94).

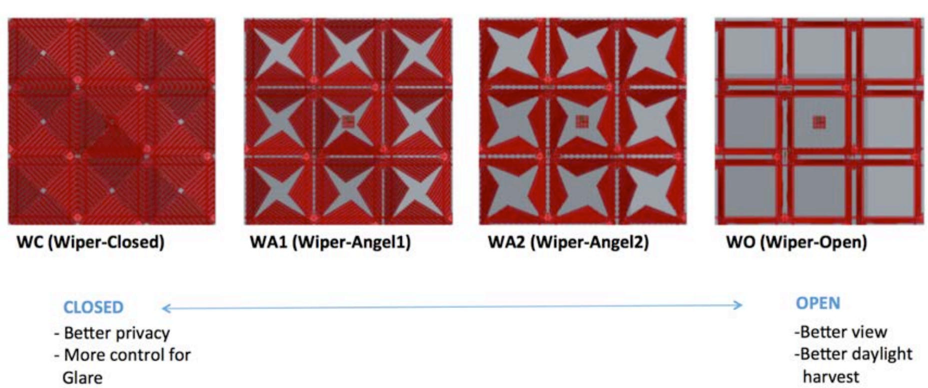

Figure 92: Scheme 1: Wiper Rotation.

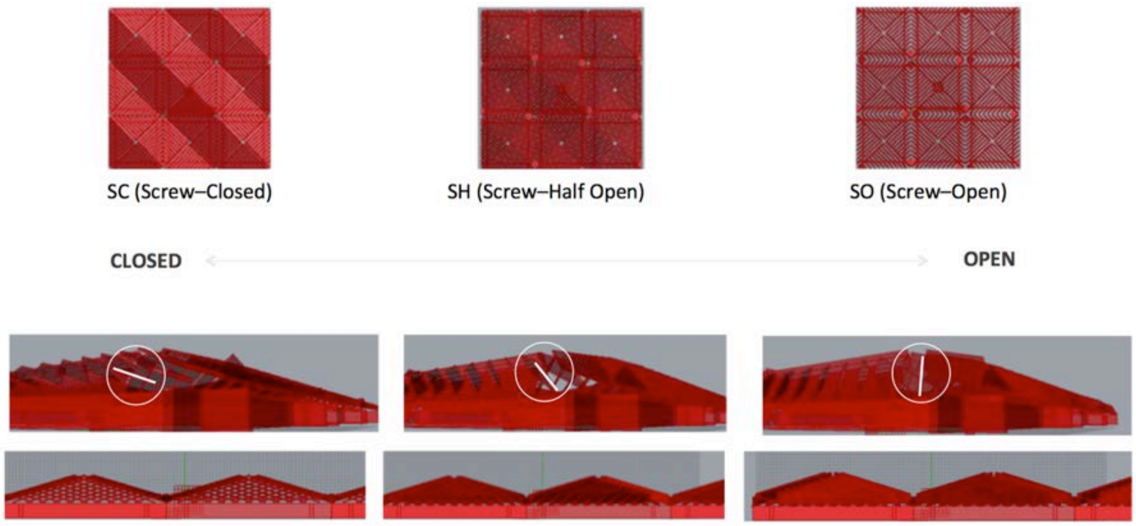

Figure 93: Scheme 2: Screw Rotation.

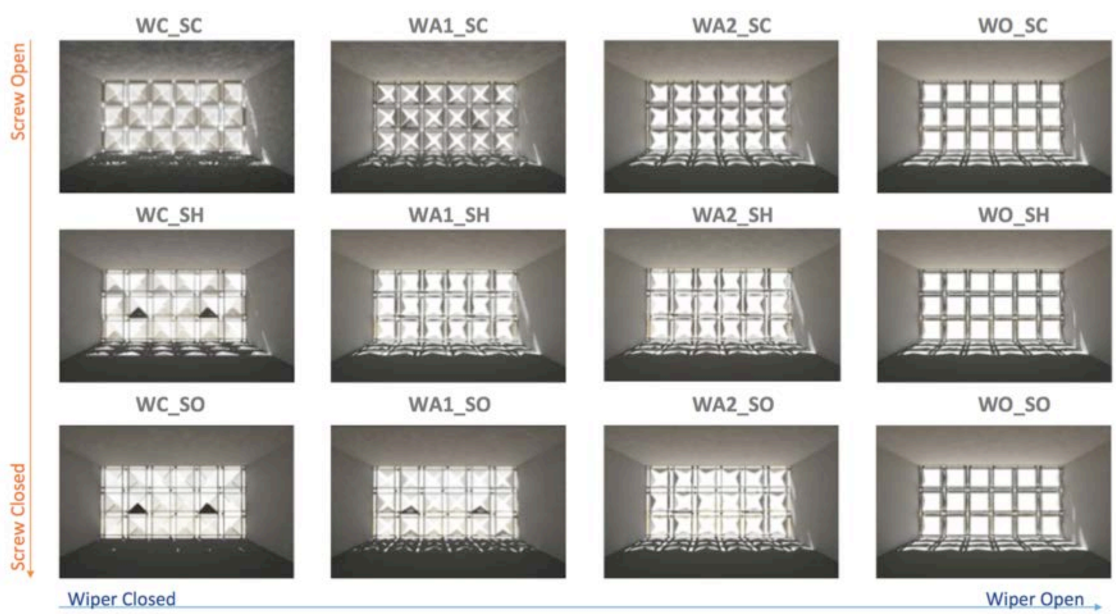

Figure 94: The twelve AURA VII settings used in the daylighting simulations.

Test Case Location: Houston, Texas

The building location was chosen because it would provide a range of weather data and a location with a density of office buildings. The chosen test case location was Houston, Texas. This area features fairly equal heating and cooling periods, and average temperatures ranging from 41^{o} F to over 94^{o} F.

Daylighting Simulations

In this research, daylighting performance simulations were studied for both Rhino and Grasshopper[67], using the same twelve settings. Grasshopper was used to parameterize the motion variables and adjust the turn and rotation of the fins (Figure 95).

The analysis plane, with 36 (6 x 6) simulation nodes, was installed at a level of 87cm (around 34”) from the floor. The height represented the general level of work planes. The daily occupancy duration was considered to be 10 hours per day and the daylight savings shift was presumed. Daylighting simulations were performed for 3,650 hours per year.

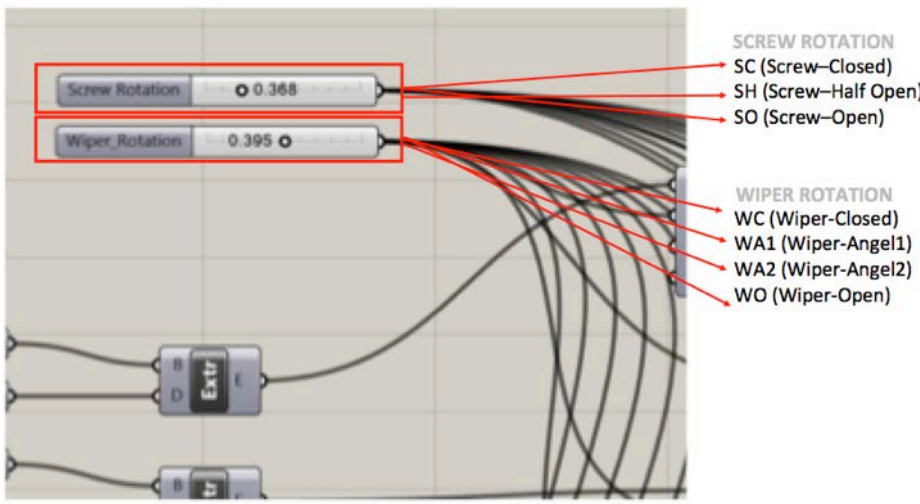

Figure 95: Two kinetic input parameters for adjusting the AURA VII settings in Grasshopper. These input parameters are rotation of each individual fin (named screw motion) and rotation of all fines together (named wiper motion).

For the AURA VII daylighting analysis, three different metrics were used: Daylight Factor (DF), Daylight Autonomy (DA),[68] and Useful Daylight Index (UDI).[69] Daylight

[67] Grasshopper is a parametric plugin for rhinoceros. The tool allows great flexibility and a introduction for visual programming.

[68] Daylight Autonomy: Percent of occupied hours in a year where the illuminance is equal to or above a set threshold, based on climate data.

[69] Useful Daylight Index: Essentially the same as Daylight Autonomy; however, this splits the illuminance into more interesting categories of percent hours of too little light, percent hours of useful light, and percent hours of too much light, based on climate data.

Factor, the conventional metric, was applied to evaluate the illumination gain of the twelve kinetic settings. Daylight Factor is a ratio representing the amount of available indoor illumination relative to the outdoor illumination present at the same time under overcast skies. Daylight Factor was calculated based on: DF = (Ei / Eo) x 100%, where Ei is the luminance due to daylight at a point on the indoor working plane, and Eo is the simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky. If DF is under 2, it is considered to not be adequately lit (artificial lighting would be required). If DF is between 2 and 5, it is considered to be adequately lit, but artificial lighting might be needed part of the time. If DF is over 5, it is considered to be well lit (artificial lighting would generally not be required, except at dawn and dusk; however, glare and solar gain might cause some problems

The twelve kinetic cases were also compared with the Daylight Autonomy metric. Six cases annually achieved the 50% of DA 300lux. All of the WO passed the 50% mark, and the WA1_SO also achieved 50% DA 300lux, though it only showed 1.3% of the Daylight Factor.

Finally, the Annual Useful Daylight Index (UDI) collects hourly time values based on three illumination ranges: 0-100lux, 100-2,000lux, and over 2,000lux. It provides full credit only to values between 100lux and 2,000lux, suggesting that horizontal illumination values outside of this range are not useful. Out of twelve kinetic settings, nine cases achieved the 80% of UDI100-2,000. However, even one successful case would be adequate for this evaluation because the system is not static and provides for the possibility of change.

When the annual potential of solar gains is compared to three conventional daylight metrics, most of the WA1, WA2, and WO cases showed positive results.

This indicates that the kinetic movement strategies of the shading system allowed for better light quality performance. Also, it shows that the daylight simulations and analyses of the TSS during the design process informed the designer, allowing her to make better design decisions throughout. The daylight analysis was not only useful for performance approval of a specific design, but also was a necessary step in the design development of the TSS design process, assisting the designer in making better decisions. A basic understanding daylight simulation is an essential piece of knowledge that a TSS designer should have.

	WC_SC	WC_SH	WC_SO	WA1_SC	WA1_SH	WA1_SO	WA2_SC	WA2_SH	WA2_SO	WO_SC	WO_SH	WO_SO
Daylight Factor (DF) >1.5							o	o	o	o	o	o
Daylight Autonomy (DA_300) >50%					o	o	o	o	o	o	o	o
# UDI_100-2000 >80%			o		o	o	o	o	o	o	o	o

Figure 96: Qualifications of AURA VII by daylighting metrics.

It should be noted that light analyses cannot be performed solely through computer simulations. Physical prototypes also help with this process.

4.8.5 Essential Basic Kinematic Knowledge

In developing TSSs, the major knowledge that the designer would deal with is kinematic knowledge. Kinematic deals with geometry of motion on its own in isolation from the forces associated with motion (Hunt 1978). Geometry of motion deals only with the first and simplest segment of kinematics, *displacements.* Usually time, as a variable, need not to be brought into account at all; the displacements or movement in mechanism is the main concern. In other word the geometry of motion is designing displacements of rigid elements in a particular ways. During this chapter, the author explained about the typologies of motion and elements of motions.

4.8.6 Essential Basic Structural Knowledge

Once a transformable system is designed, one must then deal with the position of the entities in the entire structure; this should be considered during the initial stage, throughout the transformable process, and in the final stage. The most critical phase in the development of transformable structures is during the transformable process; in this phase, the designer must take into account the compatibility of motion among every element, the integrity of the system in the transformation process, and the firmness of the elements. To this end, the knowledge of structure in the field of transformable design is very different from the basic knowledge that most architects gain during their education. Most architects deal with static buildings. To design a TSS, an architect needs a significant understanding of both static and dynamic loading and the way that the structure can resist these loads. In a TSS, a structural system is designed to allow parts of the structure to move, without reducing overall structural integrity.

In developing TSSs, structures should not be dealt with independently, but rather as a part of the entire system. In Fox's categories of kinetic structures, TSSs are a subdivision of dynamic kinetic structures. These "exist within a larger architectural whole but act independently with respect to control of [a] larger context" (Fox and Kemp 2009). As some movable elements may act independently, they are commonly considered plugin systems that do not need to work structurally with the rest of the system. However, a TSS has a built-in capability to change its state through motion while maintaining its structural integrity and stability.

As previously mentioned, there are three approaches to the AURA design process: bottom-up, top-down, and integrated. In all three approaches, basic structural knowledge is essential to integrating the AURA scheme as a part to the whole façade system. Although the basic knowledge of structure for AURA is different from what is needed for static systems, the overall understanding of structure and how loads (energy) move can help designers to design better TSSs, especially in the early design and design development stages. In all three AURA design approaches, considering the overall structural system should act as a constructive limitation.

One of the main design challenges in the TSS design process is maintaining the structural integrity of the system within the building's structure. In the bottom-up approach, there are more opportunities to miss an explicit answer overall because the main concern is developing the underlying geometry generators. For example, in the ANGULUS generator, the boundary of the design changed with the TSS's operation, which made it difficult to stay connected to the façade structural system. This simple limitation prevented the ANGULUS concept from being developed and applied in the later design stage. Therefore, in a bottom-up design approach, it is critical to consider the principles of structure during all steps, and not postpone this exercise until later in the process.

Another basic element of structural knowledge is how to connect a kinetic system to a static system (façade system). In some cases, the external boundary of the TSS can provide connection points to the façade system. In AURA's design process, most of the concepts are designed and fabricated inside a fixed frame. That frame facilitates the structural connectivity of the TSS to the entire façade system and the expandability of the system.[70]

4.8.6.1 Relationship of a Kinetic Element to the Boundary

Fox classified kinetic structures in architecture into three general categories: embedded kinetic, deployable kinetic, and dynamic kinetic (Fox 2002). In this research a TSS was developed and designed within Fox's classification of a dynamic kinetic structure. Such a system was understood to be singular and able to actively influence localized climates within a building system.

Deployable kinetic structures typically exist in temporary locations and are easily transportable. They possess the inherent capability to be constructed and deconstructed, or are collapsible. Therefore, the structure makes the scale portable. In this category, the overall structure's boundary changes during its operation. Several dome structures made previously by the author had sizes and boundaries that could change dramatically in order to provide portability and compactness. Expandable Spherical Cup I and II are examples of deployable kinetic structures (Figure 97).

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[70] In the next chapter (studio chapter), the author will emphasis on the importance of structural knowledge based on student projects.

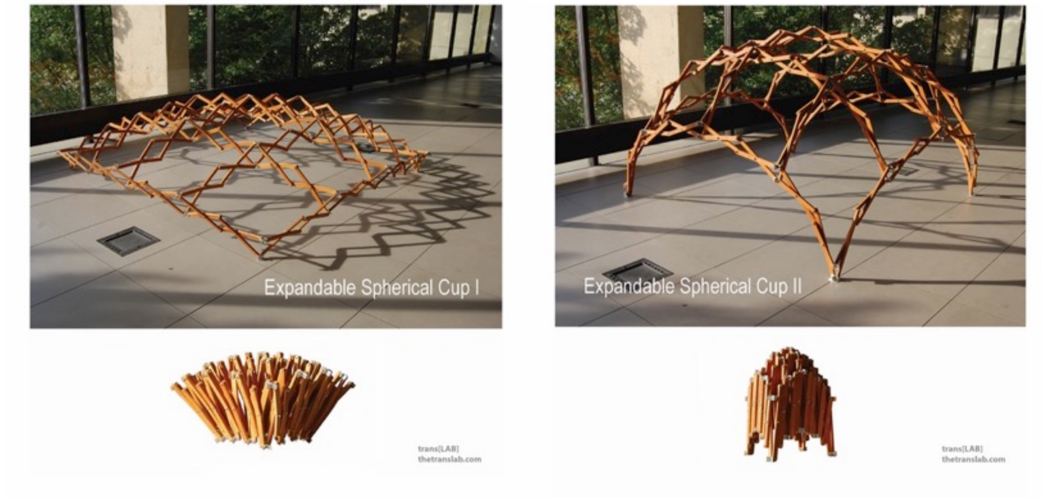


Figure 97: Expandable Spherical Cup I and II as deployable kinetic objects. Created by the author.

However, dynamic kinetic structures act independently with respect to the architectural whole. They are mostly in fixed frames such doors, windows, or ceilings. For that reason, designing a transformable system with a fixed boundary is a primary design concern. Transformable shading systems are mostly fixed in windows frames which are, in turn, fixed in façade systems. In the TSS design process, designing an underlying geometry that can maintain a fixed boundary during operation of the opening and closing mechanism is a fundamental limitation (Figure 98). Although in some cases the whole façade system can react to changes in the boundary, a successful TSS design is one that can operate without distributing physical force to its adjacent parts.

Maintaining a self-boundary in a TSS design makes the system more expandable and scalable to different façade structures and different building scales.

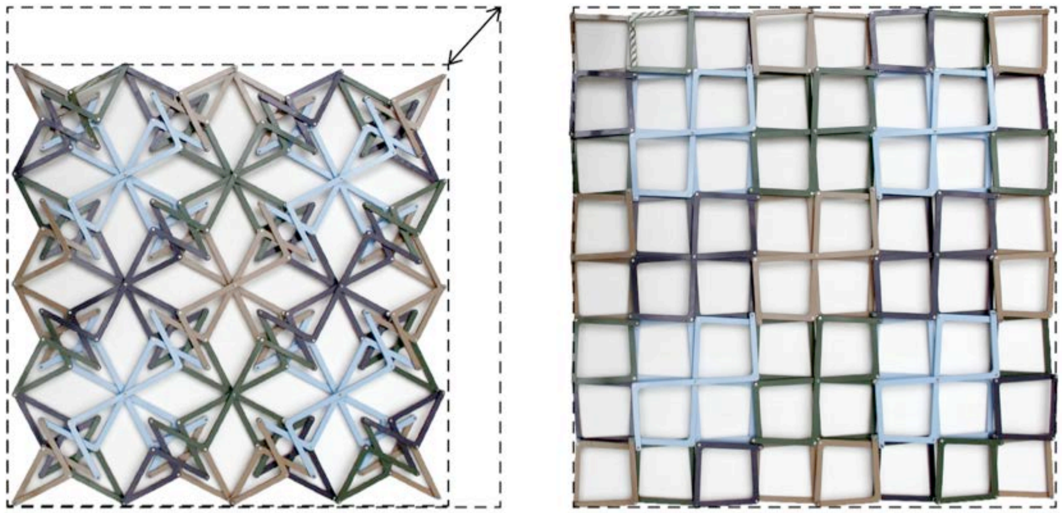


Figure 98: ANGULUG IV changes its boundary during operation.

In AURA's design process, there are different concepts that either can or cannot maintain fixed boundaries during the opening and closing process. For example, in ANGULUS IV, the boundary of the design changed according to the movement of the links (see Figure 98). Therefore, it was difficult to design a frame for this concept. There needed to be two railing systems to keep the mechanism on track, but the two other sides of the design remained free. Although this concept had very intriguing movement abilities, the changeable boundary was the biggest limitation to its being applied to a TSS. AURA VII is an example of a fixed boundary design (Figure 99). Besides structural framing, the fixed boundary provided the system with its expandability.

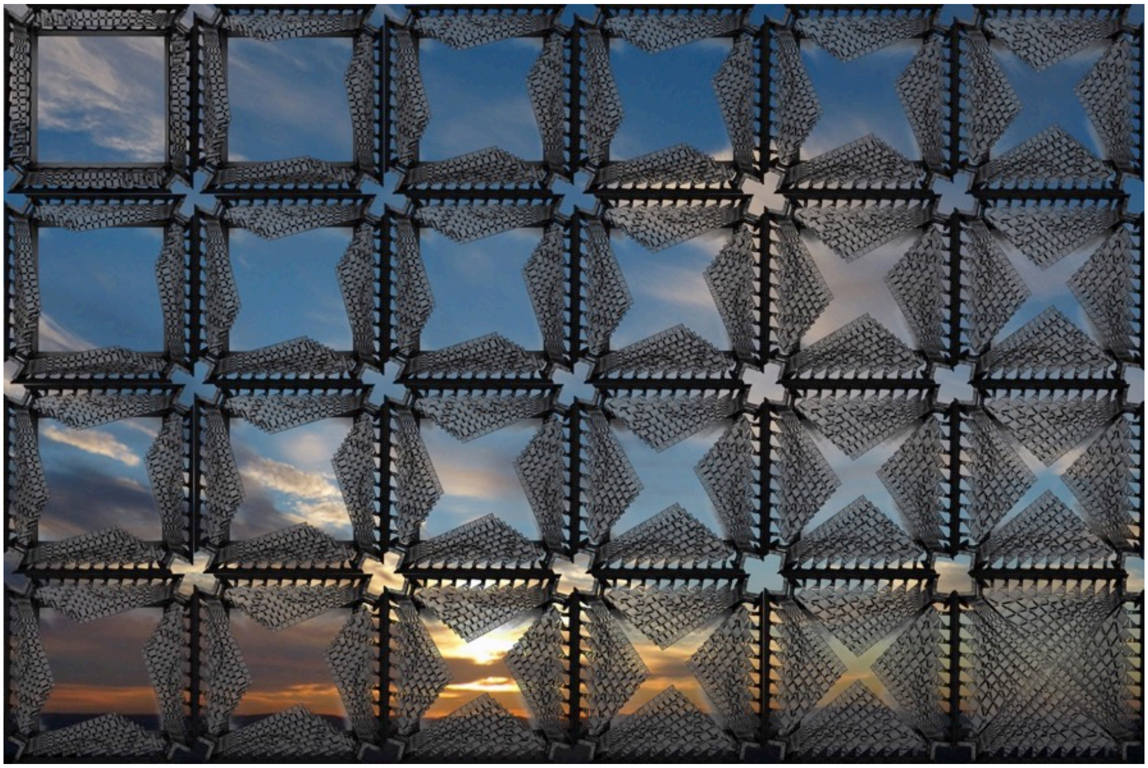


Figure 99: AURA VII's expandability allowed it to maintain its self-boundary during operation.

4.8.7 Focusing on the Geometry of Motion Rather than Algebra

Since kinematics is the geometry of pure motion, understanding geometry should be seen as fundamental to designing a kinetic system. Geometry is a branch of mathematics concerned with shape, size, and the relative positions of elements. For designers and architects, the visual nature of geometry initially makes it more comprehensive and accessible than other mathematical areas such as algebra. A graphical approach involves drawing of a series of kinematic diagrams that represent an alteration of the links in space.

In the TSS design process, the property of motion is well defined through CAD drawings and graphical constructive approaches. In this way, the movement of links and joints in a transformable shading device is translated into a set of abstract points and lines, the location of which satisfies a desired motion or stated condition. How the situation of these points and lines changes as the links move defines the characteristics of the shading device.

In the AURA design process conducted for this research, since most of the analysis of the proposed mechanisms depended on the geometry of motion, the primary focus was to study the underlying geometry of each. Here, a graphical approach was employed to clearly visualize the geometric relationship of the mechanism components during each stage of the transformation. The graphical approach was used extensively, not only to analyze the kinematic behavior of a single element, but also to find the motion of the whole mechanism.

To understand and design the underlying geometry of AURA's different models, the author benefitted from the graphical approach to geometry rather than an analytical or numerical approach. For each of AURA's specific design concepts, a series of kinematic diagrams were developed to find and visualize the best possible course of movement. In this research, the graphical approach involved preparing a drawing where all links were shown on a scale proportional to that of the actual mechanism.

There are three main elements in transformable design: linkage, joint, and point of connection (Myszka 2012). For the proposed transformable concepts in this research, the author first set up a graph of nodes corresponding to the joints and edges and conforming to specific constrains such as distance (spacing) and direction. Then, all fixed and movable joints were identified and differently colored. After observing the underlying geometry, the linkages were edited. Editing a linkage meant changing certain aspects of its geometry or motion, but preserving others. In AURA's design process, the most basic way of editing a linkage is to change the initial configuration of the link without displacing any of the joints (Figure 100). Using this approach, the author designed an overlaid assembly that matched with the initial kinematic design. To prove the functionality of the edited assembly, the author then checked the mechanism by moving its linkages in the CAD software so as to be sure about their course of movement.

Making a physical prototype was the second step in checking the movement of the proposed mechanism.

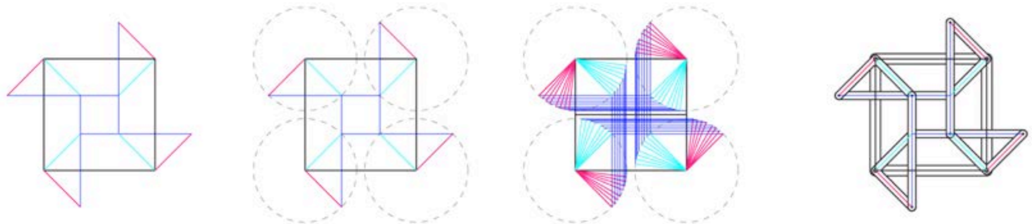


Figure 100: The graphical approach during AURA design process

Traditionally, the graphical approach has had accuracy problems; the result must be consistent with analytical techniques. However, the development of computer-aided design (CAD) systems has allowed the graphical approach to be applied with more precision. Rhinoceros and AutoCAD are the two main CAD systems used during the AURA design process. None of these platforms have the ability to check the motion simulation in their fundamental platforms; they can only draw highly accurate lines at designated lengths and angles. However, other constraint-based sketching modes in solid modeling systems (such as Inventor, SolidWorks, RhinoWorks, NX Unigraphics, and Creo) can be extremely useful in kinematic analyses. Geometric constraints such as length, perpendicularity, and parallelism need to be enforced when performing kinematic analyses.

4.8.8 The Collaborative TSS Design Process

In order to engage in the TSS design process, it is essential to consider the aesthetic, kinematic, and structural issues as integral parts of the design. A synergy among the architectural, engineering, computer, behavioral, and material sciences is needed to achieve a proper TSS design. Such synergy brings new forms of expression to architects, but it demands novel strategies from a new, interdisciplinary generation of designers, engineers, and builders capable of collaborating and exchanging knowledge. The development of concepts and designs related to transformable architecture should reflect the following:

- An initial multidisciplinary and multidimensional approach.

- Establishment of a multidisciplinary design team from the earliest stages to the end of the process (cooperation of all parties involved in the design, construction, maintenance, and use of the architecture).
- Understanding of the interrelationships among the different phases of the project by all parties on the design team; consideration of all of these aspects, from the earliest stages of the design process to manufacturing and construction, post-construction, and maintenance.
- Encouraging a close collaboration among all team members.
- Encouraging a general understanding of the other disciplines by every team member.
- Setting up a regular consultation and pursuing efficient communication with contractors, maintenance teams, and users throughout the design process.

4.8.9 Tolerance as Critical to the TSS Design Process

In the AURA design process conducted for this research, one of the main concerns was determining how wide the tolerances could be without affecting the outcome of the process. In the kinematic design process, designers usually work with exact dimensions. This is because design equations use precise values for the dimensions of geometric entities, and CAD design software offers designers the opportunity to work with exact dimensions.

Before a design can be fabricated, however, tolerances have to be specified because no fabrication process can create exact parts and no kinematic design can work without tolerance. Although engineering knowledge and expertise are needed to define this tolerance, the designer's personal experience is useful, as well.

In this research, models with higher numbers of kinematic pairs required the designer to pay more attention to tolerance. In some of the primary models, overly tight tolerances led to locking friction.

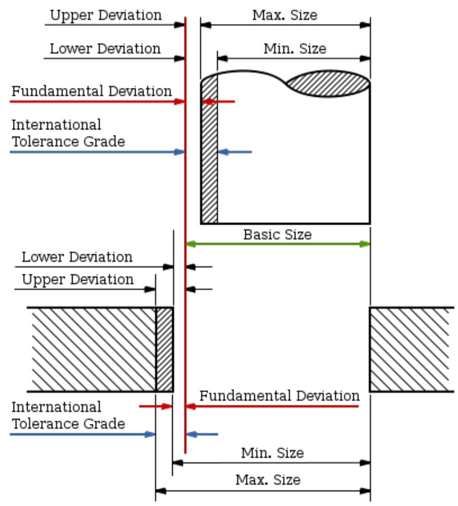


Figure 101: Summary of basic size, fundamental deviation, and IT grades, as compared to the minimum and maximum sizes of the shaft and hole.

Figure 101 is an important image for understanding tolerance and lower and upper deviation, which is essential for designing mechanism with pivoting connections.

4.8.10 Essential General Knowledge and Skill about Fabrication

General knowledge and skill about fabrication led the designer to the appropriate fabrication processes. In a TSS design process, the designer should know how and with what machines the design should be fabricated. Different processes have different limitations and specifications that cannot be ignored during the design phase.

4.8.10.1 Material Nesting and Fabrication

In the fabrication process, nesting refers to the process of efficiently arranging flat pieces (shapes) to be cut from a sheet of material for maximum efficiency and minimal material waste.[71] CAD software can help a designer create more compact nests and calculate enough gaps between parts. Although nesting is a general topic in the fabrication process, in the TSS design process it should be considered a design factor. During the design

[71] http://knowledge.autodesk.com/support/fabrication-products/learn-explore/caas/CloudHelp/cloudhelp/2016/ENU/Fabrication-UsersGuide/files/GUID-22A8AFAA-04E3-46E6-B8B7-35B3FF3B2405-htm.html

process for overlaid TSS patterns, a designer must make choices regarding the shape or size of elements that undoubtedly will save on material consumption. Sometimes small design considerations can noticeably increase material efficiency during the fabrication phase. However, to apply this type of consideration in the early design stages, the designer must understand the fabrication process and material specifications. For instance, knowledge of the available material sizes can guide the designer to the most efficient sizes for the TSS modules. Some designers make decisions about façade modules based on the building's dimensions; however, other factors (such as standard material size, fabrication tools, means and methods of shipment and installation, and the capacity and size of the storage area) can more sensibly help the designer determine the appropriate module size.

The fabrication process is another critical aspect in the TSS design methodology. In the AURA process conducted for this research, it became clear that the fabrication tools and their size limitations had a significant effect on the variables related to the proposed design concept. For example, the dimensions of the working area (or bed) of a CNC router or laser cutter is an influential factor that governs the dimensions and scale of any AURA prototypes (Figure 102).

If a designer seeks to change the scale of a model in a transformable design, they cannot scale the whole design up or down in the CAD software because all of the tolerances and gaps should be adjusted based on the specifications and constrains of the fabrication tools, regardless of the newly applied scale. Therefore, defining the right module size in the early TSS design stages can save a lot of time and prevent substantial phase redesigns and the recalculation of steps.

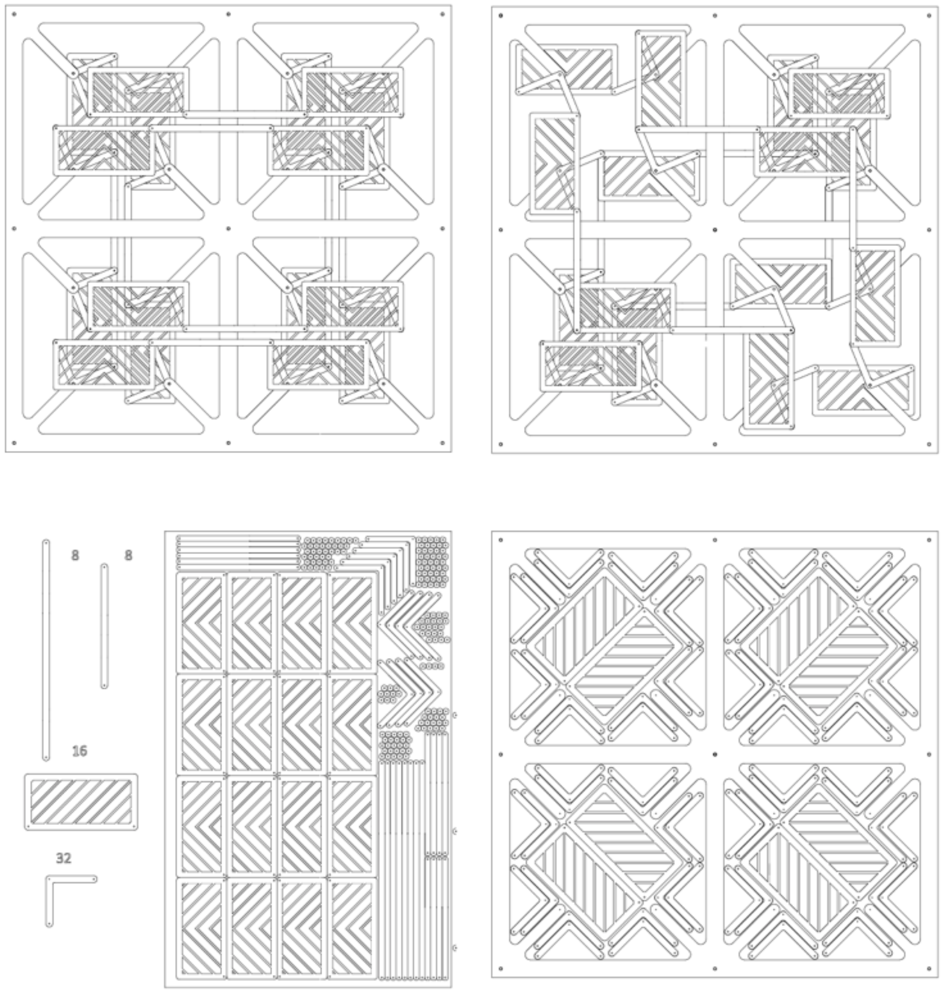


Figure 102: An example of nesting in the AURA fabrication process.

4.8.10.2 AURA's Fabrication Process

In AURA's design process, fabrication focused mostly on flat sheets of material cut with a laser cutter. In many cases, this limitation imposed certain restrictions. Unlike 3D printers or CNC routers, having different thickness of linkages are impossible when working with laser cutting machines. Thus, the linkages are mainly restricted to flat assemblies. However, there are always design solutions for such limitations. For example, in OCULUS I, to have different thicknesses, the designer laminated the layers of materials.

In design concepts such as SOL II (Figure 105), the joints could not be flat connections and instead needed to be at a certain angle. Since a 3D printer was not available at that time, the joint was a 3D assembly of different laser-cut pieces.

Figure 103: Providing different thicknesses by laminating layers of material.

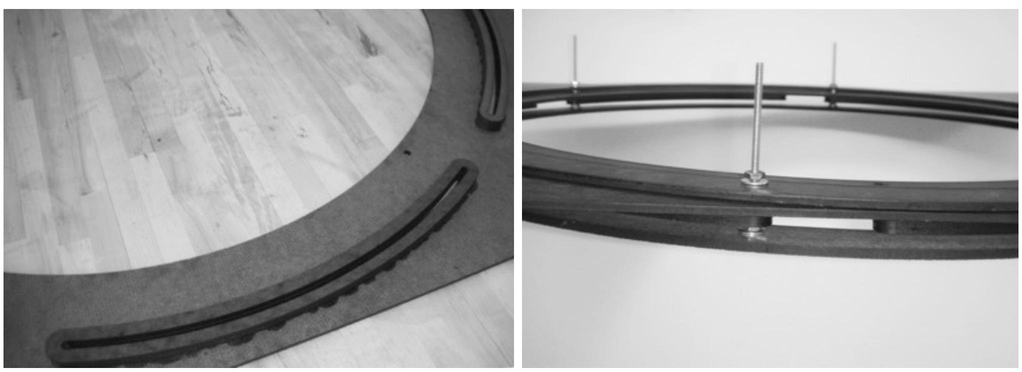


Figure 104: Fabrication process for OCULUS I. This model was fabricated by adding a few thinner layers in shapes cut by the laser cutter. If OCULUS I had been fabricated by a CNC router, its frame would have been made by subtracting materials from a thicker sheet.

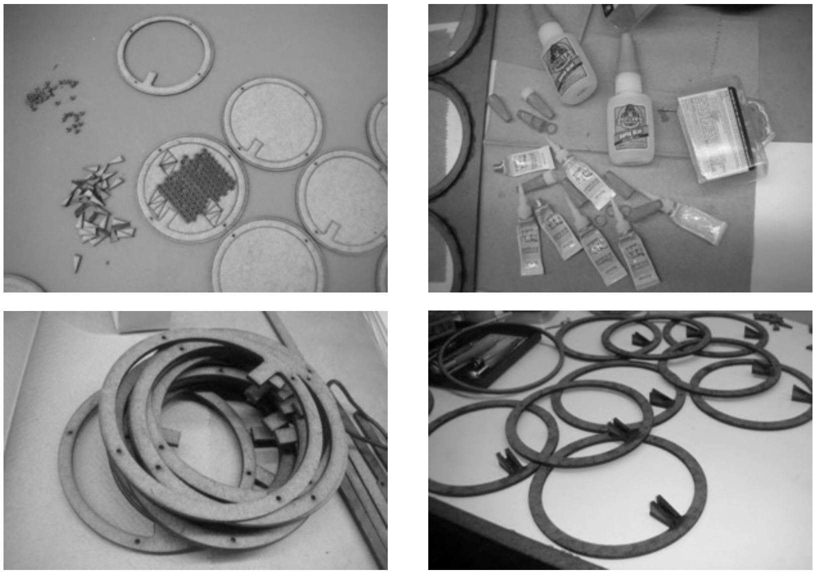


Figure 105: SOL II. In this model, the author made flat joints bent at a certain angle.

During the AURA design process, to avoid the complexity of drawing and assembly, the researcher tried to use the same size of screws (# 2-56 thread) but with different lengths. For the scale models, 2-56 thread was the most appropriate because length variations were available that ranged from ¼” to 1 ½”. For the AURA models, the following different lengths were used: 1/16”, 1/4”, 1/2”, 3/8”, 5/8”, 7/8”, 1”, 1-¼”, and 1-½” (Figure 106). With this strategy, one type of nut and washer worked for all of the screws. This made the assembly process easier and faster. Also, the fabrication drawings were less complicated because no attention needed to be paid to the size of the holes for the screws.

For some models, more layers of materials needed to be connected; therefore, longer screws were needed. Consequently, another type of machine screw (#4-40 thread) with different lengths of 1-½”, 2”, and 2-2/12” were used. Throughout the entire AURA model fabrication process, the author tried to use only these two screw diameters. After learning the tolerance of the laser cutter machine and adjusting the size of the holes accordingly, the same hole size was able to be used for all of the drawing files. This helped the researcher to avoid potential errors during the digital drawing and assembly process.

Figure 106: Sorting fasteners to facilitate the assembly process.

After cutting the pieces, the assembly process for the AURA models required a lot of attention and repeated checking. It was very easy to get lost in the pieces and layers. By scoring a code on each piece during the laser cutting and having the digital file open to check the relevant code for each linkage or layer, the author attempted to decrease the likelihood of error (Figure 107).

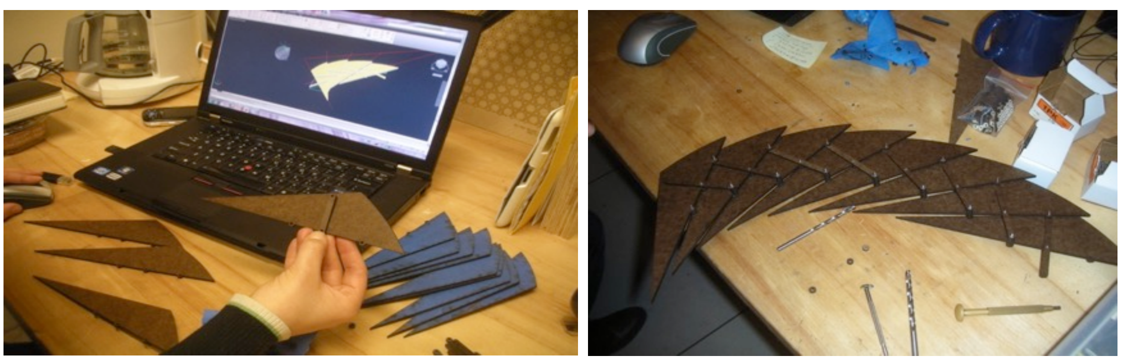
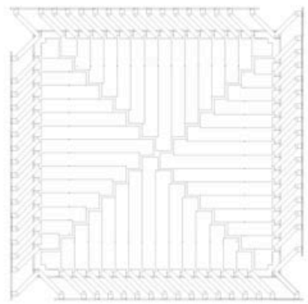


Figure 107: Digital files assisting in the assembly process.\

In more complex motion geometries (such as what was employed in AURA III, which had 68 different linkages and 132 joints), the assembly process had to be more organized and predefined. The best strategy was to arrange all of the cut pieces into different stacks and label them. Then, during the assembly process they were easily differentiable (Figure 108and Figure 109).

D 1III	Design Name: AURA III	Type of Motion: Rotation + Translation
		Number of Links: 68 (60 angulated links + 4 L shape links + 4 straight bars) Number of Joints: 120+12=132 Type of Joints: Revolute Number of Points of Connection: 64 Boundary of Design: Fix Parking Position of Movable Parts: the angulated links stack over each other inside the reference frame.

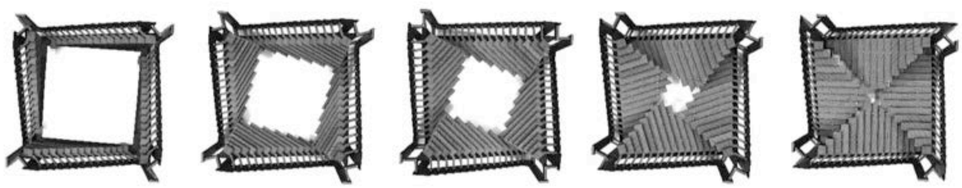


Figure 108: Numbers of linkages and joints in AURA III

Figure 109: Stacking pieces of AURA III into different clusters before assembly.

For instance, the assembly of the reference frame for AURA III required its own system of assembly. There were many pieces that went together to make the connection points ready for the fins and underlying motion system.

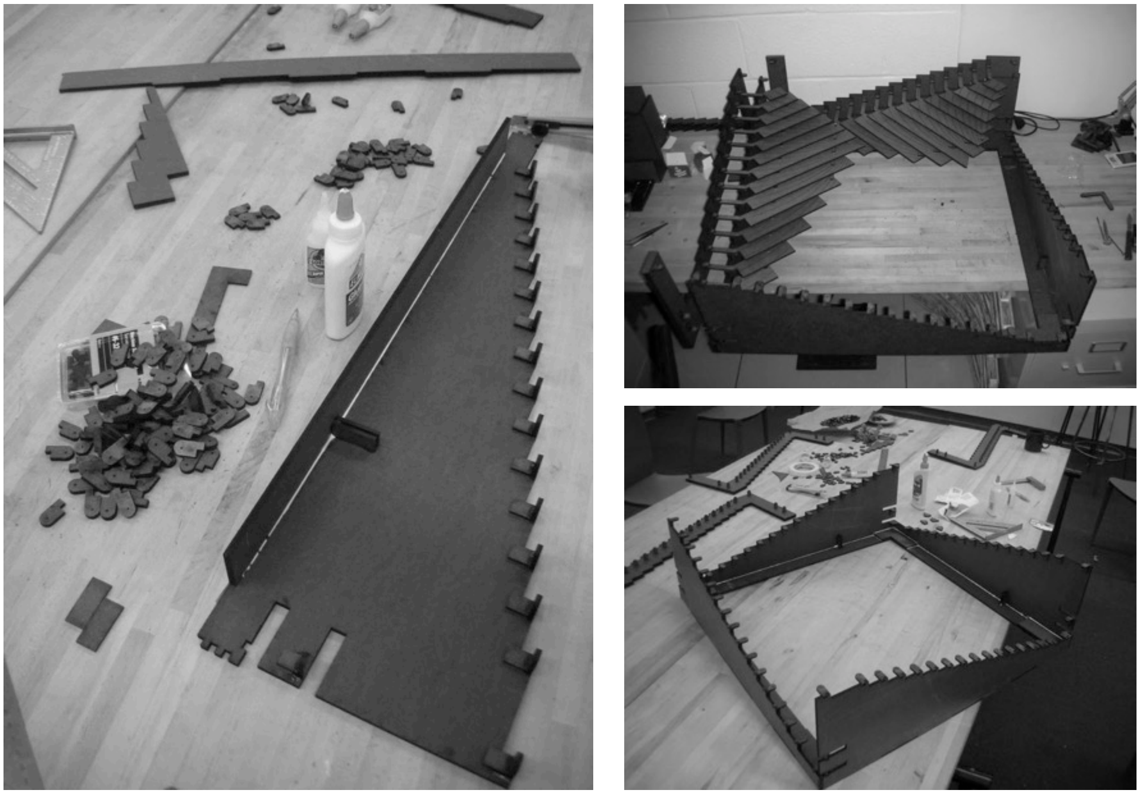


Figure 110: Process of assembly for AURA III.

After gathering and arranging all of the parts necessary for assembly, there were several steps necessary to complete the prototype:

1- Arrange the parts in order and label them;
2- Create an assembly diagram or plan;
3- Test the movement of parts after assembling them;
4- In the case of errors, check for mistakes along each step and when found, correct them; and
5- Put all of the sections together and test the integrated movement.

The next step to take after formulating a successful TSS design concept is to redesign it for manufacture and assembly. When designing for manufacturing, the main concern is to minimize the complexity of the manufacturing operation. When designing for assembly, the focus is to minimize the number of assembly operations. Both of these design stages should seek to reduce the material, fabrication, and labor costs.

4.8.11 Material Properties in the Early Stages of the Design Process

In the AURA design process conducted for this research, the following materials were chosen for prototyping: acrylic sheets, thin plywood, and hardboard-tempered panels. This decision was made after considering the specific fabrication constraints. These materials came as sheets that could be cut by a CNC router and laser cutter; these two machines were the digital fabrication tools most readily available to the author. These materials had the advantage of being rigid and acting as a strong linkage. Moreover, different thicknesses of the same materials were available on the market. As was mentioned above, this research focused on the design process of transformable shading systems designed for and fabricated from rigid materials. Therefore, this research did not cover flexible and elastic materials that might deform or deflect through the opening and closing process.

In a TSS, a rigid link is a structure whose shape and size do not change during movement. For instance, a rigid link might slide and rotate but never bend or snap under applied force. Thus, the AURA design process conducted for this research was derived from the selection of rigid materials that could transfer forces through themselves without being deformed. In AURA, rigid-body mechanisms consist of rigid links connected at movable joints. These rigid links transfer or transform motion and force. The UMBRA VIII design shown in Figure 111 and Figure 112 is an example that how a linear input can be transformed to an output that is the movement of eight perforated surfaces. Here, UMBRA VIII is a rigid body and all of the applied energy (neglecting friction losses) is transferred to the output links (parts).

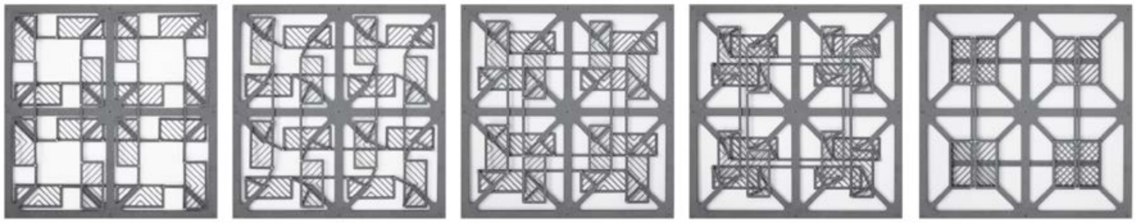


Figure 111: UMBRA VIII.

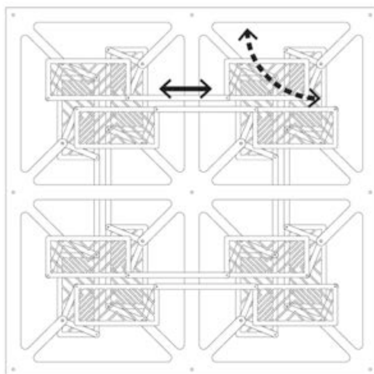


Figure 112: Energy transformation in UMBRA VIII.

4.9 Conclusion

In this chapter, the author shared the first part of her design knowledge-capturing process for a transformable shading system that was conducted through a self-immersive case study process. AURA's design process was the platform for design- decision research for understanding the design stages required for designing a transformable shading system and proposes a provisional model for a TSS design. The proposed provisional model was the result of more than 50 TSS design concepts and close observation of the whole design process. The design process of AURA was a process of creating a series of transformable shading systems and to discover how a particular set of combinations can be generated from a particular set of rules. The design process of AURA demonstrates that motion language is a set of guidelines for designers to understand the nature of motion studies and it does not reduce the complexity of motion to a set number of rules or formulas. Thus, throughout the act of designing and making, a number of different ways of addressing the key principles of motion geometry are investigated.

This self-immersive research was for understanding how motion studies can identify their relevant design parameters and clarify the structure of their design process. To conclude the chapter in the correct way, it is important to distil the essence of the geometry of motion through a design process. The main intention of conducting the design process of AURA is to understand the knowledge, skill and information that exchange during the design process of a TSS. The most important thing that comes out of the design process of AURA is to be able to look behind the given constraints and problems and how they evolve the final proposal. In this view, the TSS design process is generative rather than limiting.

- The main learning outcomes of AURA design process were:
- The Essential Loop Process of Designing and Making in the Early Design Stage
- Essential Interaction Between Physical and Digital Modeling
- Essential Nature of Working with Different Modeling and Environmental Software
- Essential Nature of Environmental Design Knowledge
- Essential Daylight Simulation Knowledge
- Essential Basic Kinematic Knowledge
- Essential Basic Structural Knowledge
- Focusing on the Geometry of Motion Rather than Algebra
- The Collaborative TSS Design Process
- Tolerance as Critical to the TSS Design Process
- Essential General Knowledge and Skill about Fabrication
- Material Properties in the Early Stages of the Design Process

AURA’s design process presents some of the challenges associated with designing, implementing, operating, and delivering transformable architecture. After a presentation of AURA’s characteristics, an overview of its motion generator was provided, followed by a discussion of the main lessons learned from AURA’s design process. Making those lessons visible when explaining AURA's environmental, operational, and technical attributes may afford a better perspective on understanding the possible challenges to and opportunities provided by transformable design. To this end, the ultimate goal of articulating the steps in AURA's design process and their various outcomes is to create a heightened understanding of the issues faced by an architect designing a transformable system.

Although specific challenges are associated with each transformable design project, the general challenges the author faced in developing AURA were divided into the following main categories:

- Reliability (including mechanism design and operation);
- Controllability (such as working with appropriate tools and proper software to design and simulate);
- Maintainability (such as preventing unexpected breakdowns);
- Testability (including prototyping, fabrication, and assembly challenges);
- Availability (including procurement of materials, supplies, hardware and accessories, logistical delays, the availability of spare parts); and
- Time management.

Handling these challenges required knowing what they were and having a plan for dealing with them (organized according to the potential of the challenge). To minimize the need to confront challenges during future AURA implementation phases, a considerable amount of time and effort was spent on the design development process.

Through each step of the design development cycle, many different concerns were at play, ranging from small details such as joints and profile cross-sections to overall structural integrity, mechanical behavior, and environmental impact. The following design variables – along with their relative visual, technical, functional, and environmental impacts – were considered for developing each AURA motion generator:

- Type of joint;
- Number of joints;

- Number of links;
- Size of links (small, medium, or large);
- Orientation of links, along with reference frame (vertical or horizontal) and oblique axis;
- Profile of links (inside chamfer, outside chamfer, straight);
- Volume of links (two- or three-dimensional);
- Type of links (regular, segmental); and
- Porosity of links.

By developing each basic motion generator in AURA's design process, the author's effort was directed toward identifying and articulating the maximum possible number of iteration scenarios to reach their convergence in the foremost design solution. By changing the values of the design variables associated with each motion generator (such as the number of links and joints, or the distribution, orientation, size, and profile of links or joints), it was possible to generate different iterations that derived from the same organizational logic.

The design possibilities of each motion generation were explored by alternating different variables in order to lead to unexpected but intriguing results. As the AURA design process progressed, most of the iterations were easily incorporated into specific categories. In some cases, it was not easy to classify a new iteration into an exact category, based on its original motion generator.

Each motion generator focused on creating the general framework necessary to build several design iterations. Occasionally, despite a recognizable core, the external appearance of a motion generator was transfigured into something unfamiliar.

In the AURA design process, each motion generator was, and still is, developed through a series of iterations of feedback information on the whole design process. Each of these iterations encompasses the entire process, from conception to completion. The sequential continuum of different iterations are aligned based on their underlying geometry and original motion generator.

The chapter showed the reader through the design evolution of AURA from its humble inception to the emergence of the final form. As the chapter documented the sequential design development of AURA from a seed idea through the fabrication phase, it gave the readers a chance to delve into the richness and vibrancy of the multi-layered design process of the integrated dynamic shading system.

This chapter strived to trace the relationship of internal and external factors that contribute to crafting a motion composition such as AURA. By drawing parallels and comparisons among different AURA prototypes and disclosing how the author could manipulate the bounds and constraints of each,

this Chapter explored new agendas for generating environmentally-informed forms through the interaction of force, geometry, and motion. The design concept of each AURA's iteration was derived from motion geometry informed by sustainable design principles. To add up to the geometric advancement, visual complexity, and choreography of motion that AURA entails, its underlying geometry must continue to become more and more intricate. Being two- or three-dimensional in its shape and position, the underlying AURA geometry is limitless in its possible visual outcomes and creates a pronounced aesthetic.

The AURA design process strives to create intricate geometric works; both the underlying geometry and overlaid pattern of AURA's models are perceived as completely structurally dominated by some level of geometric complexity.

The lateral or radial movement of overlapping elements causes many arising and decaying geometric shapes that evolve into beautiful patterns. Although the way in which AURA's overlaid geometry represents itself is intricate in detail, its underlying geometry remains strictly simple in its principles.

No matter what the final form was, the underlying geometry of each prototype resided in the space between the performance and fabrication limits. Playfully challenging the limitations of a myriad of opportunities to witness how the author could orchestrate all different aspects of the design concepts, this chapter attempted to exemplify a comprehensive transformable design methodology

AURA as a transformable shading system predominantly operates throughout time, and is able to alter the beholder's perception of time depending upon the amount of change of position before and after a movement.

Since AURA's design process mainly concentrates on exploring transformable surfaces as shading mechanisms, it slowly moves to provide a maximum amount of shade. In terms of AURA's motion components, several shapes that are merged seamlessly into one another cause AURA's appearance to progressively increase in visual complexity. In front of one's visual field, the ever-shifting patterns created by AURA are not random in their appearance and are comprised of consistent, semi-predictable forms. Building on the goal of continuously changing its direction from sunrise to sunset and from spring to summer, AURA addresses the dynamic characteristic of living places.

In the next chapter, the author will focus on the second part of her design knowledge-capturing process for a transformable shading system that that operated through an educational peer review (two design studios).

5 Chapter 5: **Knowledge Capturing in Design Studios: To Test And Refine Provisional Design Process Model For Transformable Shading System**

5.1 Introduction

To bring transformable architecture forward, the question is the extent to which the profession of architecture is in need of support from architectural education. While complaints about the declining quality of kinetic architecture and the poor performance of its movable elements has drawn urgent concerns on issues such as the lack of proper education for architects, it is essential that such discontents be addressed by looking deeply into how the structure of schools of architecture can overcome the gap between educational production on the one hand, and the formidable reality of the practice of transformable architecture on the other.

The relationship of the practice of architecture to the education of future architects is still deeply contested. The failures and malfunctions of existing transformable buildings are blamed not only on their designers, but also on what is being taught to architecture students to prepare them as qualified designers of such buildings. In addition to the existing knowledge currently offered in schools of architecture, this chapter investigates the kinds of knowledge that should have priority as new curricula, designed to empower future architects to properly design and apply motion to their buildings.

Contemporary activities in architecture education are evidence of a lack of a holistic approach to the study of motion in architecture, and the design of motion as an alternative mode of design thinking is still in its infancy. Consequently, the existing approaches should be reevaluated as a pedagogical strategy.

Despite this interest in expanding and revising architectural education, a substantial body of evidence indicates that several key topics have yet to be tackled. Drawn to themes of change, fluidity, and movement, some educators have for years demanded reform in this area. Although to some extent transformability in architecture has given rise to a new debate about the education of architects, the discussion has yet to offer a common framework for the future of architectural education. The main question is if education can offer a core of transformable knowledge to aspiring architects and if so, how this knowledge should be introduced such that it initiates a new kind of awareness about motion studies to the extent that a new pedagogical circle and design practice is born.

Despite a growing interest in the emergence of novel research into motion design, little material has proposed clear guidelines for the design of motion in architecture, and especially for the education of future architects. By provoking a reassessment of the conventional pedagogical approaches to architectural education, this dissertation explores the potential of a new pedagogical model called the Pedagogy of Motion for architecture students that incorporates motion studies into existing curricular structures. This cross-disciplinary educational approach will be of significant value to the general pedagogy of architecture. The description of such pedagogy and its advantages to architecture programs is the subject of this chapter (Kalantar and Borhani 2015).

To explore the potential of this pedagogical model, the pedagogy of motion provides a methodical series of steps regarding the best methods for teaching the principles of transformable architecture. The development of this pedagogy could recast the architectural design process, transmuting the landscape of how we do architecture (Kalantar and Borhani 2016b).

This chapter provides the basis for a discussion of movement's place in architectural education. Mapping the author's journey over the last five years in order to address the necessity of and methods for educating architects in design movement through time and space, this Chapter explores motion-based design activities in architectural education and identifies key pedagogical elements and characteristics for teaching future architects the principles of motion design.

As vehicles for examining the opportunities of the Pedagogy of Motion, two design studios in two schools of architecture at Virginia Tech and Texas A&M University were offered, occasioning theoretical overviews and practical methods for designing morphological changes in architecture(Kalantar and Borhani 2016b). In these studios, the central theme of transformability in architecture came into focus through different workshops, lectures, and reviews. Beyond taking advantage of the author's sixteen years of design research in this area, this Chapter scrutinizes the pedagogical advantages and restrictions of these two transformable design studios.

Teaching these studios prompted several pedagogical considerations that are discussed in the final section of this Chapter. Moreover, suggestions are made as to the ways in which the existing motion-related courses can elucidate the language of motion formation inherent in the Pedagogy of Motion, thus facilitating academic competency in transformable architecture.

5.2 Design Studio in Transformation

In the context of architectural education, it is critical to acknowledge that the pedagogies of architecture are altering. In recent years, the professional ecology of architecture has diversified to include emerging intellectual shifts and technological advances. By paving the way for more progression in computational modeling and simulation, innovative fabrication methods, and responsive agent-based systems in the profession of architecture, many of these advancements also seem to be woven into the fabric of architectural education. Most of the above-mentioned advances are associated with significant improvements in motion-based architectural designs, and therefore have provided the opportunity for transformable architecture to be at the forefront of architecture's pedagogical alteration.

Although motion has long been part of the architectural repertoire of 20th and 21th century, but little thought has been given to motion studies in architectural education and the existing tradition of static forms is almost the sole type taught in schools of architecture (Kalantar and Borhani 2016a).

Within contemporary architecture, there is a growing need for students, academics, professionals, and practices to create adaptive designs, building components, and architecture that changes the quality of space and the connection humans have with their environment. Concurrently, the convergence of innovations in areas of advanced fabrication, rapid prototyping, and robotics, combined with an increased exposure of architects to a new generation of physical computing and interactive media, provide many new possibilities for the design and utilization of transformable architecture as a regular element of the built environment (Kalantar and Borhani 2015).

While there is a growing opportunity and demand from the professional body to exploit transformability, very few schools of architecture have taken the initiative to make their students ready for the changing needs of the profession. Among these schools, very little time is being spent on teaching transformable architecture. Consequently, the impact of motion-based courses in the education of future architects is still impalpable.

Although an expansion of the notion of transformable architecture is evident, the question remains how to direct the future of motion studies in architecture schools, and extrapolate the existing knowledge into a future vision for architectural education. This is not to say that there has been only a minimum effort made by architecture schools to address transformable design principles. It is, however, clear that there are few comprehensive frameworks or guides that illustrate a pedagogical scaffolding that would properly instruct students in learning transformable design.

The lack of comprehensive guidelines (Moloney 2011) and education in the field of transformable architecture proves a challenge to the use of motion in architectural creation, as well as to determining its influence on architectural form (and particularly, on beginning designs). Accomplishing a wide acceptance of transformable architecture is dependent upon schools of architecture incorporating its study into their curricula.

5.2.1 Why Students Should Learn the Principles of Motion Design

Motion, as the essence of all being, should be more prominent in architectural education. Exploring the nature of time and sensing the environment created by time are practices that should be integrated early on in the design process. Currently, architectural education's relationship to motion is typically posed as a battle against the paradigms of stasis.

Although the existing tradition of static forms is the singular ambition of most architectural education, a student’s ability to harness valid design modalities and ascertain their relative values is directly tied to their breadth of experience and knowledge about both static and dynamic forms. As a pedagogical strategy, the introduction of transformable architecture is critical to students' ability to develop a greater level of conceptual rigor and expand their ways of seeing and practicing architecture.

Direct, hands-on engagement and active participation at every stage of the transformable design process will not simply alter the way students design, it will provide an extension to their thinking and produce in them a wholly new method of concrete design thought. In this case, the use of motion will be a new avenue into design culture, rather than just a design in itself.

While it is important to know what design educators should do[72] and how they should do it, it is equally important to accept that what they need most is a more profound understanding of the subject they teach. This is especially true in light of the rapid rate of technological, social, and economic evolution seen today. For instance, architectural education should address the field's growing interest in kinetics and how that interest will affect the way architectural education equips students to comprehend the concept of transformation in architecture and learn to employ it in their own work.

5.2.2 Towards a Pedagogical Approach for Practicing Motion

For far too long, the education of future architects has – with rare exceptions – been conceived of as the creative effort behind static buildings frozen in time; this notion has isolated students from their world. Future architects are still predominantly educated to build outside of time. Intended to remain static, students' building proposals are expected to dispel the workings of time. In other words, architecture students, as designers of future buildings, are trained to be less intolerant of the future and changes to their designs.

Architectural education should acknowledge the positive aspects of change-oriented approaches, and thus help students design buildings that are connected to place and time;

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[72] This would include a range of activities, such as motivating students, setting tasks, addressing problems, facilitating the learning process, and evaluating progress.

embracing the inseparable link between these two concepts will lead the field to the much broader notion of building-in-time (Trachtenberg 2010).

Due to a lack of experience in predicting the behaviors of an object in motion and sufficient background in kinematics, most architecture students face difficulties in designing the desired mechanisms for their projects. To recognize how these mechanisms should work, novices are mainly forced to use the trial and error method, which is time consuming and laborious.

The lack of clear guidelines makes it difficult for design students to imagine, design, and fabricate their motion-based concepts. Since the knowledge concerning motion design principles exists but is spread across many disciplines, the question is how to fuse the necessary knowledge that has been collected by various fields in order to generate motion design guidelines for architects.

Teaching and learning the principles of motion design should be a multifaceted process. Spontaneous courses, workshops, and activities are not adequate to systematically bridge the distance between the existing structure of architectural education and the reality of motion-related practice.

Despite its addition of a few motion-related courses and certain marginal modifications, architectural education should be criticized for creating architects who do not know how to design and apply motion in their architecture. At this juncture, it is important to make visible the pedagogical methods and content of the various motion-related courses. To fully understand what architectural education in the field of transformable design should entail, a platform for discussion about the total spectrum of motion-related courses is required. The goal should be to help educators address their challenges, share their knowledge, and explore opportunities for cultivating the notion of motion in design education.

By proposing changes in architectural education and raising questions about the impact of existing motion-related courses, this dissertation aims to set a base for this much-needed scrutiny. After determining the content and direction of current motion-related courses, this Chapter will offer a pedagogical method for teaching motion.

5.3 Motion Pedagogy

Pedagogically speaking, within the context of design studio activities, it is necessary to investigate the significance of transformable architecture across the breadth and depth of architectural education. Educational methods that introduce motion into the design process in its early stages are rare, and verge on nonexistent. Here, the concept of Motion Pedagogy(Kalantar and Borhani 2013) as an educational approach to a comprehensive transformable design methodology for promoting physical and behavioral transformability in architecture has been established and employed to structure this dissertation. The author offers this pedagogical system from the perspective of having worked for sixteen years as a designer and educator of transformable architecture.

In an attempt to circumvent the challenges inherent in designing motion, the Pedagogy[73] of Motion imparts knowledge,[74] content, skill, and know-how to future architects in an effort to open their minds to the possibilities offered by adaptable architecture.

The Pedagogy of Motion is a methodical series of iterative steps that a novice designer can use in thoughtfully adapting motion design principles to meet a stated objective. Among the fundamental elements of the Pedagogy of Motion are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.

With a goal of providing certain fundamental and generic guidelines to architecture students, transformable design pedagogy provides a path to achieving knowledge about the conception and realization of motion in architecture. By acknowledging the presence of motion from a small scale (including every detail and joint) to full scale (encompassing the whole structure), transformable design pedagogy casts light on how a concept of motion can be oriented toward shaping a better environment. This pedagogy emphasizes the simultaneous experiencing of environmental response and the application of conceptual kinetic mechanisms.

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[73] In the American Heritage Dictionary of the English Language, pedagogy is defined as "the art or profession of teaching."

[74] Based on the definition provided by the National Board for Professional Teaching Standards, pedagogy refers to the teaching skills that teachers employ to impart the specialized knowledge or content of their subject area(s). See http://www.nbpts.org/

To advocate for the potency of motion design insight and foster a complex fabric of new relationships that both directly and indirectly impact design decisions across the spectrum of transformable architecture, the Pedagogy of Motion endeavors to create a better understanding how an exploratory concept of motion can be codified to suit different technical, economic, and cultural considerations. For instance, the pedagogy of motion aims to strengthen the correlation between forms of motion and the means and methods of their fabrication.

The pedagogy of transformable design includes a methodical series of steps regarding the best and simplest methods for teaching the underlying concepts and core principles of motion design. These steps tend to emphasize that motion can be a continuous process of change in space, form, function, size, color, texture, and degree of openness that can be used to modify light, view, sound, temperature, and air quality

5.3.1 The Impacts of Motion Pedagogy

By modifying the obstacles of conventional pedagogies in architecture, the pedagogy of transformable design can be considered an alternative pedagogy for a generation of more responsive forms. By providing a deeper insight into the concept of change as it relates to design and architecture, the pedagogy of motion can be directed toward a new territory of design that introduces new forms of knowledge that are essential to the education of future architects. This knowledge can be obtained through direct interaction with movement.

Confronting the engineering, environmental, and spatial challenges of transformability, the Pedagogy of Motion aims to cast light on how an exploratory concept of motion can be oriented toward shaping a better built environment (Kalantar and Borhani 2016b). Motion pedagogy is founded on the premise that the built environment is a dynamic, rather than static, system. Therefore, the way we design architecture should be changed (Peters and Peters 2013). The development of pedagogy of transformable design as an alternative method of architectural thinking could recast the architectural design process and transmutes the landscape of how we do architecture.

By providing multifaceted transformable design experiences that develop over time to suit different circumstances and requirements, the pedagogy of motion enables designers to consider the use of motion as a strategy in design, rather than just a design in itself.

Since motion's interaction within architecture presents a new form of educational alignment, the development of motion pedagogy highlights a shift in the overall direction of architectural education. As a step towards addressing this transformation, this pedagogy could directly affect the core of architectural education and influence the formal and informal learning objectives established by schools of architecture.

5.3.2 Principles of Motion Pedagogy

As discussed above, several motion-related courses have been dedicated to developing the potential of transformable design. Unfortunately, though, they have focused on what education in the field of motion is about, or how it should be addressed. It is essential to determine ways by which future architects can obtain the knowledge required to design transformation. In order to establish the content of motion pedagogy and measure its major impacts, there is a need for a clear consensus on how students should be educated to incorporate the principles of motion design in their work environment.

In the Pedagogy of Motion, two main questions should be addressed:

What should beginning design students be taught, as they begin designing and applying motion to their architecture?

How can this subject be taught so that the stored knowledge in learners' memories is accessible when and where it is required?

Motion pedagogy demonstrates essential subjects for early designers eager to understand transformable architecture. The primary goals of the pedagogy of transformable design are twofold. First is to reveal the internal structure of the language of motion formation by exploring physical shape-finding methods. Second is to explore ways of observing how buildings or their components might move by fostering an active engagement with designs that are adaptable to change.

Motion pedagogy needs to be brought into architectural education with the mission of disseminating motion language. By engaging the vocabulary and syntax of motion language and manipulating their bounds and constraints, the Pedagogy of Motion views this language as expansive and containing insightful and practical guides to the motion design knowledge especially important to architecture students.

There are at least five preliminary overlapping phases that must be considered by a designer of transformable architecture. These include: (1) inspiration/ideation, (2) design development/verification, (3) actualization/fabrication, (4) operation/control, and (5) maintenance (Asefi 2010). From among the above-mentioned phases, the inspiration/ideation and development/verification phases should be emphasized to beginning designers. For these designers, the first two phases should embrace the following aspects: (1) introducing the typologies of motion based on a choice of rigid or deformable materials, (2) designing and refining the geometry of movement, (3) explaining the desired impact of the motion by changing the space, function, form, or size, (4) developing iterations based on possibilities, and (5) designing components and details.

In general, by identification of the major decision–related nodes in the process of transformable design, a pedagogy of transformable design could have the following learning outcomes for architecture students:

Offer a theoretical overview and practical methods for a creative engagement with new ways of thinking about transformation itself as a design parameter;

Offer principles, theories, and applications that govern creative thought processes from the formation of motion through the creation of the physical environment;

Deliver a fundamental base and practical knowledge of transformable systems/strategies in building components;

Explore the capabilities and limitations of transformable architecture;

- Provide a hands-on understanding of various modes of physical behavior, control, interaction, and actuation (whether through manual interaction or controlled motorization);

- Present new classes of objects capable of self-transformation by using a number of analog and digital fabrication machines; and
- Provide a hands-on familiarity with CAD software to produce simulations and animations.

Specifically, a pedagogy of transformable design for beginning designer in the field of motion will have the following advantages:

- Provide an understanding of transformable design parameters, such as kinematic, material, and behavioral;
- Offer an understanding of the vocabulary and syntax of motion language;
- Allow students to be more familiar with the concepts of underlying and overlying geometry as major sub-syntaxes;
- Provide opportunities for hands-on experiments and prototyping (digital and physical) as a part of the design process and design thinking;
- Facilitate an understanding of assembly as a process;
- Provide an understanding of the relationship between the whole and the parts by encouraging the design of proper details and considering appropriate levels of precision; and
- Allow students to become familiar with the iterative process to generate a set of possibilities out of fixed rules.

The pedagogy of motion establishes different horizons related to the education of a beginning designer. The followings are two considerations about motion study in schools of architecture that should be explored by motion pedagogy:

- Students should understand what they know about motion, and realize what they don't.
- Students should be asked to incorporate movement into their designs in order to explore the nature of time.

The Pedagogy of Motion reorganizes the trajectory of architectural education into the following approaches:

- Transformable design is a multi-disciplinary endeavor, highlighting reciprocity among art, design, science, and engineering.
- The goal is the integration of information, knowledge, and skill.
- Environmental studies have a profound impact on motion pedagogy.
- Prototyping is a way of knowing and knowledge gathering.

5.4 Transformation in a Design Studio: A Description of Two Transformable Studios

As discussed, in spite of a growing interest from designers, academics, and theorists in recent years regarding the applications of transformable architecture, it is not yet generally taught in architecture schools. Since the majority of architecture educators tend to treat buildings as static objects, today motion-related courses are barely a minor branch of many design curricula. The dominance of static-based courses is largely responsible for this marginalization of motion-based instruction. Except for in a few institutions, courses on transformable architecture are not available alongside other architecture courses, and there are less courses for design students that address a comprehensive transformable design methodology. Students are often at a loss when asked to design motion, and currently there is not sufficient evidence to determine the consequences and impacts of the establishment of a motion design process. For all of the reasons stated above, motion pedagogy should be integrated into the studio environment.

Figure 113: transLAB – 4th year studio – Virginia Tech University- Spring 2014

Figure 114: tranSTUDIO – 4th year studio – Texas A&M University– Spring 2015

In the spring of 2014 and 2015, two transformable design studios called transLAB[75] and tranSTUDIO at Virginia Tech and Texas A&M University were offered to fourth-year architecture students (Figure 113& Figure 114).

As an academic and experimental research platform, both studios were a new initiative in response to the emerging demand for adaptability and the lack of instructional design knowledge and skill seen in architects exploring the potential of motion in their architecture. On this occasion, the author described her own journeys as a designer and educator in the field of transformable architecture, creating and witnessing the emergence of new, transformable-based designs.

[75] transLAB was co-taught by Negar Kalantar and Chip Clark.

tranSTUDIO, still evolving, attempts to follow the premises and outcomes of the 2014 transLAB. As a developmental and progressive approach to addressing transformable architecture, tranSTUDIO's pedagogical structure recognizes the diverse and changing needs of the transformable design process. tranSTUDIO has tried to leverage the complementary strengths of mechanistic- and electronics-based motion design approaches, effectively eliminating the limitations of both.

In both studios, there was the hope that students would tune in to the experiences associated with the presence of motion. In the best interest of the students' long-term professional lives, these studios attempted to bridge the lack of understanding between static- and motion-based architectural educations. The expected outcome of the studio's blurring of the boundaries between these two approaches was the incorporation of motion into students' ways of thinking, and the elimination of the clear gap in knowledge in the area of transformable design and related design contexts, relative to the education of future architects.

By inspiring new avenues in the exploration of transformable design pedagogy, these design studios attempted to expand the current domain of transformable architecture to a broader perspective of architecture pedagogy, and contributed toward adding value directly into the content of the curricula, and thus into the field of design education as a whole.

In general, both transLAB and tranSTUDIO acted as laboratories for creative interactions, with curricula infused with transformable design principles and performed as an indispensable mediator in reifying the Pedagogy of Motion. Specifically, transLAB became a testing ground for the pedagogy of transformable design, bringing forth the opportunity to examine the concept of transformable design pedagogy within the context of an accredited architectural program.

transLAB-2014 had eight students and tranSTUDIO had fourteen students. The two following diagrams represent the gender distribution of students in both studios (Figure 115 & Figure 116).

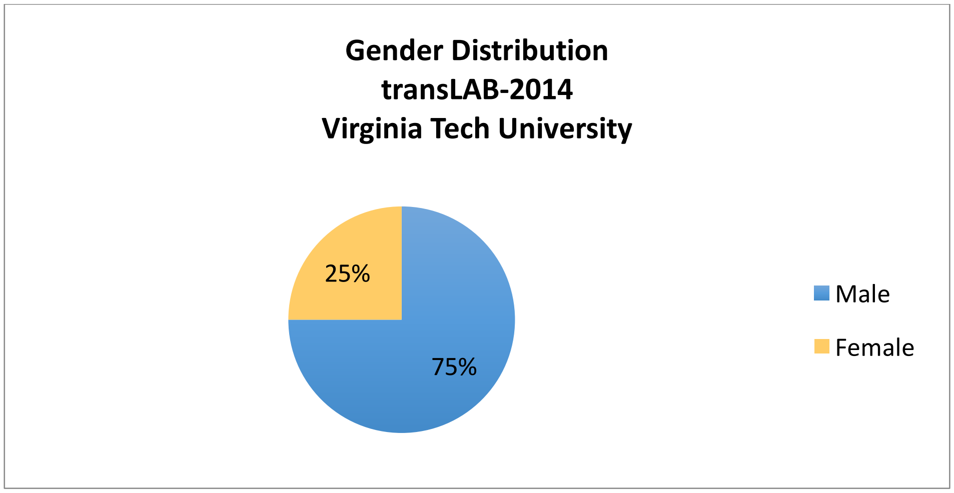

Figure 115: Gender Distribution in transLAB (transLAB-2014 had eight students).

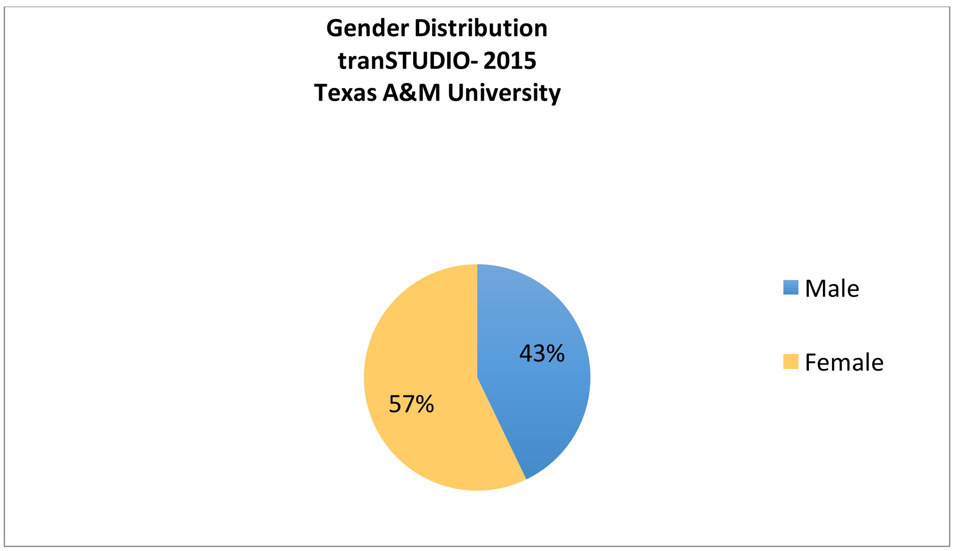

Figure 116:Gender Distribution in tranSTUDIO (tranSTUDIO-2015 had fourteen students).

Based on the primary surveys conducted in the two studios, none of the 22 students in attendance had been exposed to the design process or methodology of transformable architecture. The following diagrams demonstrate the level of students' exposure to the principle of transformable design in both transLAB and tranSTUDIO (Figure 117 &Figure 118).

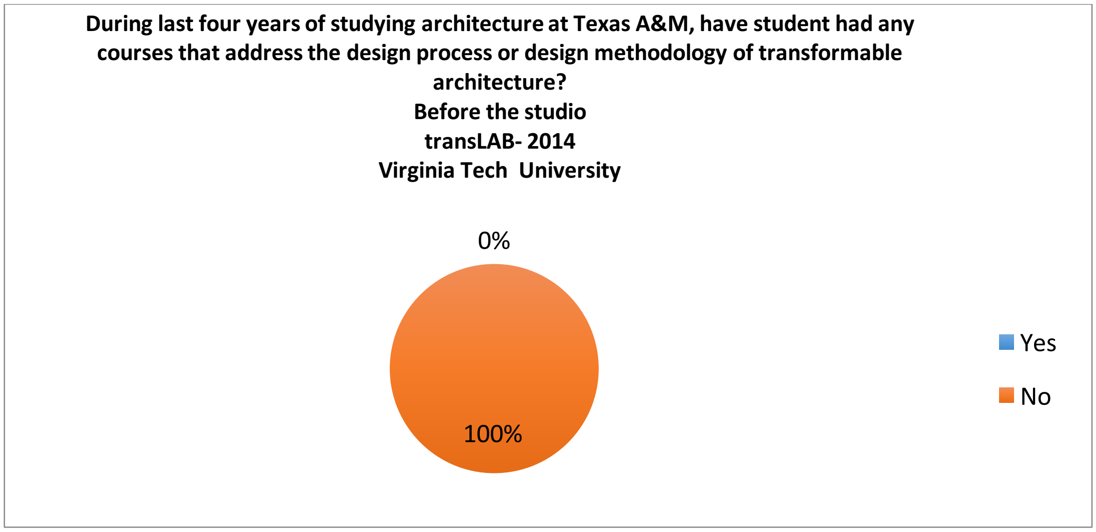

Figure 117: Student Exposure to the Principles of Transformable Design before transLAB-2014 (at Virginia Tech University).

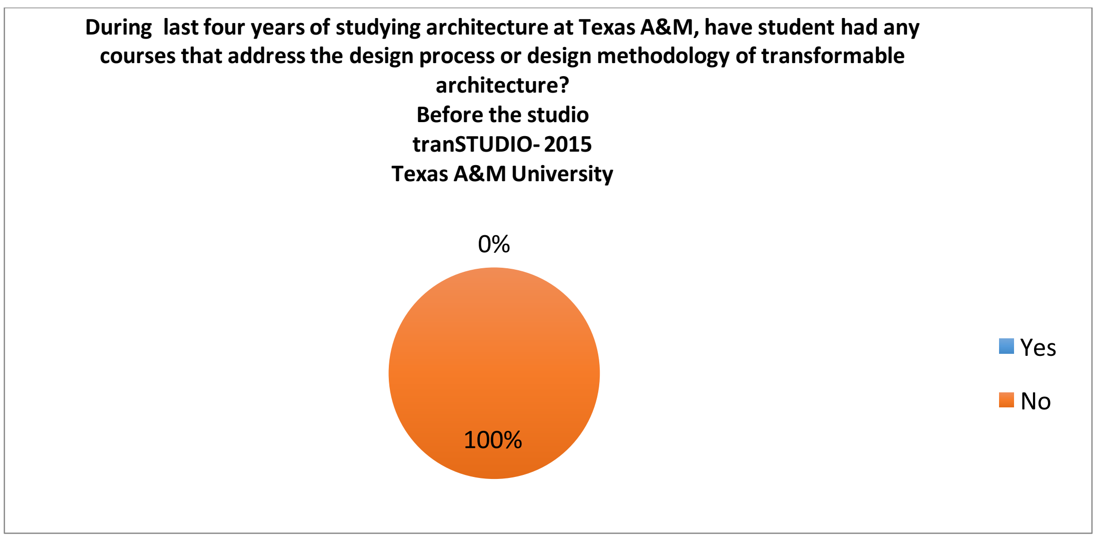

Figure 118: Student Exposure to the Principles of Transformable Design before tranSTUDIO-2015 (at Texas A&M University).

These surveys helped the author as an instructor understand students' levels of familiarity with the topic of transformation in architecture. Although more than 30% mentioned that they were not very unfamiliar with the principles, factors, and decisions governing the transformable design process, two other questions (querying if during the last four years of their education they had been educated about the transformability of design or had ever designed any transformable architecture projects) clarified that 0% of students had any educational experience with this topic. Based on the detailed descriptions offered by students, the 70% who felt themselves to be familiar with transformable design attributed this familiarity to a cursory knowledge of architects such as Jean Nouvel, Diller Scofidio Renfro, Olsen +Kundig, and Santiago Calatrava. The following diagrams represent the familiarity of students with the governing principles, factors, and decisions nodes of the transformable design process before students' participation in transLAB and tranSTUDIO (Figure 119 and Figure 120).

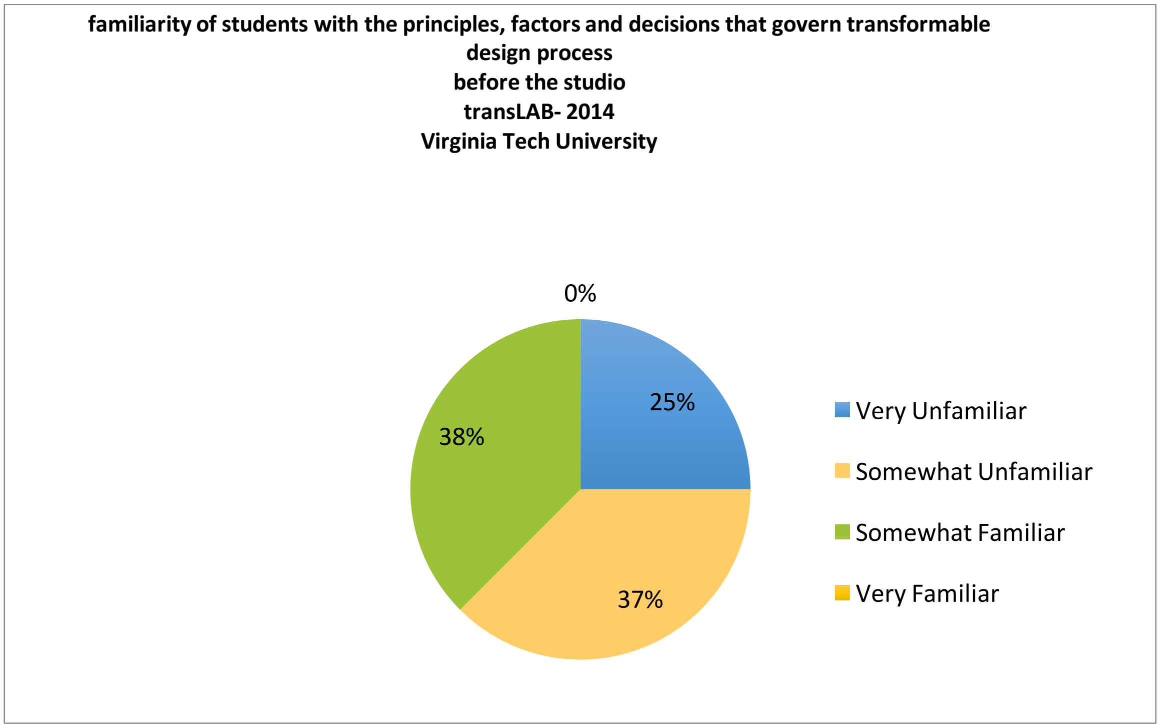

Figure 119: Familiarity of Students with the Principles, Factors, and Decisions that Govern the Transformable Design Process before transLAB-2014 (Virginia Tech University)

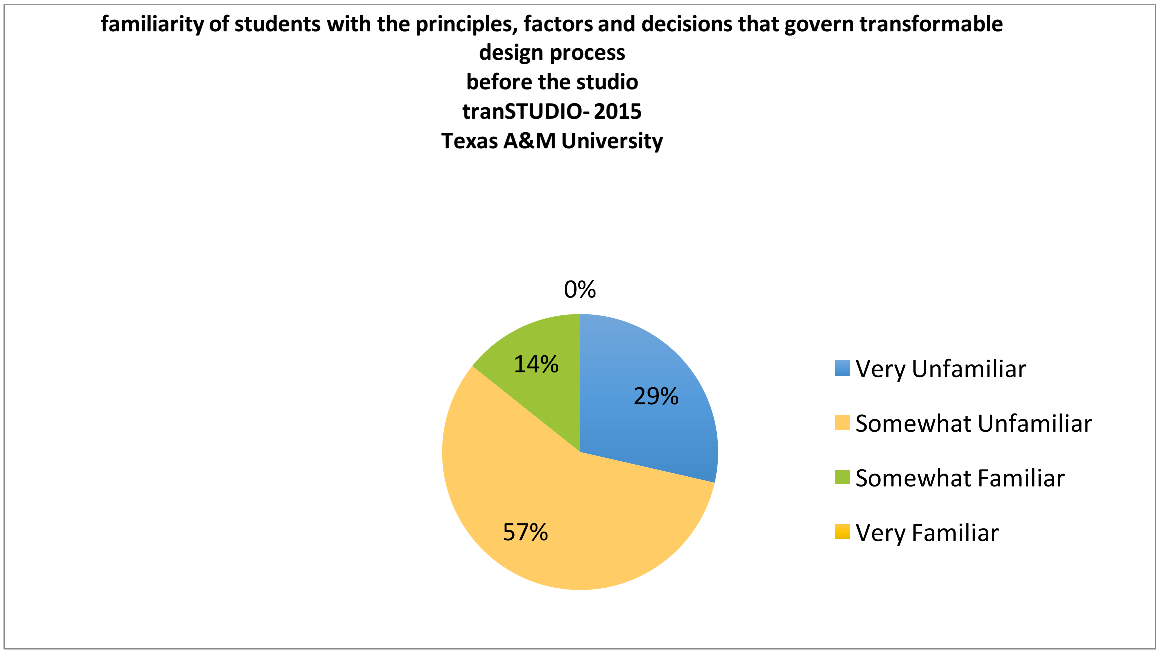

Figure 120: Familiarity of Students with the Principles, Factors and Decisions that Govern the Transformable Design Process before tranSTUDIO-2015 (Texas A&M University)

In the first questionnaire distributed in the first of the two studios, in response to the question: "How do you see the development and use of kinetic envelopes extending architectural theory?" students expressed their understanding of the value and importance of a kinetic knowledge of architecture. Below are their responses (Table 16).

Table 16: Students of transLAB and tranSTUDIO expressed their understanding of the value and importance of kinetic knowledge in Architecture (T stands for Texas A&M students and V represents Virginia Tech students)

T1	I believe that the study of kinetic envelopes will expand our understanding of architecture as a truly "living/ever-changing/breathing" object. By studying and using these kinetic envelopes, we will be able to establish theory that better addresses the needs and concerns of the twenty-first century. As architects, we need to understand how we can better … relate systems and theory. I am excited to be learning about how these emerging envelopes are beginning to change the way we experience architecture and how we can extend these practices to theory.
T2	Buildings now begin to move. They react. They sense things. It adds a new dimension or sense or canon to the requirement[s] for architecture.
T3	The simple fact [is] that the world changes (such as weather and light). These factors are major influences of building design, so it only makes sense that kinetic envelopes become common elements of buildings. If we want to make architecture sustainable, it needs to be able to respond

	better to the changing environment.
T4	I think it is a component [that] will be very influential as we come to a time when digital fabrication is mainstream, and machining cheap, and precise parts on the jobsite become routine. Transformable buildings offer better performance, yet I don't think every building will become transformable. I do hope that this is used, in practice, to produce architecture that is more contextual.
T5	I really like the idea of kinetic envelopes. Personally, I am not a big theory person but I can see these ideas challenging current trends and thinking.
T6	We are so stuck on designing on the usable ornamental level; learning about the usable mechanical level will take our designs to the next level by exponentially increasing interactions between the object and the user.
T7	The development of kinetic envelopes helps further expand on a design level. Now we can design buildings that look a specific way, and transform completely when light penetrates it. With this [in] mind, architectural systems, mechanisms, and structures can all mix in to produce a new idea of design.
T8	Not only designing envelopes that can adapt and change based on temperature/humidity/desired program, but also entire architectural spaces similar to what Diller Scofidio and Renfro are doing with the Culture Shack in NYC.
T9	We assume architecture will improve through materiality, structure, and design since technology has allowed architects to use various software to pursue extreme geometries, structural advances, and new ways of designing.
T10	I think the use of kinetic envelopes extending architectural theory is great. Architecture fabrication gives a different and more interesting aspect to the field.
T11	I think kinetic systems could create an entirely new realm of theory in architecture because of the potential of these systems. If we are designing new biological materials to build our buildings and applying moving skins to our buildings, where does it end? At what point could an entire building become adaptable?
T12	Some architects have begun their design of a building with a core idea. Incorporating … transformable envelopes into the design would be able to further enhance the idea behind the building.
T13	Architecture becomes less stagnant and more subject to change and evolution.
T14	It will transform our views of architecture tremendously, as kinetics systems become more available and evident in our society. Most think of architecture [as] being just buildings. By extending kinetics systems knowledge, the views of what is and isn't architecture will shift, creating a mesh of static and dynamic in one category.

V1	It would no longer mandate a static moment, or experiencing in time. It would force the theory to consider the opportunity + possibility of a building that never stops changing or providing new environments to inhabit.

V2	I think it will become an extension of how people react … and adapt to their surroundings.
V3	Architectural theory can be extended by the use of kinetic envelops by means of functionality and longevity. It can open up discussions about sustainability and faster adaptation to a world that is already [turning to] technology for answers.
V4	As we progress as people, our buildings should also progress to adapt to the changing environment around us.
V5	Architectural theory is continually expanding, so with kinetic envelopes becoming more frequent with modern technology, there is no telling where it could end up.
V6	I see it changing the theory of architecture quite a bit. It almost seems that the new focus on architecture can simply be placed on the façade/envelope. Although I hope this is not the case, seeing the rest of the building [as] just as … important, a goal for a stronger facade idea may be critical.
V7	Technology being brought into architecture will challenge the preconceptions of architecture's autonomy from other bodies of knowledge.
V8	No answer

5.5 The Role of the Motion Pedagogy in the Studios

To effectively show why the motion pedagogy is significant, serious attention must be given to contemplating how motion-related courses should be taught. With coordinated efforts between students, instructors, and professionals in the fields of interest, motion pedagogy should evolve over time. By positioning the study of motion design within the wider context of the role that the motion pedagogy can play in the education of future architects, this pedagogy should embrace further feedback from audiences employing transformation within the design studio.

In an effort to deliberately teach to architecture students those principles that underlie the motion pedagogy, transLAB and tranSTUDIO facilitated to examine the challenges and opportunities architecture programs may face in addressing the application of motion design principles as an element of architectural form-giving.

Since Both studios aimed to investigate the role of motion pedagogy in conceptual change about the required theoretical and practical knowledge related to the basic concepts of force and motion, they provided a great opportunity to make more apparent the strengths and weaknesses of the motion pedagogy. In this case, more maturity and autonomy can be expected from the future studios. To foster a studio model for transformable design, it is essential to demonstrate how these two studios were developed in two different schools in terms of their method, work process and results. Therefore, this chapter aims to examine the impact of such pedagogy in the context of two design studios for fourth year architecture students. The outcome of these studios leaves open the question of how motion-related studios should be taught and what might be the long- and short-term knowledge and skills that students should gain from a transformable design studio.

Motion-related courses occupied virtually no time in the architectural pedagogy of both Virginia Tech and Texas A&M University. As the main hypothesis, the motion pedagogy was forged the curriculum and integrated into the studio environments of these two universities. Since the design studio is the core of its architectural pedagogy, both studios sought to explore and examine how the motion pedagogy can be incorporated into the studio environment. Fortunately, both transLAB and tranSTUDIO functioned within both universities as a conduit of motion-related concepts for students and faculties in an intense, active, and productive manner.

As a step to expand architectural education to incorporate a new body of sustainable practices, both studios reflected the shift in the understanding of today's architectural education.

5.6 General Activities in transLAB and tranSTUDIO

The first two-thirds of each studio brought a holistic perspective to the topic of transformability, and therefore introduced a conceptual framework, historical trajectory, methodological approach, and technical summary of the most relevant mechanisms underlying transformable architecture. It was from this holistic perspective that each studio provided insights into how one might apply an array of 2D and 3D fabrication methods and utilize a series of software and hardware tutorials. In the remaining portion of each semester, with this broad foundation of both theoretical and practical knowledge, students were afforded the opportunity to apply their new knowledge to transformable designs – specially, shading devices – incorporating issues of detailing, assembly, and installation.

Within these studios, there were three main subjects upon which students were asked to focus:

- First, through an introduction to motion language, the studios explored how motion takes place in architecture and transforms existing building components.
- Second, the studios identified issues, problems, and solutions common to most transformable building components. Among the various possibilities, transformable shading devices afforded more opportunities for development in the studios. The ultimate goal was to evolve a specifically-designed movement for shading devices, eventually transforming them both functionally and aesthetically as a main component of a building envelope system.
- The third subject was the reciprocity of movement-making and digital fabrication issues that accompany the complexity of a full-scale operable shading system. It was through this reciprocity that the installation, maintenance, and control aspects of students' design proposals were verified. By bringing a deep focus on and dedication to the execution of their projects, the students explored the invaluable and tight interplay of material, fabrication, and mechanical design parameters that the physical transformability of their concepts demanded.

The internal structures were similar for tranSTUDIO and transLAB. By addressing intense, comprehensive, and inspiring design assignments, these studios broadened the students' visions and enriched their perceptions of motion in architecture. The studios' assignments helped students challenge their own preconceived notions regarding motion in architecture.

In their assignments, students tried to tackle numerous design concerns, including: purpose, function, the user, value, service, and technology. Organized around three main assignments, transLAB and tranSTUDIO were proposed a meditative process for intertwining the wealth of theory and practice available in the field of transformable architecture. Advancing new relationships between architecture and its surrounding environment, the studios emphasized the simultaneous experience of environmental response and application of conceptual kinetic mechanisms. Students were urged to see the significance of an abstract mechanism and how it could fit into a transformable shading device.

5.6.1 The Relation of the Motion Pedagogy and Motion Language in the Studios

To more effectively educate architecture students on addressing transformation itself as a design parameter, the pedagogy of transformable design is founded on a pervasive comprehensive transformable design methodology called the "Language of Motion Formation" which should be initiated in the initial stages of architectural education. The language of motion formation, as an integrated learning framework, offers a common foundation for the design of transformable architecture.

Through the identification of the major decision-related nodes in the process of transformable design, the language of motion formation addresses the study of motion on two levels. The first level involves an analysis of possible changes from one form to another within a given movement and identifies the relationships that generate the motion form. The second level facilitates an understanding of how to use these rules to design a motion composition. Here, a motion composition includes a variety of shape shifting forms that offer the possibility of change.

The language of motion can help students explore how to unpack some of the inherent complexities involved in their transformable designs. On the one hand, the language, as a comprehensive form-finding framework, clarifies how the complexity embedded in a design emerges from basic rules and simple motions, and on the other hand, it high-lights how students can maintain this simplicity within the governing rules as their designs grow in complexity. The language is not only about a compromise of form and motion but also about how students can arrive at a genuine form of motion.

In this language, motion beginner designers can identify disconnected segments that belong to a whole. By providing consistent clarity to link the simple principles of motion design, language of motion is complex enough to integrate a diverse set of elements that play a role in a motion composition.

The language of motion can be defined in accordance with two main factors: vocabulary (the components of formation) and syntax (the rules of their combination).

Here, vocabulary means a range of primary basic motion forms. Students are introduced to three basic motion typologies: translation, rotation, and scaling. In this language, the main device for revealing the order of motion language is syntax. Syntax is defined by canons that show why certain compositions can or cannot be actualized. Through four dominant threads, the main sub-syntaxes are developed as the transformation of geometry, connectivity, materiality, and behavior (Kalantar and Borhani 2016b).

The language of motion is not assumed to be a closed system of predefined instructions, but rather an open-ended form of guidelines associated with a student's exposure to a number of topics and basic wellsprings of knowledge significant to an understanding of motion study.

Since the language of motion attempts to create an opening to accommodate a systemic approach to motion studies in ways that are more appropriate for future architects, both transLAB and tranSTUDIO strived to highlight the significant role of this language as a vehicle for providing a better understanding of transformability in architectural education. Engaging architecture students with direct and hands-on experimentation with the design of movement through the language of motion led to a realization regarding the capacity of the pedagogy of motion as it could be applied in architecture programs.

Language of motion can be used as a schematizing, organizing and generative medium for motion design. Both of studios asserted the pivotal role of the language of motion in the pedagogy of motion design and proved that language of motion can be useful as both a conceptual and organizational design tool to students.

The motion language advocated for the potency of motion design insight. In both studios, the inherent educational value of motion language, as a critical component of transformable design pedagogy, was a commitment to leveraging students' cognitive and intuitive understandings of the transformable design process.

This language was introduced into students' design as an element of architectural form-giving. By employing the principles of this language and manipulating its bounds and constraints, transLAB and tranSTUDIO students explored designs requiring movement in multiple directions.

5.7 Studio Environment

Conducting at two different universities, the author examined the Pedagogy of Motion within the context of design studios. Before reviewing the outcomes of these studios, the author would like to briefly describe her educational approaches in each.

By prioritizing the education of an architect as a person over the academic subject of architecture as content, the cornerstone of design education rightly becomes the detection of each individual's performance in an effort to hold them responsible for pursuing their goals and achieving their fullest potential, within the context of planned activities. To offer an elegant blend of sensibility and creativity, the authors' teaching emphasizes a fostering of each student's ability to think independently and cooperatively.

The author believes that an instructor should also let students be active participants in their own learning process, and take responsibility for their own understanding of the subject matter. In such cases, education opens up opportunities for students to be self-regulated and empowers them to be lifelong learners. By holding back from explicitly telling students what is right and what is wrong, students can be persuaded to engage in a creative search for new design possibilities that is based on their own judgment, and explore unexplored territories without fear of mistakes. In such an environment, design schools educate students and do not merely train them.

As an educator, the author strongly believes that the goal of design education should be to help students reach their fullest potential. Therefore, students must be made aware of why, what, and how they are learning. In the author 'design studios, teaching students why and what to learn takes precedence over teaching students how to learn. The author believes that the object of a design studio should be rooted in how to provide a framework that focuses on new ways of looking at problems, rather than just solutions themselves. Subsequently, the studio should purposefully navigate in the spaces between the desire to walk in the world of the unknown and the desire to bring that unknown into the domain of the known. Regardless of the specific courses, education in the field of architecture should include learning experiences that encourage students to reconcile domains of unknown and unknown.

These studios exposed students to the synthesis of knowledge domains, skill sets, and integration of these two to strengthen the correlation between forms of motion, and the means and methods of their fabrication in sustainable architecture.

In general, several groups of students took transLAB and tranSTUDIO because of the followings:

- The enthusiasm for sustainable or green design approaches
- The desire to fabricate and build
- The interest to learn new domains of architectural knowledge and skill
- The demand to know new modeling and simulation software or to work with emerging technology
- The tendency to explore motion in architecture
- Personal reasons

Regardless of the initial motivation of students, the motivational behavior of them encountered in the studios was placed into two main categories:

The majority of students were categorized as the first group. This group of students was intrinsically motivated to learn and persuade their goals. Although these students might enjoy the principles of motion design or find it interesting, they were more likely to stick to their own motion-based concepts and invest more time in them, fostering their design rather than merely completing tasks. Their design concepts improved dramatically as a result of interest in the use of the language of motion.

With not as much of a desire to participate in the studio like the first group, only a few students shaped the second group that were less likely to either perform well or fulfill tasks with a high degree of involvement. These students who were uninterested to engage in intensive motion design activities were less consistently motivated, comparing to the first group whose reason for working on their assignments involved intrinsic motivation. The second group partially did their assignments a result of at least some level of extrinsic motivation (such as a better grade). Students who were more extrinsically motivated wrapped up tasks but did not endeavor to adopt learning goals of the studio's assignments.

Fortunately, there was not any student in both studios who had neither intrinsic nor extrinsic motivation. Towards the end of semester in both studios, students' intrinsic motivations were increased rapidly when they felt a sense of mastery and competence in being able to relate their designed mechanism to real situations in the built environment. At the end of semester, students' efforts towards making their final working prototype in a more technical way reflected their intrinsic motivation to more deeply understand transformable architecture rather than extrinsic motivation such as the need for good grades, or avoiding negative educational consequences. At the end of both studios, most of students developed a genuine interest in what they did mainly for the sake of expressing knowledge and skills that which the studios offered to them.

To increase students' motivation and involvement, students were allowed to address each of their assignments in whichever way they wished as long as the predefined educational tasks and the assignment goals were attained. In some cases, students were free to modify assignments deliverable as they saw fit. The treatment of the assignment deliverable was done in such a way that students could begin to discover different aspects of their design concepts on their own.

To support situation-specific learning approach, a transformable design studio requires a learning environment that allows an instructor to focus on individuals needs, developing a way of being-with and being-in designing circumstances. In both studios, recognizing that each student's needs and capabilities could be varied by assignment played a broadened role in mediating the learning of individual students.

5.8 The Process of Designing Motion in the Studio

In both studios, there were close relationships to be found and analogies to be made among the various student approaches to designing motion. In the first weeks, it was imperative to communicate on a level in which students without previous exposure to motion design challenges might arrive at a systematic progression of knowledge regarding transformable architecture (i.e., there was an attempt to put the focus and attention on learning connection elements and their relationships to types of movement). Then, in the weeks that followed, students gradually evolved to a higher level, one in which they could thoughtfully apply their acquired knowledge and skills in practice. Towards to the end of semester, students in both studios did not need as much help with their primary design concepts as requested for its development. During the last weeks of both studios, further applications of motion to real-world problems in building were investigated. At the end of the semesters, students evolved to a higher level, one in which they could thoughtfully apply their acquired knowledge and skills in practice.

The growth of the student designs was not seen only in the final models or their final digital representations, but rather at every step in the evolution of their design process, from their back-of-the-envelope sketches through the performance analyses and practicality of their study models. Based on the studios' survey results, all students felt comfortable with the process of gaining integrated skills and knowledge about motion design principles. Most of them believed that they succeeded both academically and personally.

To reduce the influence of unknown variables that could derail a transformable design project and diagnose the possible challenges involved with the overall design process, students were asked to break up their project into manageable phases. By focusing on a subset of their project independently while considering the integration of these subsets into a whole, this approach helped out to predict all of the things that could go wrong and assure their proper functioning. To rectify the challenges those were spread across students' projects, a major advantage to this approach was that students dealt with their challenges more holistically in a managed fashion. The studios included a sequence carried out in the following six phases:

Phase I: Learning three basic motion typologies

During the first phase, to bring their design concepts to life, students were introduced to three basic motion typologies: translation, rotation and scaling. For instance, to master the basics of motion design, students in transLAB were asked to design a transformable cube by using these basic motions. To address the basic motion typologies, tranSTUDIO's students designed transformable doors. In the first phase of their design, students developed several regular and irregular transformable mechanisms without reference to force or mass.

Phase II: Designing an underlying geometry of a mechanism

In the second phase, students were introduced to regular and irregular transformable mechanisms based on the knowledge they gained in their first phase. In this phase, after designing their transformable mechanism, they dealt mainly with the underlying geometry of that mechanism.

Phase III: Designing an overlying geometry for a mechanism

In this activity, students were asked to design a series of geometries over their underlying geometries.

Phase IV: Checking the materiality of the mechanism and means and methods of fabrication

In their concept design phase for transformability, materiality and means and methods of fabrication became important for examining the operation of the mechanism. Through physical and digital modeling, students reviewed their designs. Gradually, students incorporated more aspects of movement into their design to explore their possibilities. The studios attempted to open up a dialogue between students and their design intent, design process and workflow about detailing, fabricating, installation, delivering, and interacting with a transformable device.

Phase V: Designing a transformable structure based on environmental requirements

After understanding the basic design characteristics of transformable design, students were considered ready to ponder more decision-making parameters than just the kinematic rules. A consideration of environmental parameters affected the entire design process. As a result, students had to revise the geometries, choices of material, and behaviors of their designs. Towards the end of semester, to assuredly complete their final design, students were progressively introduced to pragmatic constraints confronted "real" circumstances in designing a transformable shading system. Without sacrificing their design intent, students had to make immediate decisions about modifications that allowed fabrication or assembly processes to move forward.

Phase VI: Evaluation phase

Students became familiar with some basic light and mechanical simulation software to evaluate their designs. In the course of semester, students were encouraged to discuss critically the origins and the nature of the problem of their designs. Throughout mutual conversations among students and a round of discussion, the studios aimed to cultivate students' motivation to teach themselves the basics of motion design and take responsibility for improving their design projects. On the one hand, their found knowledge guided students in creating avenues for what they were going to design. On the other hand, the studios' commitment to providing students with an experimental focus, directed by loosely knit boundaries, gave students confidence and excitement for investing in their own design concepts (Birch 1986).

The above-mentioned phases provided a framework within which students identified possibilities, explored alternatives, and envisioned new realities derived from pedagogy of transformable design. To raise curiosity levels in students and drive them to learn more in a productive manner, the studios structured in a way that the instructor did not arrive with pre-prepared answers to disseminate or administer the entire process of student learning outcomes. In contrast to many other design studios with conventional student-teacher dynamics, the entire studios teaching approach was not teacher-driven. By reducing the instructor intervention to a minimum and relying more on students' side of involvement, the studios, as an inquiry based-learning environment, drove students to come with their own queries and learn at their own pace and effort. To deliver to students a source of skills and knowledge on a sequential mode, in many cases, the author intentionally attempted to act as mentor or facilitator to help them learn with a motivated mind and active interest in a sense to explore other possibilities. With the active help from the author, students were persuaded to help others and get help from others too. By interacting with other students to learn on a mutual basis, students could compare their works, assess their design approach, and later try to improve it.

In both studios, to find a solution to the problem at hand, students were offered the opportunity of unprecedented experiments to circumvent possible impasses of their projects. As evidenced by both studios, knowledge was created during the design exploration of transformable devices in a highly experiential way.

In the studios, students were asked to design a series of relationships between a range of potentials from which a particular design concept was proposed. By iterating back and forth between several alternatives for each assignment, different concepts were considered and mutated. Each of the design iteration was handled as a project in itself being completed through an analysis, conceptualization, preliminary design, detailed design, fabrication, testing, and evaluation process. Once stronger concepts were re-reviewed for their adherence to the goals and requirements of the assignment, they were funneled through the process again to make sure the final project outcomes would meet the intent.

Due to the iterative nature of motion design process, it was required to set internal and external metrics in the studios. Each of design iterations had to be cross-validated with one or more verified metrics within the context of experiments. Internal metric concentrated more on the nature and consequences of design activities themselves, for instance geometric complexity of a motion composition. To measure the resulting designs, the center of attention in defining external metric was the implication, appropriateness, contextual limitations or difficulties of the product of design activities such as structural and mechanical capacity.

It was the author' intent to run the design studios in which students were immersed in the mindset of transformable design throughout their design process. All too often, interdisciplinary thinking was assimilated into the students' mindset. Therefore, to reach the optimal design, students were not resistant to change or modify their design.

A logical method of generating motion with governing rules, variables, relationships, and required systems of mechanisms was an integral part of the design process, and not a task done prior to or separate from it. Here, the emphasis was on an exploration of the motion design guidelines beyond the technical domain itself. Hence, in-depth explorations of these guidelines and their practical applications in relation to the students' design concepts were orchestrated from an architectural design point of view.

5.9 Design Assignment and Projects in the Studios

In both studios, different assignments were purposely structured based on the above-mentioned learning phases to allow the author as the studios' instructor to examine and reflect on the different aspects of motion pedagogy from various angles.

By connecting the pedagogy of motion to variety of topics that form the foundation of transformable design, the author brought forth a series of tailored motion-based assignments, serving to expand students' knowledge and skills. The assignments of both studios were conducted in ways to challenge the students to develop a much broader prospect of what transformable architecture is and what it does.

Developing with the capacity to instigate students' interest in different subjects and activities associated with motion design, each assignment set out special provisions and procedures to ensure its outcomes. Creating a balance between the content and corresponding resolution of each assignment, the studio learning outcomes, and students' individual progress put great demands on the studio instructor.

Including introduction, directions, objectives, and deliverables, the studios 'assignments gave enough room to students a variety of explorations and personal reflections. By taking into consideration a loose framework of obligatory regulations, guidelines, or deliverables governing the final outcomes of each assignment, students were able to tailor an assignment context to engage the full breadth of a dynamic learning experience in each facet of their design. The goal was to not lock the assignment outcomes in a single direction. Although the openness of students' design approaches could present struggles for the instructor. Remarkably, this was not the case.

It was through this lens that students 'assignment deliverables were a result of a constant process of exploration, ideations, improvisations, compromises, and approximations that unfolded over time and in steps. Facing some adjustments, the deliverables of some assignments evolved to remain relevant to the overall studio activities in the face of ever-changing circumstances.

Almost the same assignments were offered in both transLAB and tranSTUDIO. These assignments were used as the primary method of delivering motion design principles to students. Students' assignments operated across scales to position motion as an active design agent in continually changing contexts. These assignments ranged in scale from a small movable joint to building envelope. Depending on the target scale, these assignments took in the range of a week or a month in their entirety. Towards the end of semester, the overall context of students' assignments gradually developed into higher levels of integration, and also complexity. In all of the assignments, the making of a series of iterative models, as a way of knowledge gathering and design thinking, was integrated into the design intent. These assignments, along with several workshops, lectures, and review, delved into deeper exploration of motion design principles.

These studios formulated a series of assignments including movement within structures, architectural components, and materials. These studios did not address flows of people, traffic, or services in architecture. Organized around six main design activities, students learned and handled the motion design principles in transLAB and tranSTUDIO via the following assignments:

5.9.1 Exploring movement itself:

Beginning an investigation into the motion of a door (in tranSTUDIO) or transforming a cube (in transLAB), the first assignment was part of the learning and experimenting of basic ideas of motion in the studios (Figure 121 & Figure 122).

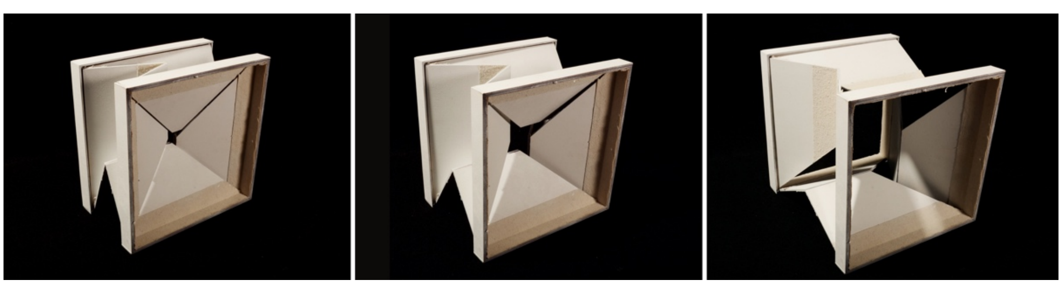

Figure 121: Transforming a cube, first assignment in transLAB-2014

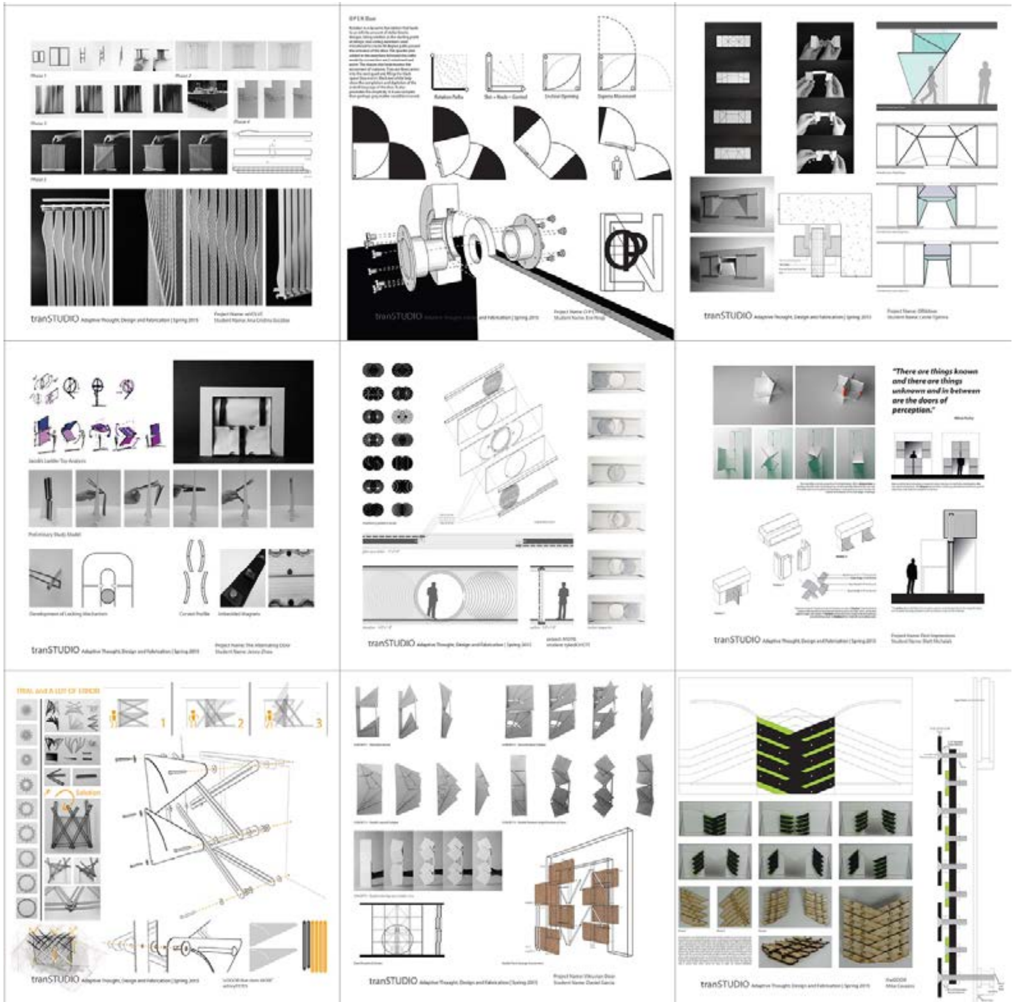

Figure 122: Door Assignment in tranSTUDIO

5.9.2 Design regular/irregular kinetic tessellations as angulated scissors polygons:

In both studios, students explored angulated scissors through a fourteen-sided deployable polygon. To test the movement of their polygon designs, students constructed physical models with the school's laser cutters. These prototypes served as the physical verification of the movement of their design in Grasshopper (Figure 123).

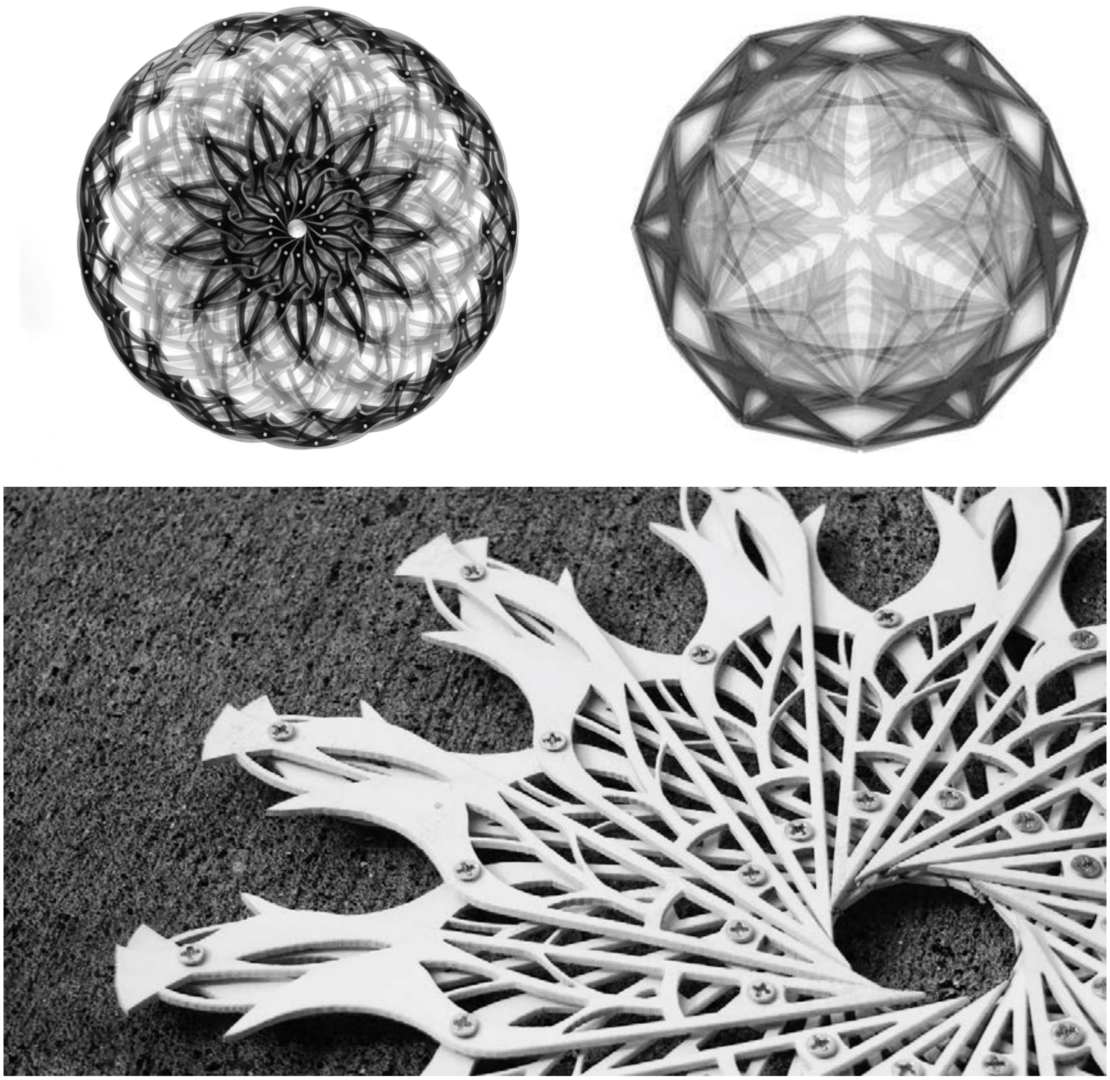

Figure 123: Exploring angulated scissors through a 14-sided deployable polygon in both transLAB and tranSTUDIO.

5.9.3 Design a kinetic joint:

Exploration of movement in 3D printed parts for making different mechanisms (mainly by using Fused Deposition Modeling (FDM) 3D printing technology) (Figure 124).

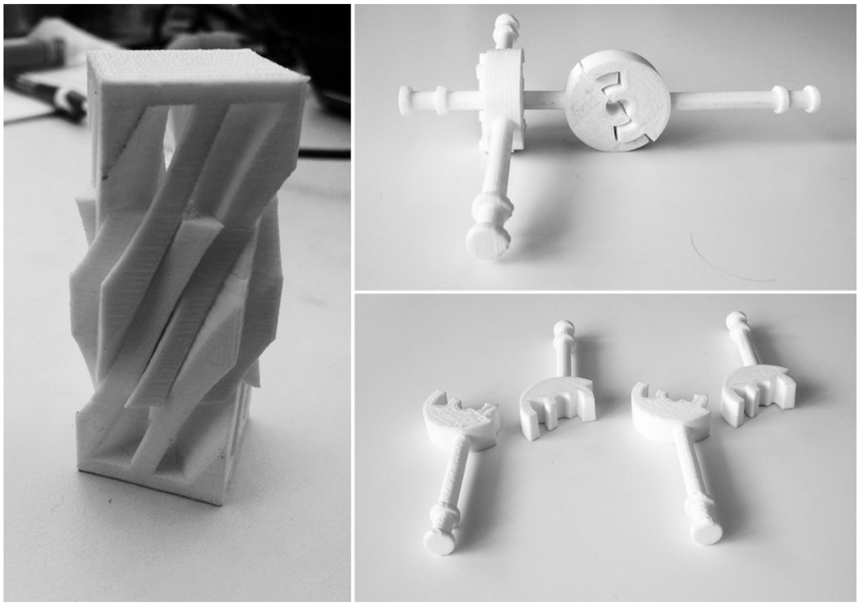

Figure 124: 3D printed joints able to serve different purposes when designing and building different mechanisms. In transLAB and tranSTUDIO, students were able to investigate joints in transformable design.

5.9.4 A transformable spatial exploration as an architectural intervention:

Design a transformable canopy for the open plaza in front of Cowgill Hall at Virginia Tech University (in transLAB) and a suspended transformable ceiling called “the fifth wall” for the Review Space on the fourth floor of Langford A Building at Texas A&M University (in tranSTUDIO) (Figure 124 & Figure 125). Both of these projects constituted three main phases namely inception, elaboration, and construction. For instance in its inception phase of the fifth wall project, students began the project by having several conversations with the client[76] to figure out what the project was. Students were divided to three groups. After several group discussion sessions, the general aspects of the project including the key constraints, requirements, and its scope were identified.

[76] The client of this project was the head of the department of architecture, at Texas A&M University.

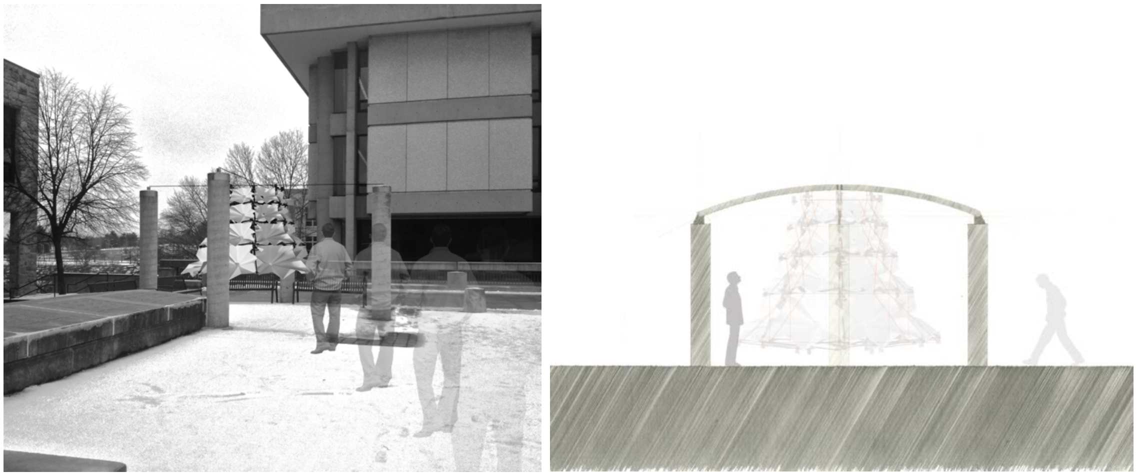

Figure 125: Spatial exploration through designing several transformable canopies designed by transLAB students.

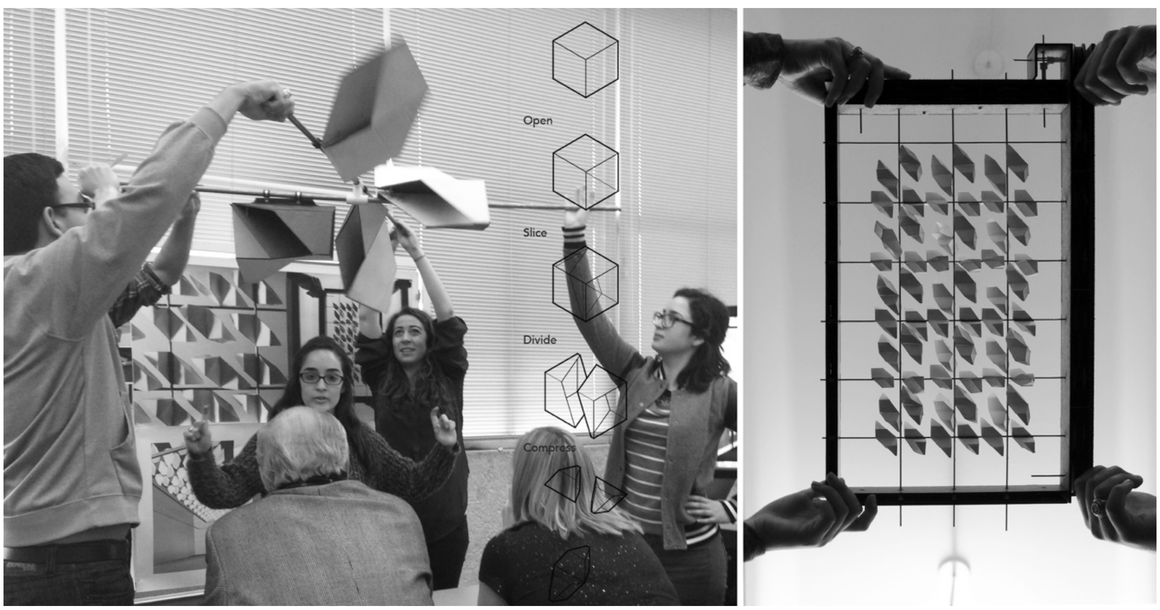

Figure 126: A transformable spatial exploration. Full-sized mockups (partially) demonstrated to the juries the scale of movement achieved by tranSTUDIO students.

5.9.5 A Transformable shading system as an architectural mediator:

In the last design activity of both studios, students were principally introduced to the interdisciplinary nature of transformability through the typology of shading devices. Since a shading device is a manifestation of various fluctuating spatial and environmental considerations, the final assignment provided an opportunity for the exploration of the sustainable advantages of transformable shading systems. In transLAB, designing moving shading elements aimed to optimize the energy and visual performance of a long west-facing window wall of the Art + Architecture Library, located in Cowgill Hall at Virginia Tech. To provide filtered sunlight to the galleries of the Museum of Fine Arts Houston (MAFH) and protect valuable artworks from the sun's UV rays, students in tranSTUDIO were asked to design operable shading systems imbued with environmental response (Figure 127).

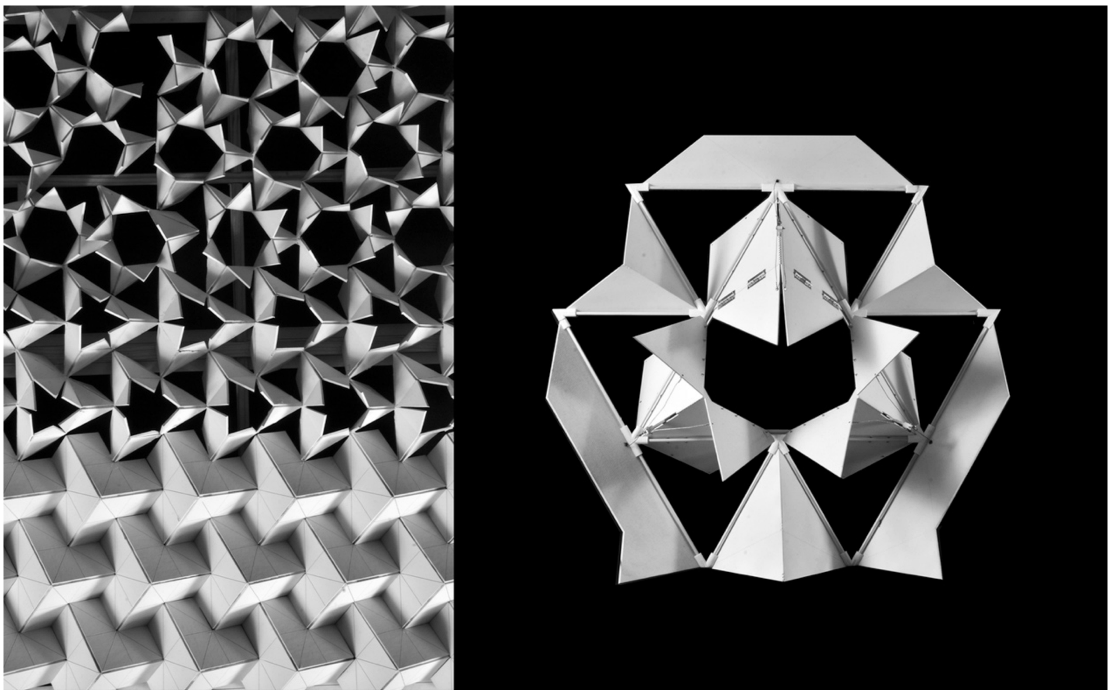

Figure 127: Transformable Shading System. Designing a sequence of movements that occur over time in order to enlighten one's change of position from a stationary condition to a new circumstance. In tranSTUDIO, through the undulating and faceted surface of a transformable shading system, the geometry was designed to rupture and provide from 2/3 openness to complete coverage of the glazing. Each module was made up of a series of triangular panels that fold back onto themselves to varying degrees, in order to affect the amount, direction, and volume of light passing through the glazing. This movement was controlled through a system of interconnected levers and cords.

5.9.6 A Transformable Wall (Cyber Space Generator):

Just in tranSTUDIO, students designed and constructed a full scale deployable curved surface as transformable wall/ceiling to fully experience the whole process of transformable design, from concept to realization (Figure 128). In this assignment, a reciprocal learning process among the geometry of motion of the wall elements, available fabrication techniques, and material experimentation was instituted.

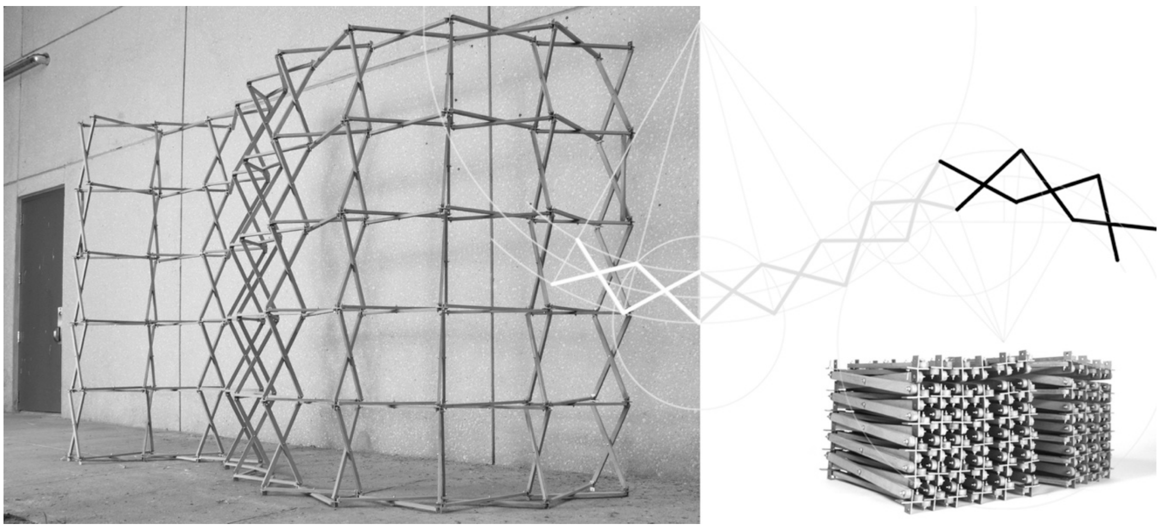

Figure 128: tranSTUDIO's students designed and constructed a transformable wall to fully experience the whole process of transformable design, from concept to realization.

The following table lists the design assignments used in both transLAB and tranSTUDIO. Although the assignments were not identical, the purpose and learning objectives were similar (Table 17).

Table 17: List of the design assignments for transLAB at Virginia Tech and tranSTUDIO at Texas A&M

transLAB – 4th Year Studio – Virginia Tech – Spring 2014	**tranSTUDIO – 4th Year Studio – Texas A&M – Spring 2015**
01_Transformable Cube	01_Design a door where its movement is the intention of the design
02_Regular-Irregular Kinetic Tessellation	02_Regular-Irregular Kinetic Tessellation
03_ Design a Joint: Fused Deposition Modeling Exploration	03_ Design a Joint : Additive Manufacturing Explorations
04_Transformable Spatial Exploration as Architectural Intervention: Design different canopies	04_Spatial Exploration as Architectural Intervention: Design a Fifth Wall

05_Architectural Mediator (for the dynamic control of light and sight)	05_Architectural Mediator (for the dynamic control of light and sight)
06_Robotic Exploration	06_A Transformable Wall: Deployable Curved Surface Cyber Space Generator

The six phases of transformable deign pedagogy have their own particular learning objectives (Table 18). These objectives were used to structure several design assignments. However, there were a few other influential aspects that guided the topics and scales of the projects, including the fabrication facilities available, availability of external funding, and experts accessible to the students.

Table 18: Objectives in six phases of design pedagogy

Objectives of the Phase	**transLAB – Design Projects**	**Objectives of the Phase**	**tranSTUDIO – Design Projects**
Learning three basic motion typologies	5.9.6.1 01_Transformable Cube	5.9.6.2 Learning three basic motion typologies	01_ Design a door where its movement is the intention of the design
Designing an underlying geometry	02_Regular-Irregular Kinetic Tessellation	Designing an underlying geometry	02_Regular-Irregular Kinetic Tessellation
Designing a joint and exploring fabrication	03_Fused Deposition Modeling Exploration	Designing a joint and exploring fabrication	03_Additive Manufacturing Explorations: Design a Joint
	04_Transformable Spatial Exploration as	Designing an	04_Spatial Exploration as

Designing an overlying geometry	Architectural Intervention	overlying geometry	Architectural Intervention: Design a Fifth Wall
New fabrication possibilities	05_Robotic Exploration	Designing and fabricating a transformable structure (full-scale)	05_Deployable Curved Surface Cyber Space Generator
Designing a transformable structure based on environmental requirements + Evaluation phase	06_Architectural Mediator (for the dynamic control of light and sight)	Designing a transformable structure based on environmental requirements + Evaluation phase	06_Architectural Mediator (for the dynamic control of light and sight)

5.9.6 Required Knowledge, Skill, and Information (KSI) in Transformable Design Studios

Designers may not have to know all of the required knowledge by themselves, but they should know what they need to know and when they need to know it. The Pedagogy of Motion represents a direction in architecture that emphasizes the active role of building elements to redefine architecture itself. Although the Pedagogy of Motion does not imply that all motion-related courses should exhibit similar trends, cover the same topics, or employ identical approaches, these courses should emphasize a certain category of information, knowledge, and skill. In addition, based on the AURA self-immersion process, a foundation was developed for understanding what knowledge, skill, and information are required to design transformable shading systems (Figure 129)

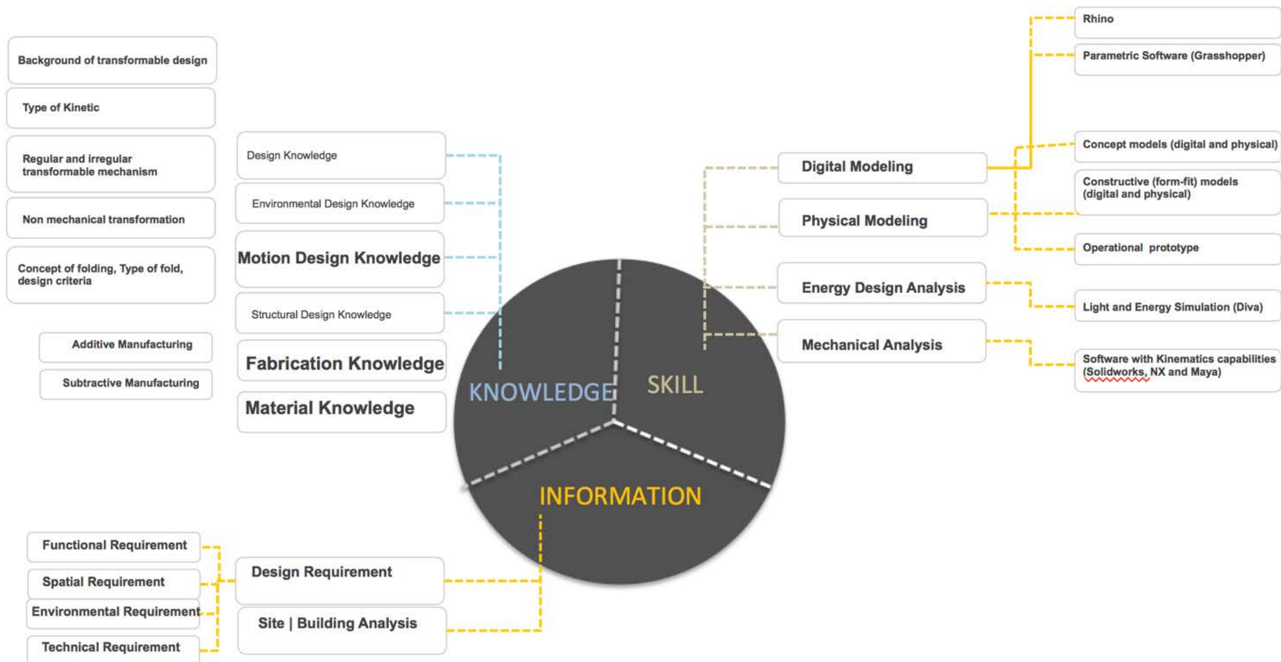

Figure 129: Main knowledge, skill and Information required in the transformable design process

The following table demonstrates the required knowledge, skills, and information of each design process phases of transformable architecture *(*Table 19*)*.

Table 19: A primary classification showing the required knowledge, skill and information in different stage of design process.

		Knowledge	**Skill**	**Information**	**Process**	**Output**
Design	**Early Design Studios**	Basic motion design knowledge	Hand Drawing +Digital Drawing	Basic information about design projects	Specify the design requirements	Establish the design criteria
	Conceptual Design	Basic motion design knowledge	CAD Software: Such as Rhinoceros, Grasshopper, Solidworks, AutoCad		Brainstorming, Motion form-finding process, Solving the geometry of movement, Iterations based on geometry, Shape	Concept design

	Design Development	Motion design knowledge (materiality, geometry of motion, and behavior); and structural design knowledge	More parametric CAD software: such as Solidworks, Grasshopper, Inventor, NX7	Positions of shading devices relative to the façade. Position of shading devices relative to inside-between-outside.	Component design, Physical characteristics (size, material), Structural and mechanical simulations, Ways and means of operation and control	Preliminary prototypes
		Environmental design knowledge	Simulation software: such as Diva, Radiance, eQuest, Ecotect, IES-Pro	Climate, Location, Site, Building type, Façade type	Environmental simulations, Optimal shading, Optimal orientation, Optimal openness and closedness	Visual comfort, Thermal comfort, Acoustics, Ventilation
	Design for Fabrication	Material knowledge	Scheduling software	Cost analysis, Transportation	Material and technical specifications, Building regulations and standards, Workmanship	Actual mockup

5.9.7 Main Knowledge Required in Transformable Design

In general, motion pedagogy is concerned with what is knowable, as well as commonalities across specific projects. In the pedagogy, an educator assumes that most students do not emerge well-versed in the information, knowledge, and skills necessary to succeed in transformable design, or are unable to use those information, knowledge, and skills as they progressed in their design education throughout the semester. For these students, some aspects of motion design are knowable but other aspects are not. In many cases, the principles of motion design are partially implicit to students but are not explicitly defined in the whole process of design. These students deal with many of the conflicts caused by the opaqueness of these various discrete topics from different disciplines that continuously play a vital role in the design process. To scaffold a design concept toward a deliberate transformable design, students can gradually notice that they might not have to embrace all of the required knowledge by themselves to design a motion composition; however, they had to know what they needed to know and when they needed to know it. Therefore, in both transLAB and tranSTUDIO, instead of using lectures to store potentially valuable knowledge in students' memories, acquired knowledge was recruited during students' in-studio projects. Students were asked not only to explore motion design's existing knowledge structures, but also to produce new knowledge through their design studio projects.

In the studios, by looking critically at their own works, students became adept at combining and internalizing three main domains of knowledge: structural, mechanical (e.g., geometry of motion), and environmental. The development of students' prototypes exhibited the various turns that accompany a transition from a tectonic imagination to a physical model. Among these turns, the most significant were the geometry of motion of a proposed mechanism and its material character.

The main knowledge domains that kinetic studios should cover consist of:

- Design knowledge;
- Environmental design knowledge;
- Motion design knowledge;
- Structural design knowledge;
- Fabrication knowledge; and
- Materials knowledge.

Of these required knowledge categories, the two kinetic studios focused mainly on:

1) Fabrication knowledge;
2) Materials knowledge; and
3) Motion design knowledge.

Since the studio times were limited to one semester and the motion design topics were completely new to the students, topics had to be prioritized and more time allocated to the more unknown and essential areas of knowledge.

5.9.7.1 Establishing a General Understanding of Fabrication

The first effort made in communicating fabrication knowledge prompted students to recognize three key fabrication methods: 1) subtractive, 2) additive, and 3) deformation. Then, the studio focused on additive manufacturing and 3D printing in the kinetic design process.

Additive manufacturing has three significant benefits over other methods:

1- Students are able to design their own non-flat joints that offer new possibilities to architects and designers. For instance, for designing deployable canopy structures, students designed and 3D printed different joints for their scissor structures (Figure 130).

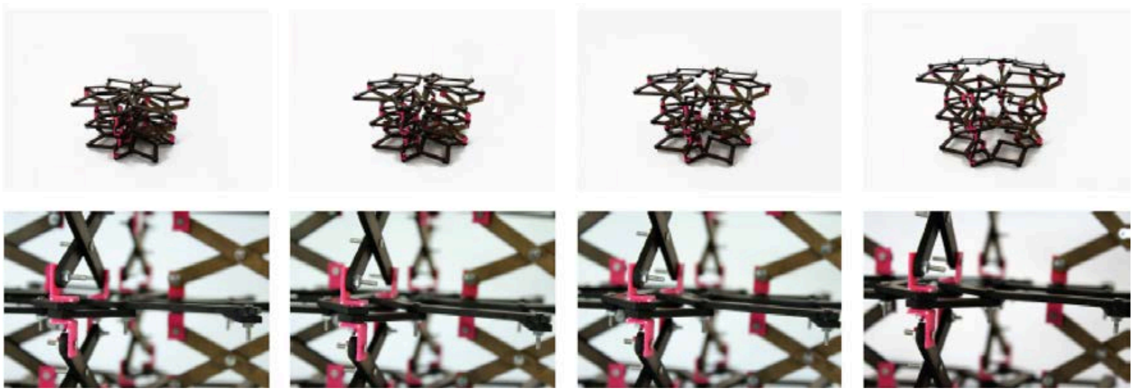

Figure 130: For making a deployable canopy structure, a student used the available 3D printer in transLAB to 3D print all of the required joints.

2- Students could design linkages and joints as part of a single subject and 3D print the result as one piece; therefore, the designer could design and make the entire kinetic system to be a single identity rather than as pieces of linkages and joints. This method of fabrication is relatively a new opportunity to address a better transformable design process, allowing the designer to think about the whole system as an integrated mechanism, rather than as individual elements. No other fabrication process has this ability. During the transformable studios, explorations of this new realm of fabrication were embedded in students' design projects in an effort to expose them to the advantages of 3D printing in transformable design (Figure 124). In the design process of AURA, the author designed and 3D printed complete apertures for shading devices and eliminated the process of assembly of parts (Figure 131).

Figure 131: In the AURA design process, 3D printing opened up new design opportunities. Thinking 3-dimensionally and integrating elements are two main advantages.

3- 3D printing has the ability to print different materials (from rigid to flexible) together; this opens up a wide range of possibilities in the field of kinetic design.

5.9.7.2 Establishing a General Understanding of Material

As a designer, it is critical to understand the proper materials for one's design. A kinetic design is the result of an accurate geometry of motion, as well as the appropriate choice of materials and fabrication processes. This is essential knowledge that students must gain during their education. In the kinetic studio, the emphasis was on imparting a general knowledge and recognition of the importance of understanding the properties of materials, and specifically, of how to choose the right material for the specific design. In studios, prototypes are not just formal representations of ideas and how they should perform when in motion; students also learn how the appropriate materials properties can help their designs perform in structurally and mechanically satisfactory ways.

Unfortunately, in architecture and design schools, the making of physical objects has been replaced with computer models; this is due to the cost associated with the facilities needed to make physical objects. Some schools are closing fabrication courses and related degrees because of their "costly" and "space-intensive" character; instead, they are offering more computer-based courses.[77] The performance of a structure is determined by the amount of deformation permitted.

The main properties of materials that can affect motion design performance are:

- Stiffness: The ability of a material to stand up to forces being applied without bending, breaking, shattering, or deforming in any way.
- Surface friction: Contact friction conditions define how two surfaces are able to slide on each other.
- Tensile strength: The ability of a material to stretch without breaking or snapping.
- Elasticity: The ability of a material to absorb force and flex in different directions, returning to its original position.

In both studios, the first design projects were based on students' previous design skills. Students began their kinetic designs based on knowledge gained during their past three years, and their understanding of materials and fabrication processes. One of the critical issues mentioned in the "weaknesses" section of the self-evaluation questionnaire addressing the first projects was a lack of understanding of materials properties.

There were two types of weak approaches to the choice of materials:

1- Some students ignored the materials' properties; they thought that accurate computer modeling would ensure the physical performance of their kinetic models.
2- Some students expected too much from their materials, hoping they would react or behave in particular ways in response to forces exerted during the motion process.

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[77] http://www.dezeen.com/2014/11/13/design-education-tragic-says-jonathan-ive-apple/

5.9.7.3 Establishing a General Understanding of Motion Design

Every motion construct can be broken down into a combination of three control categories: materiality, geometry of motion, and behavior (Figure 132).

Material: The physical qualities of the matter in which the motion is embedded, affecting the perceived nature of the motion. Materials can be categorized into three general classes: rigid, non-rigid, and a combination of the two. The combination can be in a layered composition of rigid and non-rigid materials, or in a skeleton arrangement in which the rigid materials are bones covered by non-rigid tissue-like material.

Geometry of motion: The physical and spatial design of how motion is created. The geometry of motion consists of underlying and overlying geometry. In most architectural kinetic systems, large-scale movement occurs at the detail level.

Behavior: The temporal control structure of motion. Behavior is an important aspect of transformable design because it defines how motion is perceived in the system. The speed, acceleration, delay, pattern, and direction of movement are key design decisions. For example, not all changes in object positions produce visual experiences of motion; some occur too rapidly, and others too slowly. The control aspects of a transformable system can make or break the observer's perception.

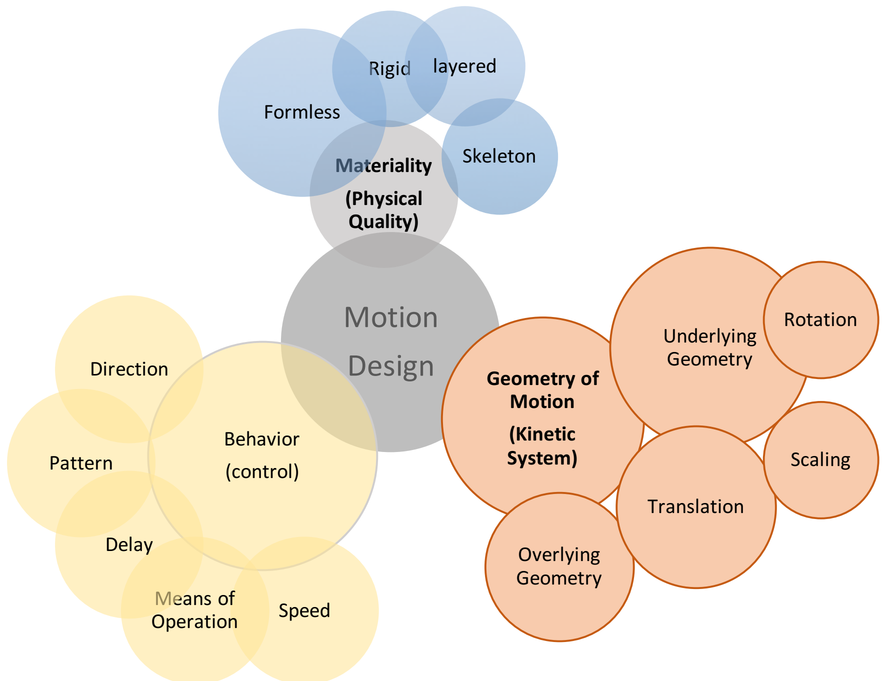

Figure 132: Each motion design has three control categories.

5.9.8 Main Skills Required in Transformable Design

There are four main skill domains that should be addressed in transformable design studios.

- Digital modeling
- Physical modeling
- Energy and light design analysis
- Mechanical analysis

To better understand and assess students' levels of skill, a questionnaire was sent to the students before the studios began in order to evaluate their knowledge of and skill in digital modeling, parametric modeling, and energy design analysis. Based on the average scores for each category, a series of lectures and workshops were offered (Figure 133). The transformable studios focused on Rhino, Grasshopper, and Diva for Rhino. These sets of software were considered to be the most effective, based on the AURA design process.

Making was integrated into the design intent, and prototyping was considered to be a methodology for knowledge gathering and design thinking. Therefore, in the transformable design studios the methodology was to make a series of iterative prototypes, ranging from small to full-scale mock-up that addressed the core elements of transformable design knowledge (Table 20).

With regards to physical modeling, students had to wrestle with three types of prototyping:

1) Concept model;
2) Constructive (form-fit) model; and
3) Operational prototype.

Table 20: How different types of prototypes (conceptual, constructive, and operational) correlate with the three basics of motion design knowledge (kinematic, material, and behavior)

Core Elements of Transformable Design	**Kinematic**	**Material**	**Behavior**
Knowledge of Motion Design	**Geometry of motion -** Rotation, Translation, and Compound - Stretch, Roll, Bend, Shear, Flutter, Gather, Free	**Rigid material -** Rotation, Translation, and Compound - Deformable materials (Stretch, Roll, Bend, Shear, Flutter, Gather, Free)	**Control system -** Speed, Excel, Direction, Delay, Pattern,
Prototyping and Modeling	**Concept models (Digital and Physical) -** Primarily models for visualizing and checking the concept and developing an underlying geometry	**Constructive (Form-fit) models (Digital and Physical) -** Models for visualization and assembly (how well parts fit together), basic motions/functions, and checking the underlying and overlying geometries	**Operational prototype -** Functional model for testing, material, scale, actuation, dimensions, and detailing

Following are some of the advantages of the physical and digital modeling in transformable design studios.

Physical prototype advantages:

- Establishes a general understanding of kinetic system behaviors;

- Establishes a general understanding of motion design and motion design parameters;

- Helps with understanding the underlying geometry;

- Helps with designing an overlaying geometry;

- Helps form a better understanding of material properties, such as friction and expansion;

- Helps with understanding overall assembly behaviors;

- Physical models are sharable, and thus able to receive feedback from peers and fabricators;

- Helps with understanding the value of different types of prototypes (concept, constructive, and operational models); and

- Establishes a general understanding of detailed design.

Digital prototype advantages:

- Helps with designing and testing the underlying geometry;

- Helps with understanding abstract diagramming;

- Delivers a higher level of precision; and

- Help with analyzing TSS energy and light performance.

	STUDENT NAME	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	
Categories	Architecture Software															
Architecture Modeling	AutoCad	3	3	3	3	3	3	3	3	3	3	2	3	3	3	2.93
	SketchUp	2	2	2	3	3	3	3	3	3	2	3	3	1	3	2.57
	Rhino3D	2	1	3	1	2	1	0	3	2	0	1	2	0	3	1.50
	3D Max	1	1	2	1	1	2	0	1	1	0	0	1	1	0	0.86
	Maya	0	3	0	2	2	1	0	0	3	1	0	2	1	2	1.21
	Other (:)			Revit: 3						Z-Brush: 1			Revit: 3			
Parametric Modeling	Grasshopper	0	0	0	1	1	0	0	1	0	0	2	1	0	0	0.43
	Dynamo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
	Other (:)															
Sustainability Software	Design Builder	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
	Ecotect	0	1	0	1	2	1	1	0	0	0	0	0	0	2	0.57
	Diva for Rhino	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
	Diva for Grasshopper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
	Energy Analysis for Revit	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0.07
	Other (:)															
Rendering Software	V-ray	0	1	1	1	0	0	0	0	2	2	1	1	2	0	0.79
	Maxwell Render	1	2	2	0	1	1	0	1	2	2	0	0	1	0	0.93
	Mental Ray	0	2	2	2	0	0	0	0	3	0	0	2	0	0	0.79
	Other (:)				Keyshot: 2					keyshot: 2		Kerkythea: 2				
3D Cad Software	Solid Works	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
	Other (:)															

Figure 133: This questionnaire was developed to assess students’ skills with certain software. The scale was 0-3 (0: never used, 1: beginner, 2: intermediate, and 3: proficient).

In digital modeling, there were five categories of software skills considered helpful to students taking transformable studios: architectural and parametric modeling software, sustainability software (focused primarily on light and energy simulations), rendering software, and solid cad modeling (with the ability to incorporate motion simulations). The survey was distributed before tranSTUDIO began. Therefore, the author was able to organize the series of workshops based on the students’ proficiencies.

Alongside these fundamental pieces of software, students were asked to learn how to document the movement of their models. Video editing software such as Windows Movie Maker, iMovie, and Adobe Premier were taught and used in the studios. Moreover, some features in Photoshop (such as animated GIFs) were very helpful for displaying animation. With GIFs, students were able to make short animations from a series of images they took while opening and closing their models. The students lacked experience with motion documentation and often were unable to capture, document, and present information effectively. Consequently, these topics were also gradually added to the software workshop series (*Table 21*).

Table 21: tranSTUDIO software workshop. This workshop introduces parametric modeling techniques and performance analysis methods. It consists of three main sections: 3D Modeling, Parametric Modeling, and Simulations. Each session covers fundamental knowledge and skills, and allows students to develop example models. Topics cover from an introduction of parametric modeling to daylighting analysis tools currently used in the industry. Students learn basic parametric modeling, and performance simulation, interpretation, and implementation.

Sessions	Topic	Contents
3D Modeling		
1	Introduction to Rhino	Session 1 introduces Rhino's basic interface and expected final outcomes. This session will facilitate students' understanding of overall workflow, and give them an idea of what they will learn during the parametric design workshop.
2	2D Drawing	Session 2 focuses on the way students can draw and edit 2D curves. This session covers all commands used in making and editing points, lines, and curves in architectural drawings and modeling.
3	3D Modeling	Session 3 introduces NURBS modeling techniques. This session will facilitate students' understanding of NURBS modeling, and assist them in creating freeform 3D digital models.
4	Practice	In Session 4, students will practice making building models using the techniques introduced in Sessions 1, 2, and 3. The example model will be ROW HOUSE designed by Ando Tadao. Various modeling techniques and presentation skills will be introduced during this session.
Parametric Modeling		
5	Introduction to Grasshopper	In Session 5, the concept of parametric modeling and its associated benefits will be presented. In this workshop, Grasshopper, a visual programing interface for Rhino, will be used.
6	Development of Parametric Model 1 (building model)	In Sessions 6 and 7, students will develop a simple building model with a parametric relationship among variables such as height, size, and number of columns. Students will learn how to develop parametric models based on techniques developed in the "3D Modeling" session.
7		
8	Development of Parametric Model 2 (math)	In Sessions 8 and 9, students will learn how to use math equations to develop parametric relationships. These sessions will integrate mathematical geometric shapes and formulas into a parametric model.
9		

10	Data Structure	Sessions 10 and 11 will address the data structure of parametric modeling. Learning data structure is the most important element of the Parametric Modeling portion of this workshop series.
11		
Simulation		
12	Introduction to Daylighting Simulation	This session will provide students with a basic background in daylighting simulation, metrics, and methods. Students will learn: 1) how daylighting models are developed, and 2) what the required elements are for daylighting simulations.
13	Diva for Rhino	In Session 13, students will learn how to use Diva, a daylighting analysis platform for Rhino. Based on an example model, student will carry out daylighting simulations and learn how to analyze the results.
14	Diva for Grasshopper	In Session 14, Diva for grasshopper will be presented, with examples. The integrated implementation of parametric modeling and daylighting simulation will allow students to experiment with their designs in ways that support their design decisions. In addition, an optimization process will be introduced for advanced implementation of parametric modeling.
15		
16	Wind Analysis	Session 16 will introduce Flow Design, a virtual wind tunnel software package developed by Autodesk. Students will experiment with how their design affects wind flow.

5.10 Methods of Transferring Knowledge, Skill and Information

These categories of knowledge, skill, and information assisted in the drafting of a comprehensive syllabus for a transformable design studio. There were four main approaches taken to transferring these knowledge categories, skills, and information (KSI):

1- Lectures

2- Workshops

3- Review and critique sessions (individual and group reviews)

4- Exhibitions

In both transformable design studios, there were four main methods of transferring knowledge, skill, and information, including:

5.10.1 Lectures

The author has evolved in the belief that the greater students' knowledge of motion the better their ability to design it. Both studios, as places of design exploration and realization, attempted to close the gap between theory and practice. By looking for possible solutions grounded on students' theoretical knowledge as well as on evidence from hands-on design activities, these studios pointed to the significance of mediating between theory and practice.

As opposed to lecture courses where the flow of information is in one direction, through a continual dialogue in the design studios, a great body of knowledge was passed from the author as the studios' instructor to student and from student to student. By learning for themselves and by themselves, both students and the author became learners who drew upon their previous knowledge and experiences about motion to interact with one another in a collaborative setting, moving from concept to valid form.

Largely, the studio lectures of both studios introduced students to fundamental behaviors of different kinetic mechanisms through a discussion of rules gleaned from geometry and physics. The lectures concluded with a range of historical and contemporary mechanical and architectural examples that demonstrated how these mechanisms were deployed.

During both studios, the lectures had three main areas of focus:

- Lectures about motion design knowledge
- Lectures on software skills
- Lectures of fabrication methods

5.10.1.1 Lectures about motion design knowledge:

The intention of these lectures was to educate students on the basic knowledge necessary for transformable design. These lectures were progressive, beginning with a basic knowledge of kinetic geometry and ending with more advanced mechanisms (Table 22).

Table 22: List of lectures on motion design presented in transLAB and tranSTUDIO

Lectures on Motion Design	Concept of transformable design
	Classification of transformable structures (typologies)
	Mechanism basics; Interesting historic linkages · Types of kinematic connections · Degrees of freedom · Points of connection to the reference frame (ground) · Types of joints · Types of scissor structures · Angulated linkages - basic geometry
	Expanding polygons; An irregular-design technique
	Expanding structures - 2D
	3D structures (2) - expanding
	Practical fabrication techniques
	Adaptive facades; Architectural integration issues
	Kinetic origami
	Strategies for control (very basic)

5.10.1.2 Lectures on software skills:

The software survey completed by students before the beginning of their studio evaluated their proficiency with different pieces of software. A series of software sessions were designed and offered during both studios. The intention of this lecture series was to enhance the software skills of students such that they would be able to work with the tools required to design transformable systems. Based to the survey results, three emphases were selected for the software sessions: architectural modeling software, parametric modeling software, and sustainability software (focused mainly on light and energy simulation). Rhino, Grasshopper, and Diva were the main software packages used in these studios (Table 23).

Table 23: List of software lectures presented in transLAB and tranSTUDIO

Lectures on Software Skills	[Rhino] Basic: Interface Intermediate: Facade roof1, Modeling a complex surface
	[Grasshopper] Basic: Interface/basic geometry (circle, cylinder, pipe, box)/surface (evaluate, divide, explode, random height) Intermediate: surface modifications (move and loft, list item, sublist, 4 point surface) Advanced: Advanced surface modifications (fillet diagram, full and curve on surface) Additional exercise: Creating a roof structure, parametric twisting tower, Virginia tech Grasshopper workshop Exercise:
	[Diva for Rhino] Basic: Model Setup Basic: Running an image-based metric (radiance image creation, time settings, glare metrics) Basic: Running a grid-based metric (daylight autonomy, daylight factor, useful daylight index, and LEED4.0 daylighting)

5.10.1.3 Lectures on fabrication methods:

There were a few studio lectures focusing on different types of fabrication and concentrating primarily on additive manufacturing systems. Different types of additive manufacturing were introduced in the lectures. Students conducted research on how each 3D printing method worked.

- Binder Jetting
- Material Jetting
- Material Extrusion
- Directed Energy Deposition

- Powder Bed Fusion
- Sheet Lamination
- Vat Photopolymerization

During their research, these five major questions were investigated:

01_What is the range of materials used for this technology?

02_What is the producible scale of this technology?

03_What is the resolution of the material and technology?

04_What is the process used to work the material?

05_What is the typical application of this technology in the industry?

The author strongly believes that knowledge of the fabrication process helps designers make better design decisions during the design process. Fabrication knowledge broadens Design creativity and opens new possibilities.

5.10.2 Seminars/Workshops

To promote cross-disciplinary fusion in the studios, several specialists were invited to serve as guest experts. Each gave a one-day seminar/workshop to the studio to address emerging theories/technologies. These workshops varied each semester, based on funding and the experts' availability (Table 24).

Figure 134: Different workshops in both studios:

Structural Design Workshop, Industrial Manufacturing Workshop, 3D printing workshop and Robot Workshop (Top pictures from left to right)

Metal Workshop, Foundry Workshop, 3D printing workshop and CNC Workshop (Bottom pictures from left to right)

Table 24: List of workshops offered in transformable design studios at Virginia Tech and Texas A&M Universities.

Workshops and Field Trips	Virginia Tech	Texas A&M
3D printing workshop	DREAMS LAB	In studio
CNC	Research + Demonstration Facility	Fabrication Lab
Industrial Manufacturing Workshop	Center for Innovation-based Manufacturing (CIbM)	Fabrication Lab
Structural Design Workshop	In studio	Invitation from Aerospace Department
Foundry	Virginia Tech Foundry Institute for Research and Education (VT-FIRE)	In studio and woodshop
Robot Workshop	Research + Demonstration Facility	
Rhino (5 sessions) + Grasshopper (6 sessions) + Diva 4 Rhino (4 sessions)	transLAB	tranSTUDIO

Figure 135: Robot Workshop led by Nathan King, Chip Clark, and Negar Kalantar with the transLAB students at Virginia Tech.

5.10.3 Critics

Just as studios are at the heart of architectural education, reviews are at the heart of the studio learning process. During the transformable studios, there were desk, informal, interim, and group critiques, as well as final reviews; they ranged in size from two members to the entire studio. A critique is essentially a discussion between the designer(s) and a critic; it is used to evaluate designs or works in progress. Inviting critics from different disciplines such as materials science, robotics, construction, structural engineering, and mechanical engineering provided a vast set of opportunities for students to discuss their transformable design concepts and look at the topic from a broader perspective. Unlike the usual architectural studios where critics would come to final review sessions, in these studios the critics were invited to make progress comments (Figure 114). The critics were thoroughly engaged with the design process and helped students gain the knowledge and skills necessary to help their work succeed.

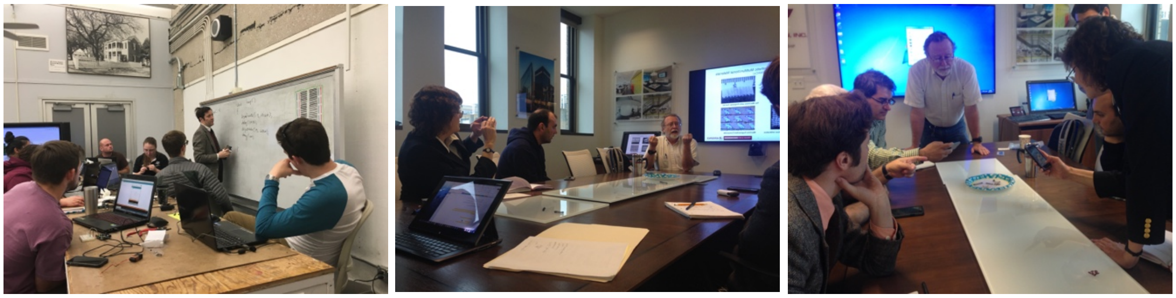

Figure 136: Critics were coming to the studios frequently to advise students during the design process

5.10.4 Exhibitions

"...The best schools connect with [as] many people, places and communities as they can ... to provide an atmosphere where students encounter as many ideas and people as possible, often in unplanned and unpredictable ways."[78]

Feedback was a critical part of the methodology employed in these transformable studios (the model of the studio was cyclic). Loops helped these young designers "find errors faster" in their design processes; therefore, iteration became automatic. The studio environment established communication as a critical element of the studio.

There are three different directions of communication involved in the design process:

- Designer with their design;

- Designer with other professionals (designers, fabricators); and

- Designer with non-professionals (clients, observers, investors).

Exhibition, one of the main means of communication, is a tool often used in architectural education, and an important part of any sound pedagogical strategy. Proper communication creates, in a democratic way, a shared, objective opinion that respects individual points of view as being of lasting value to the creative process. Because motion pedagogy is not well known, exhibition is an attractive pedagogical direction.

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[78] Supplement to Domus. (2013). Europe's Top 100 schools of Architecture and Design. Milan: Roto200.

One of the key aspects of the exhibitions conducted for this research was public education, the goal of which was to inform a wide range of students, faculty, and experts about transformation in architecture and the educational aspects of the studios. The main characteristics of the exhibitions were:

- Informal discussions between students and reviewers;

- A wide range of exhibition visitors; and

- Longer discussions among students, reviewers, and visitors.

During both studios, students engaged in several public exhibitions. These exhibitions provided an appropriate context for exchanging knowledge, skills, and information. The final exhibitions for both studios were one-day demonstrations in the public areas of the schools; this increased the level of interaction and students enjoyed from receiving wide range of comments (Figure 137, Figure 137 and Figure 138).

Figure 137: For the final review in tranSTUDIO, a wide range of reviewers from throughout the university visited the exhibition and gave comments to the students.

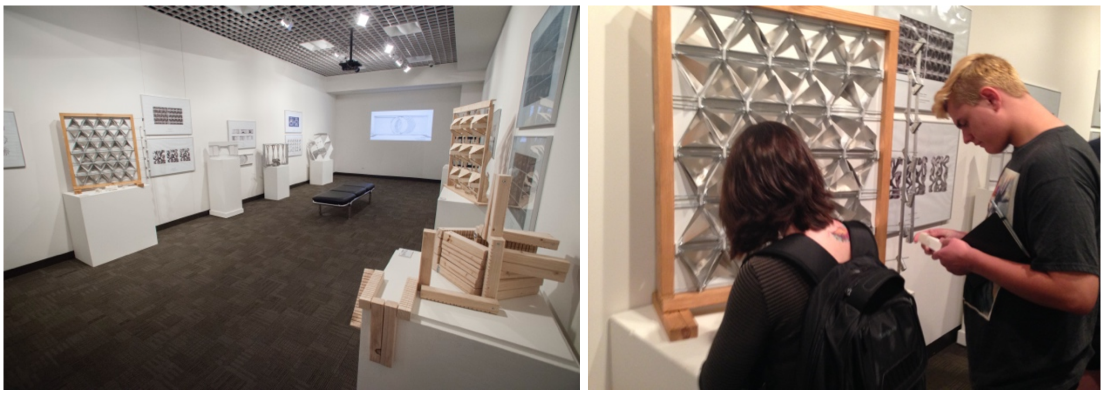

Figure 138: Summer exhibitions.

Figure 139: In transLAB, the students presented their studio projects to the public three times. The growth of the student designs was not seen only in the final models or their final digital representations, but rather at every step in the evolution of their design process, from their back-of-the-envelope sketches through the performance analyses and practicality of their study models.

Beside the college-level presentations, during the summer 2015, selections of student projects were presented in the university galleries. These exhibitions had a strong public education focus.

As mentioned in Chapter I, one of the limitations of transformable design in architecture is people's lack of knowledge of these systems and their benefits. These exhibitions directly addressed this problem by educating people about transformability.

5.11 The Influence of AURA's Design Process on the Studios

Both studios attempted to build upon the previous body of knowledge gained through AURA's design process that deployed the potential of transformation in spatial, physical and sensuous experiences. In a similar vein to the design process of AURA, both studios strived not only to draw students' attention into a new territory of environmental, technological, spatial, and formal innovation of motion in architecture, but also to establish an ongoing body of design research examining the potential for transformable and environment-responsive building skin.

As a next generation of operable shading systems, AURA not only performs to modify its surrounding environment such as light, thermal gradients, air quality and noise, but also to promote dialogue between inhabitant and environment. In the same manner, different operational scales in students' design process were tied together through a methodology that concerned the importance of light, shading, occupant and space.

The design process of AURA frequently transverses the boundaries between actual and imaginary settings. This design process of is a path that travels through a methodology incorporating multivalent and sometimes contradictory agents, forces and contexts. And therefore, AURA's design process is conceptualized as an ongoing inquiry and a field of experimentation. To drive new potentials for students 'works, the studios leveraged the design process of AURA to explore transformable architecture through both success and failure.

In addition to expanding students' repertoire of reasoning frameworks about transformable architecture, the design process of AURA helped students explore how to think about some of the inherent complexities involved in their transformable shading design as well. Through witnessing the design process of AURA that employs the concept of transformability as an exquisite design tool, the architecturally-geared process of designing transformable shading devices observed and scrutinized through the disclosure of several studio activities.

While the act of design transformable architecture is inherently forward-looking, the study of precedent for the understanding of mechanism underlying transformable objects often plays a central role. In both studios, whether through the analysis of AURA's motion generators, mining of their design principles, or application of their mechanisms, the study of AURA's models as tangible precedents was of interest for a number of occasions to introduce new ways of thinking about shading systems.

5.12 Main Lessons Learned from Students' Designs in transLAB and tranSTUDIO

The thirteen attributes that represent main lessons learned regarding students' design processes will be discussed below. Eleven attributes are similar to the lessen learned attributes of AURA's design process. Here, two more attributes are added. The main lessons learned in both studios include the followings:

- The Essential Loop Process of Designing and Making in the Early Design Stage
- Essential Interaction Between Physical and Digital Modeling
- Essential Nature of Working with Different Modeling and Environmental Software
- Essential Nature of Environmental Design Knowledge
- Essential Basic Kinematic Knowledge
- Essential Basic Structural Knowledge
- Focusing on the Geometry of Motion
- The Collaborative TSS Design Process
- Tolerance as Critical to the TSS Design Process
- Essential General Knowledge and Skill about Fabrication

- Material Properties in the Early Stages of the Design Process
- Spatial Quality Offered by a Transformable Design
- Representation and Documentation of Motion as a Way to Narrate the Notion of Change

5.12.1 The Essential Loop Process of Designing and Making in the Early Design Stage

In schools of architecture, students mainly create discrete and fixed physical and even digital models. Making a series of fixed but different models is fundamentally different from models that present a sequence or series of mutable configurations in a single dynamical flow. Belonging to the "making disciplines," a transformative model that provides a new experience punctuated by specific motions hones students' hands-on creativity and fabrication skill.

At a time when the education of an architect is becoming ever more detached from making things, students normally have little or no opportunity to track their design propositions from concept to fabrication. Since the author believes that making is a way of thinking and knowledge gathering, "Learning by doing" was of primary importance in both studios (Figure 140).

In the studios, by reinforcing the connection between hand and mind, the close engagement with kinetic prototypes offered students the chance to reconcile the disparity between "making" and "thinking". By constituting a foundation in a world of discovery, the design studios became a place where students could purposively navigate the intersection of the universe of ideation, and the universe of physical reality. Through a more in-depth survey of materials and an iterative process of making, students gained insights into the connections between what was imagined and what was constructed, between the probable and the ideal. By confronting a variety of issues such as the behaviors of materials, fabrication constraints, tolerance, and assembly logics, the studios were a vehicle for reflecting upon the reciprocal relationship between forms of motion and the means and methods of their fabrication.

Figure 140: In motion pedagogy, making and prototyping is a way of thinking. Making is integrated into the design intent and prototyping is considered a methodology for knowledge gathering and design thinking

transLAB and tranSTUDIO allowed students to arrive at a personal catalogue of tectonic possibilities that they can access when actually making their designs. By working back and forth between toolsets for a given task, students contemplated not only how the nature of craft begins to change with a change in tools, but also how their design concepts can be open to a negotiation with the tools they utilize. In the studios, the close ties to the currently available but limited resources of both analog and digital fabrication at Virginia Tech and Texas A&M provided an opportunity to drive more thorough and thoughtful investigations upon the very ways the existing tools might be employed.

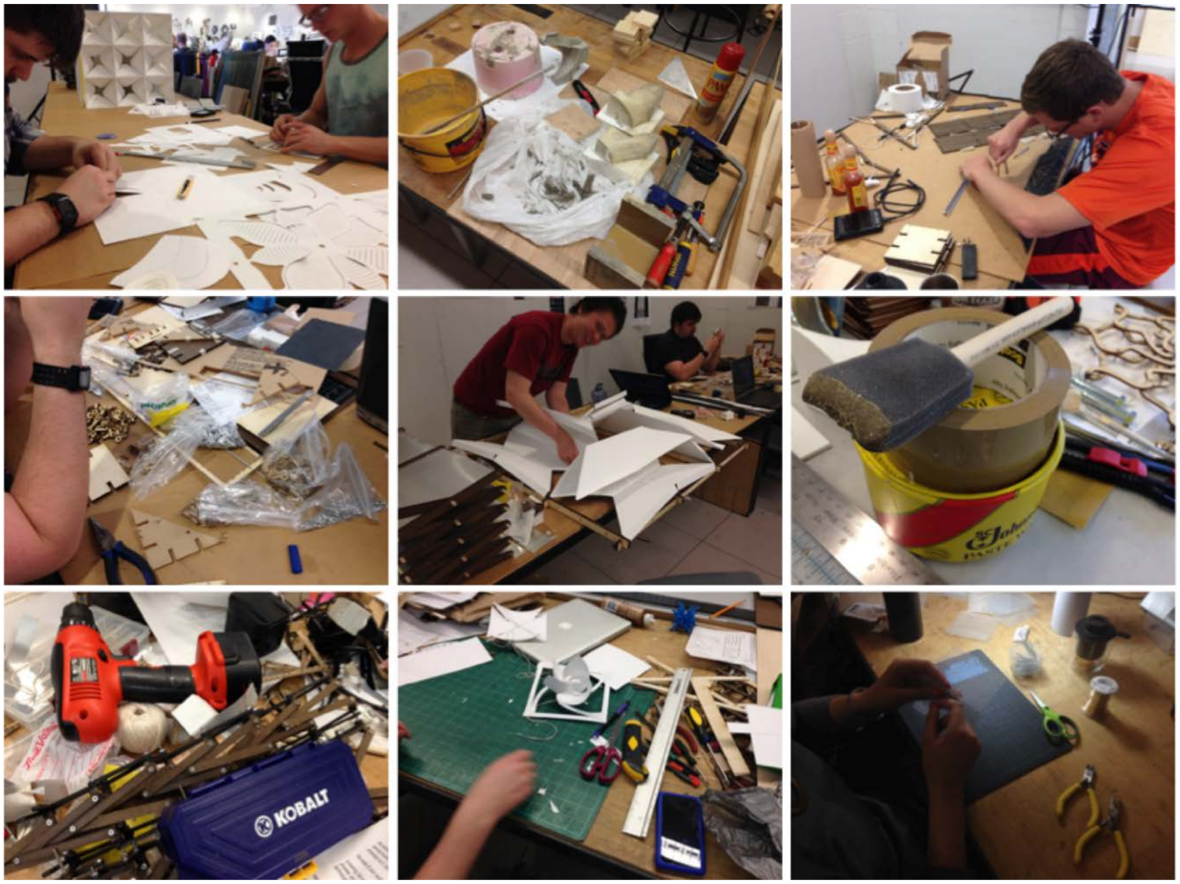

Figure 141: Prototypes remain the dominant form of communication in the transformable design studios

As Mitchell (Mitchell 2001) mentioned, architects draw what they can build, and built what they can draw. At a time when architecture students can draw nearly any non-standard geometry through their use of the current collection of parametric digital tools, it is essential that they obtain a more profound understanding of the ongoing advancements being made in the area of fabrication. Students will have insufficient knowledge regarding the capabilities of the fabrication process if they take a limited approach and understand fabrication only as a technological means, and study fabrication solely in terms of its technical effects.

Aiming at a broader understanding of fabrication, one of the studios' objectives was to develop an approach toward processes that engage students with "techne" (or the craft of design and construction) instead of "technology"[79], while incrementally introducing them to concepts of transformability in shading devices. Thus, the studios highlighted the need for critical engagement with the actual effort of making, whether that making is digital or in an analog form.

Throughout two semester-long studios, the relationship between architectural ideas and the tools used to express them underwent a profound transformation. Student gradually understood that It was not enough to have an idea: they should be able to make it real and tangible. In response to students' tangible learning experience, the use of prototypes became a constant in both studios. Making their models in a variety of scales brought students into real-world situations and gave them an embodied experience to gain insights, skills and understandings. At the end of semester, "know-how" was the key to translating students' design thoughts into working prototypes.

By thinking about industrial scale of fabrication, the studios were a place where students encouraged to constantly evaluate why their component were made the way they were. Underlying pressure to make their final models in a significance way and a healthy fear of failure persuaded students to think about how the tools they used could conduct a novel inquiry into craft and making. For example, to mark a shift from a handcraft small model to rapidly manufactured shading devices as working prototypes required students to establish a conversation between an internal organization of material assembly and a digital model (Figure 141).

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[79] Although technology is the study of techne, Aristotelians differentiate techne from technology. From this point of view, technology implies an understanding of craft and refers to the knowledge that things are made without the ability to make certain other things. Techne - as the mastery of specific techniques - is a kind of knowledge that is practically applied and associated with the making of a particular craft.

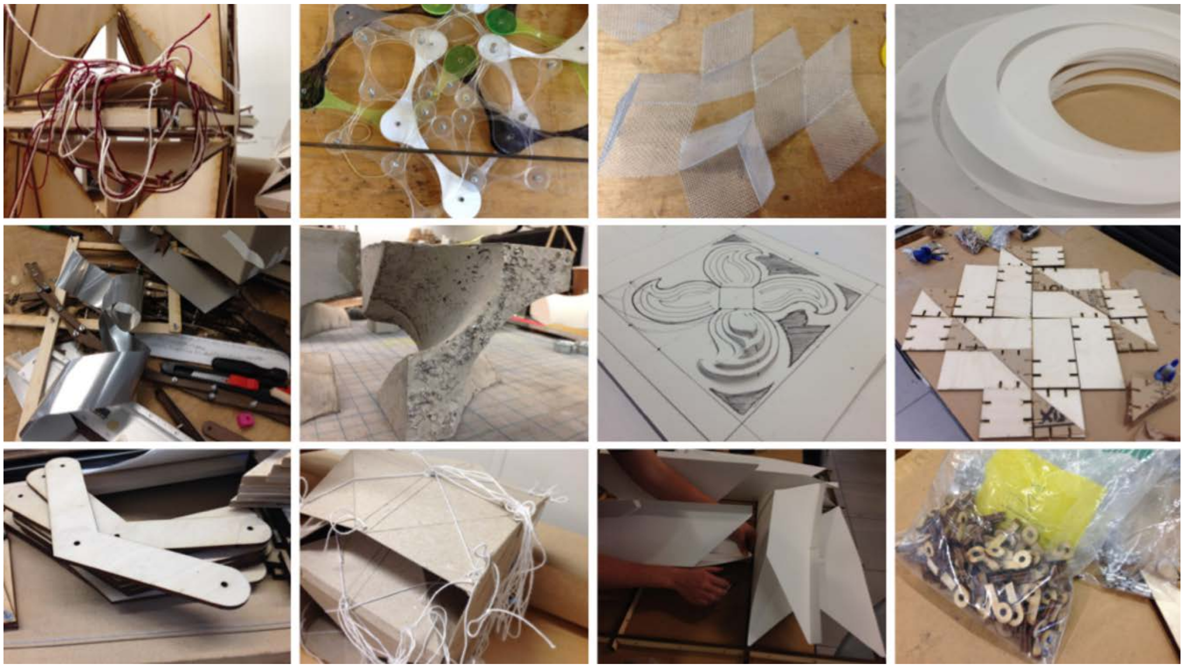


Figure 142: A file-to-fabrication approach works effectively when the file creator has an explicit understanding of the materiality of the final design medium.

As mentioned before, a part of tranSTUDIO was devoted to a semester long group research project, which winded up in the design, fabrication, and installation of a full-scale transformable wall. This project leaned on the efforts of all students. As a group project, students had free reign to explore about the specifics of the transformable wall (Figure 143). The initial design, material exploration, and fabrication experimentation of the wall project began simultaneously about half way through the spring semester of 2015. This simultaneity created an active information loop to feed the design process as students proposed and tested different material and techniques for making the required joints and scissor like bars. In this group project, all the details of joints and bars were carefully elicited.

Figure 143: The transformable wall fabrication process

Beyond what to design, but how to design a kinetic structure at full scale, this assignment was an endeavor to alter students' perspectives of the reality of constructing ideas. Those students that engaged in design and fabrication of the wall were subject to substantial knowledge gain through hands-on activities. In the end, students' ability to see failure or success was an essential stepping stone directly to the students learning both the pragmatic and theoretical.

The last assignment of both semesters provided an opportunity for students to design and fabricate at full-scale transformable shading components through the integration of environmental constraints, form and material (Figure 144).

Figure 144: Transformable shading system. The Pedagogy of Motion endeavors to create a better understanding how an exploratory concept of motion can be codified to suit different technical, economic, and cultural considerations.

5.12.2 Essential Interaction Between Physical and Digital Modeling to Craft Motion

In the studios, the making of a series of iterative digital and physical models, as a way of knowledge gathering and design thinking, was integrated into the design intent. Therefore, different models, ranging from small detail drawings to full-scale mock-ups, were made to thoughtfully engage motion design principles and manipulate their bounds and constraints.

Direct, hands-on engagement at every stage of the transformable design process did not simply alter the way students design; it provided an extension to their thinking and produces in them a wholly new method of concrete design thought.

In the course of a semester, by their development of a constructional craft[80], students' progress was manifested in the act of continuous prototyping and modeling. The conscious development of prototypes became an integral part of design development phases.

In both studios, each of students was asked to make different digital and physical models, not only as a pedagogical tool for providing hands-on experience, but also to illustrate how such prototypes can serve as momentary crystallizations of an ongoing progression that allows students' sensibilities about the design process to be examined and cultivated.

By translating the students' design thoughts into tangible experiences within the context of motion, the following transformable models were made:

1. **Concept models:** by representing the primary ideas, digital and physical models helped students not only to understand their own designs in better ways, but also to communicate their thoughts and workflows to receive feedback from peers/other students.
2. **Constructive (form-fit) models:** by visualizing how well the parts of their designs could fit together and analyzing how those parts could move either separately or together, students built several constructive models to examine the

[80] Based on Frampton's definition of architecture. (Frampton 2001)

underlying geometries of their mechanisms and facilitate the discovery of any errors.

3. **Operational prototypes:** by checking material behaviors, scales, dimensions, and final detailing, students verified the functional and operational aspects of their designs and finalized the overlying geometries of their mechanisms.

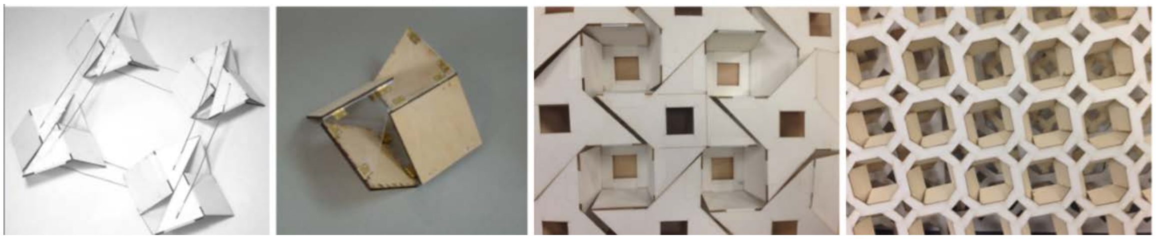
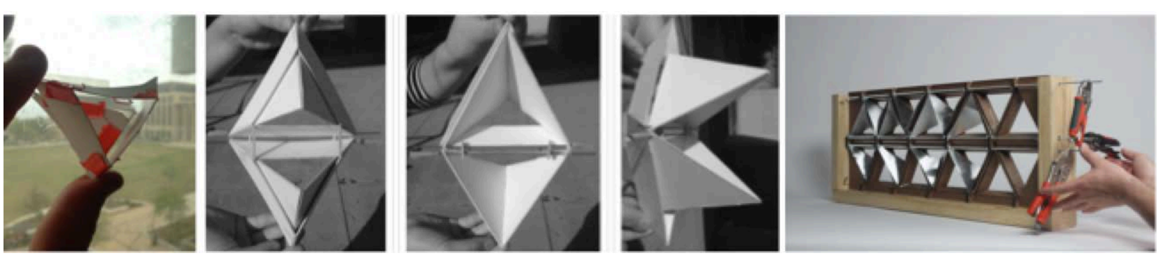


Figure 145: Concept models (digital and physical) -Constructive (form-fit) models (digital and physical) -Operational prototype

The above-mentioned students' prototypes and models challenged the territory between scales (Figure 145). Somewhere between the one-to-one working models and small-scale models, the true implications and magnitude of these prototypes were much more eminent than the scale of the work they initially exhibit.

A result of thinking with and through the digital and tangible artifact, each model or prototype was not so much a finished product as it was a motivator of the innovation process. In addition, students' physical or digital models did not serve as ultimate endpoints to design concepts. Through constant evolution, their models became a medium by which they could make inquiries regarding the process of how a transformable device might be fabricated to be a product (Figure 146).



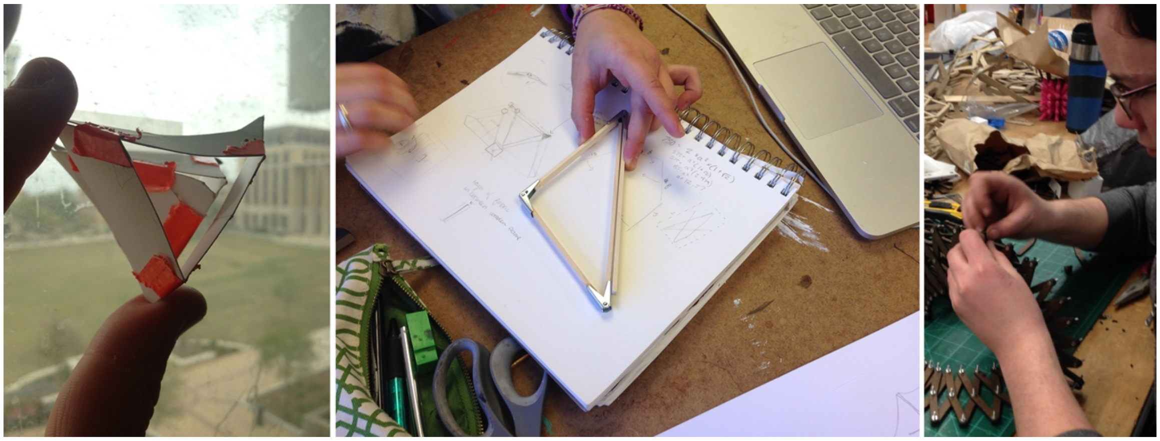


Figure 146: Making as a way of thinking

Through making different prototypes and models for different purposes, the opportunity to intellectually move between process and product deepened students' understanding of form, material, structure, and movement not as separate elements, but rather as complex interrelations (Menges and Ahlquist 2011). In the twinned coexistence of process and product, students thus arrived at the fundamental question that must be asked of themselves through the course of making their prototypes: was it the process leading the product, or the product leading the process? In a determined search for the answer, the studios permitted iterations of the final product to be embedded into various feedback loops, thus forcing it to traverse a diverse landscape of expectations, possibilities, and investigations. As such, the finished product - as a manifestation of various different forces - embraced the exploratory nature of design research to find new drivers for design conceptions.

During the early days of both studios, some of the physical models produced were a bit crude, with less explicit issues of craft (Figure 147 and Figure 148). At these early stages, the modeling materials and details often lacked the proper precision to effectively demonstrate full-scale mechanical and structural behaviors. However, this imprecision, stemming from a lack of experience with designing kinetic mechanisms in their previous classes, opened the door to new forms of experimentation and further speculation within the transformable design field. Gradually, students accustomed to making more refined models were thrust into the process of dealing with the actual tools required to realize their visions. They learned how to selectively constrain or expand their proficiencies to leverage both analog and digital methods of production.

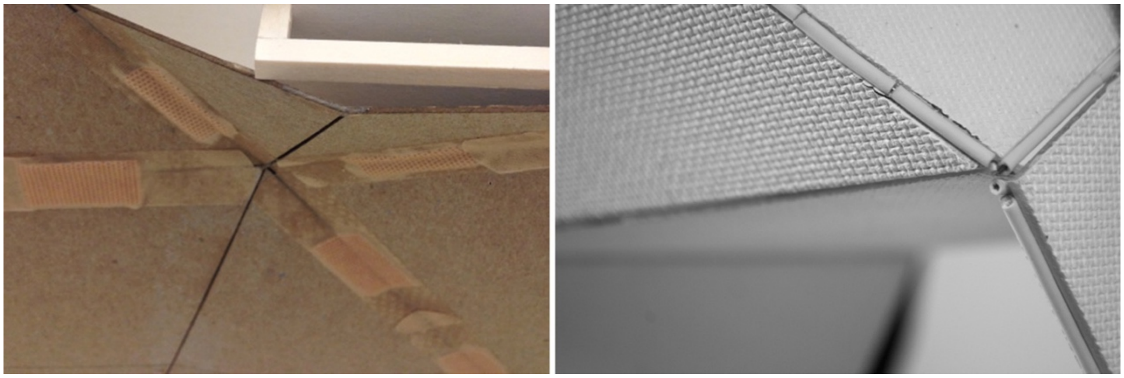


Figure 147: Development of details for a folding door, tranSTUDIO, Texas A&M, Spring 2015

Figure 148: Some of the models produced were a bit crude, with less explicit issues of craft

The resulting different types of prototypes and models encouraged students to push their proposed mechanisms' behaviors to their limits (Figure 149). By allowing students' digital models to be physically manifested and truly examined, these studios assisted students in leading their own investigations into how the constructive reality of their concepts unfolded in time as natural forces such as weight, friction, and the resistance of materials engage with them.

Some of students' prototypes approached the limits of possibility. Though these prototypes remained uncompleted, in the studio setting they opened up new avenues of exploration regarding methods of making. Comparisons between digital models and the completed or uncompleted physical models helped to demonstrate an essential subject for students hoping to understand the ways in which transformable architecture should be acknowledged in the early design stages: the correlation between forms of motion and means and methods of fabrication. Establishing this correlation does not simply mean accepting any deterministic approach to fabrication techniques. Beyond whatever advanced technology is available, there is a chance to see tectonically primitive prototypes. In this manner, the working prototype was a test of the student's will and skill; it was the space in which their vision was ultimately manifested in the continuous improvement of knowledge of fabrication.

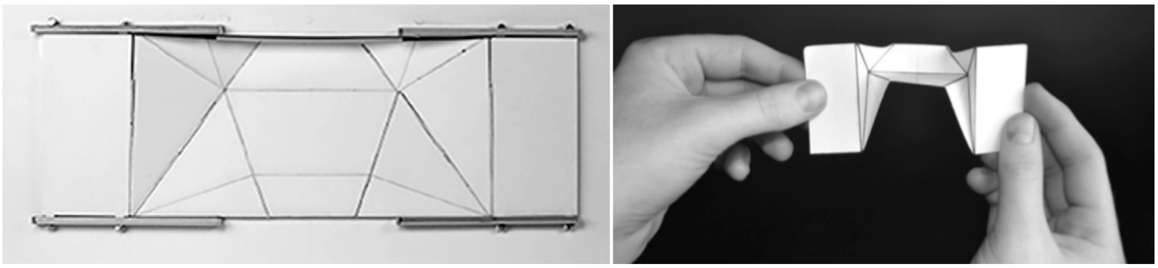


Figure 149: Developing concept models in different scales, tranSTUDIO, Texas A&M, Spring 2015

To reach an acceptable level of craftsmanship and quality of finish within the length of a semester, the front-end research into the required materials, driving mechanisms, or control systems and the time-intensive prototyping and fabrication process of a transformable shading system were not inexpensive and sometimes necessitate financing.

As a place for both digital and physical experimentation and prototyping, the emerging fabrication technologies were a part of the studios. To minimize the often expensive, demanding, and messy processes of physical prototyping, students' concepts emerged alongside the utilization of various digital fabrication tools such as laser cutter, 3D-printer, CNC router, or robotic arm. For instance, when designing and building different mechanisms, 3-D printed parts were able to easily serve different purposes in different scales. In one of student's project in transLAB, the joints of an inverse cone-like structure with angulated scissors were made out of 3-D printer (Figure 150).

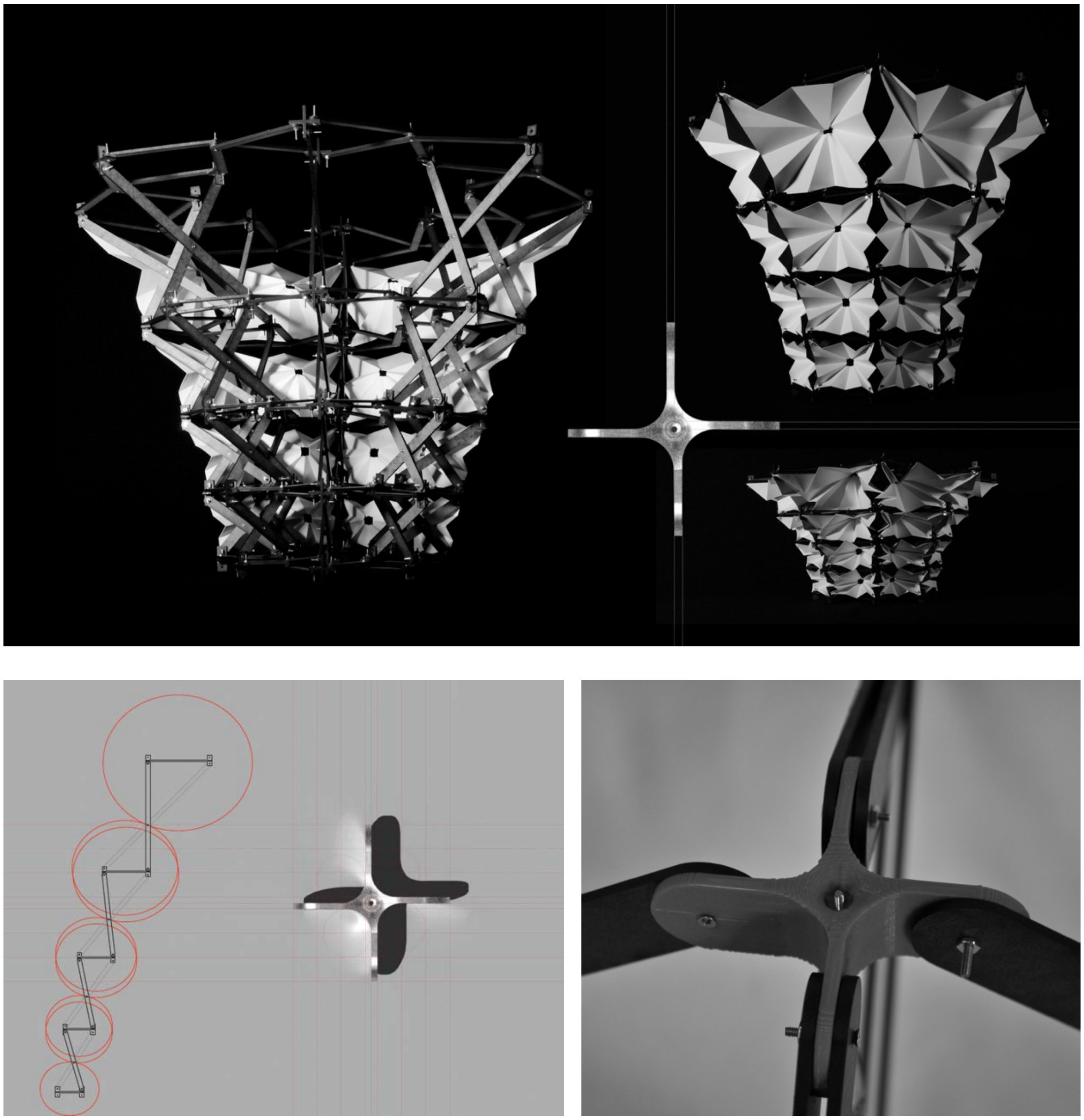


Figure 150: This image is of a transformable structure with angulated scissors and 3D printed joints. The joints were created so the fins that attached to the arms would be offset, no washers would be needed, and the number of fastener pieces would be minimized.

For making their prototypes, students in both transLAB and tranSTUDIO took advantage of the school fabrication facilities inside and outside of the campus. Unfortunately, in some cases, locating the studio space far away from one of the school shop located out of the campus that had full-bed four-axis milling machines limited the tight interplay between tactile explorations of motion and prototyping. Moreover, these facilities initiated a new direction in the development of students' thought process. However, the lack of sufficient "machine-time" to complete all the individual projects was a major challenge. Since digital fabrication machines require complementary operational skills, experiences, and knowhow to be successfully used by students, some students ran the risk of failure to fabricate a fully functional prototype by using unfamiliar tool sets.

5.12.3 Essential Nature of Working with Different Modeling and Environmental Software

At a time when the notion of perpetuity and timelessness has stayed deep-seated in the architectural education and practice, an adaptable architecture is left too far behind in terms of environmental performance. Since, the author believes that it is in the hands of architecture schools to meet this important need of today, both of her studios endeavored to tackle such shortcoming under the rubric of transformable architecture by strengthening the link between motion study and environmental performance analysis.

As the studios progressed, the studios' workflows offered the opportunity to be familiar with the basics of environmental analysis software. Through the end of both studios, students learned more about energy and climate-based daylighting analysis techniques. Specially during the last assignment, learning the basic concept of daylighting emerged from an in-depth consideration of the role played by shading devices as environmentally performative elements of a building envelope.

With a heavy focus on the performance alongside the appearance of students' proposed shading devices, performance analyses software helped to sharpen the students' instincts for kinetic design and helped them find the necessary drivers for their design conceptions. For instance, to better understand the performance integrated design and explore more the dynamic behavior of shading devices, students' competences and experiments were extended with DIVA, an optimized daylighting and energy modeling plug-in for the Rhinoceros. An active information loop provided by DIVA helped students to interact dynamically with feedback mechanisms that facilitated their decision-making process at the early design stage. In transLAB, the efficiency of a transformable shading system of the final assignment was simulated on a west-facing wall at different degrees of opening by using DIVA light simulation. Using DIVA assisted students to learn more about potential impacts of different design decisions that went into their proposal.

Another key objective was to provide students with the fundamental skills and knowledge necessary to develop parametric digital models and analyze their performance. Through several workshops, the introduction of parametric modeling tools, the fundamental knowledge of parametric design methods, and the basic techniques for performance analysis were covered. By reviewing several case studies, students became more familiar with performance simulation, interpretation and implementation techniques. In the studio, by varying one or more parameters over some ranges, students' concepts emerged alongside the use of Grasshopper, a visual programming platform for the Rhinoceros. to produce a series of alternatives through successive loops of observation and modification.

In terms of transformable shading system, meeting specific daylighting requirement should be dealt with carefully due to complexity associated with analyzing visual comfort. To this end, students investigated the possibilities of their shading design concepts via some parameters using Grasshopper. When students developed their parametric models in Grasshopper, they were able to manipulate with only few parameters to change the opening and closing ratio of their design without any addition modeling process and transform the overall geometry of shading devices accordingly. Then, by using DIVA and defining the scope of daylighting analysis, analysis metrics, required period, locations and orientation of their shading devices, students compared different alternatives to ensure whether occupants could get enough daylight level, and whether light in the space was well distributed. By reviewing the variation of proposed design quickly, students could envision different daylighting performance scenarios for a year as the parameters were changed. Students were encouraged to apply optimization algorithm in order to get a better simulation result (Figure 151 and Figure 152).

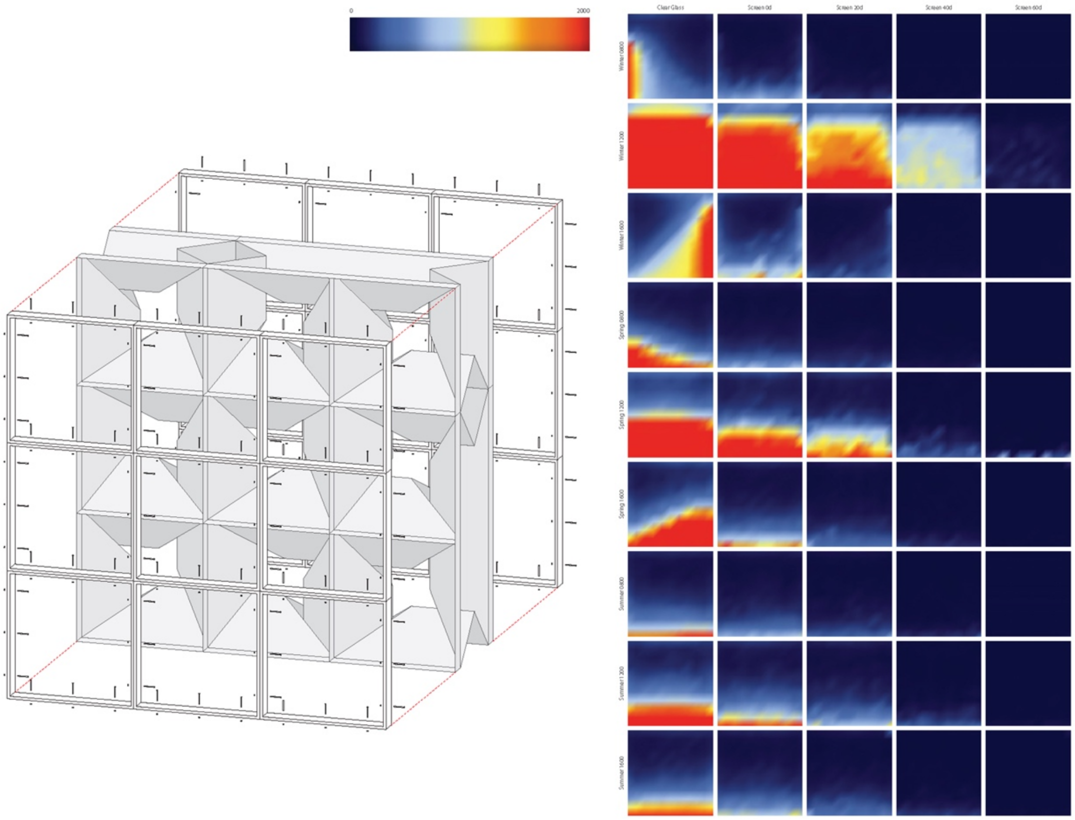


Figure 151: DIVA light simulation. The efficiency of the transformable shading system was simulated on a south-facing wall at different degrees of opening.

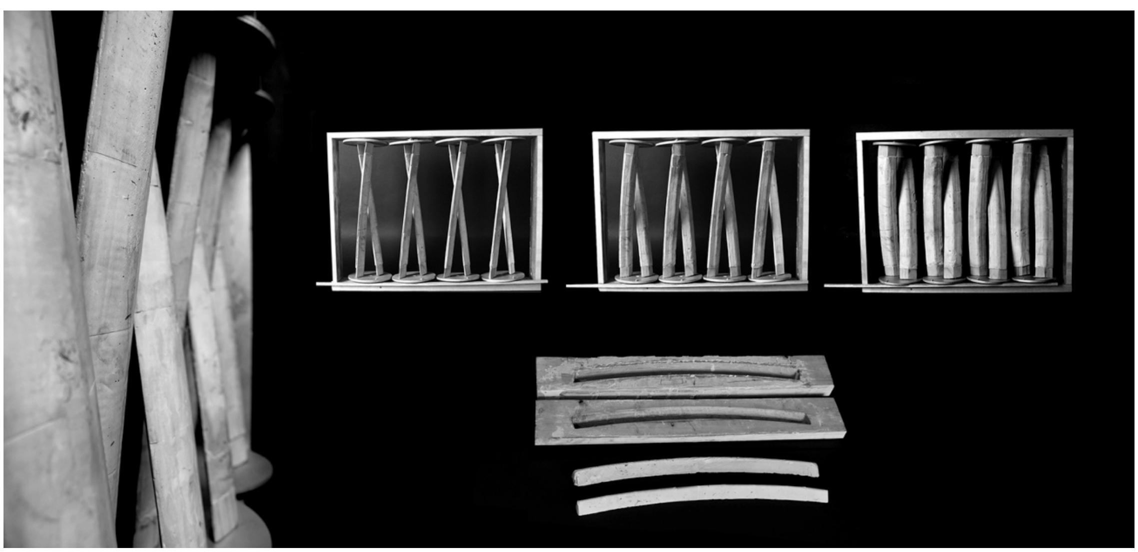


Figure 152: Concrete releases heat at a rate slower than that of most other materials and can serve as a passive heating strategy. To achieve the slender form, steel wool was chosen to reinforce the concrete. When the system is fully opened and closed, the surface area coverage ranges from 15% - 85%, utilizing the concrete formwork.

In Grasshopper, since the geometry of model is temporary, the possibility of changing variable over time is gone after converting the geometry into Rhino and baking the model. After backing, their models were not mutable any more. By missing the temporal change following baking, any future alterations in Grasshopper will not be reflected in the baked geometry. After baking their final digital model in Grasshopper, students had to introduce the motion of their models into a sequence of static frames that underlie a family of continuous variations (Figure 153).

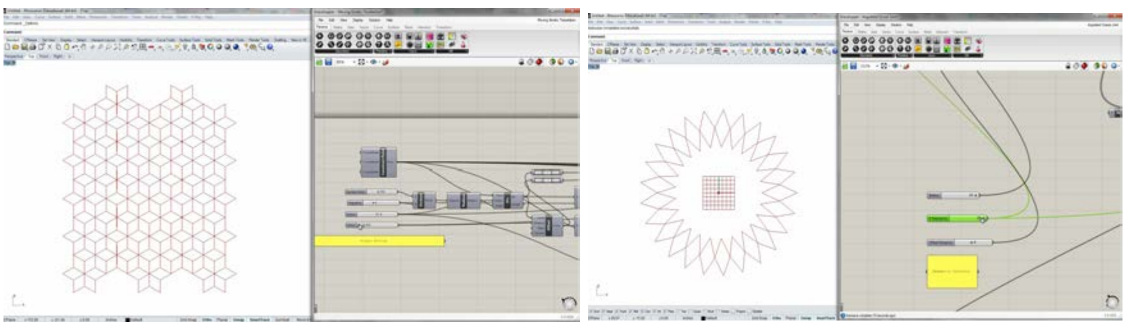


Figure 153: Motion studies in Grasshopper

At the end of semester, along with extensive use of Rhinoceros and Grasshopper, and dedication to Diva for Rhino, students led to establishing a better understanding about motion by integrating motion design proficiency with a broader view on performance analysis.

5.12.4 Essential Nature of Environmental Design Knowledge in Students' Designs

There is a belief that environmental awareness should be embedded in the education of architecture design students. If this education hopes to inspire a valuing of environmental consciousness, it must also find significance in adaptable design strategies to augment the creation of a more sustainable environment. Additionally, it should motivate the next generation of architects to use motion to develop a better understanding of how buildings can reconfigure themselves physically to adapt to change. By enabling architecture students to explore the concept of adaptation as it relates either to environmental circumstances or the will of the building's inhabitants, the pedagogy of transformable design has the capacity to evoke powerful questions regarding a new way of living through new forms of interaction.

In a world undergoing changes, in order to be effective agents of change for the future of architecture and in response to increasing concerns about sustainability, the pedagogy of transformable design is driven by an interest in exploring the capacity of built space to adapt to becoming an integrated part of its fluctuating environment. Motion pedagogy is brought into architectural education with the mission of improving the quality of our living environment. This pedagogy emphasizes that no transformable design concept should be implemented without a strong awareness of the associated environmental factors. From this perspective, transLAB and tranSTUDIO attempted to establish a path by which architectural education might cultivate better connections between motion, buildings, and their environment by asking the following question: How would the next generation of architects engage with movement as a design medium to create a meaningful level of building malleability?

Although the primary role of motion – to improve environmental performance – has been acknowledged by scholars for decades, it has not been made an overarching priority by typical curricula addressing sustainable studies. As a result, sustainable design courses focus only sparely on the role of motion in creating a better environment.

In the studios students' ultimate aim was to probe the potential of their designs for performing a range of environmental function, in which motion was an essential part of students' design proposals. Students' prototypes were not mere neutral applications of a particular technique; they fused with their creators' understanding of the environmental aspects of their designs. Through the performance analysis of their digital and physical models, the students developed an intimate awareness of the interplay between environmental requirements and mechanical constrains.

By incorporating more environmental considerations into their final assignment, the conclusive design outcome of both transLAB and tranSTUDIO was supposed to be dynamic and adaptable shading devices for windows wall of the Art + Architecture Library, located in Cowgill Hall at Virginia Tech University and the Museum of Fine Arts Houston (MAFH). In students' design proposals and prototypes, the functional expression of the operable shading devices was translated into active architectural geometries that sponsor new relationships between the museum man and environment. In their design as an external or internal shade, students mainly designed different panel open and close to block or admit light. Focused on the light performance of shading devices, students' design proposals did not aim to change the existing shape or structure of building envelope.

The design process of final assignment in both lasted approximately 25 days. In their final assignment, students' prototypes became larger in size and intricate in detail and served as a touchstone for examining the performance of possible design approaches.

In the final assignment, although students had to deal with window walls with predetermined dimension placed in predetermined location, students realized a huge potential left open for discovery. In the assignment, students themselves laid out a whole new set of directions as they engaged to design challenges of a shading system.

Based on own design process as a research-oriented approach to creating shading devices capable of functioning as a part of building skin, students were permitted to deliver dynamic or even static shading systems. For instance, one student in transLAB and a team of two students in tranSTUDIO decided to proposed the aggregation of an individual concrete module as their shading system. In their students' designs, when the modules were stacked together, the system created perforations in a structural wall (Figure 154 and Figure 155). Their shading system required no mechanics or wiring as its pure materiality and function was static. However, when light awakened, it flooded the pockets transforming the system into a kinetic, yet beautifully subtle, light show.

Figure 154: Self-continuous concrete module designed in transLAB

Figure 155: Self-continuous concrete module designed in tranSTUDIO

At the same time, by changing with climate, need or purpose, the other student designed transformative mechanized shading systems in which several mechanical arms control individual modules and the overall movement of the proposed systems (Figure 156).

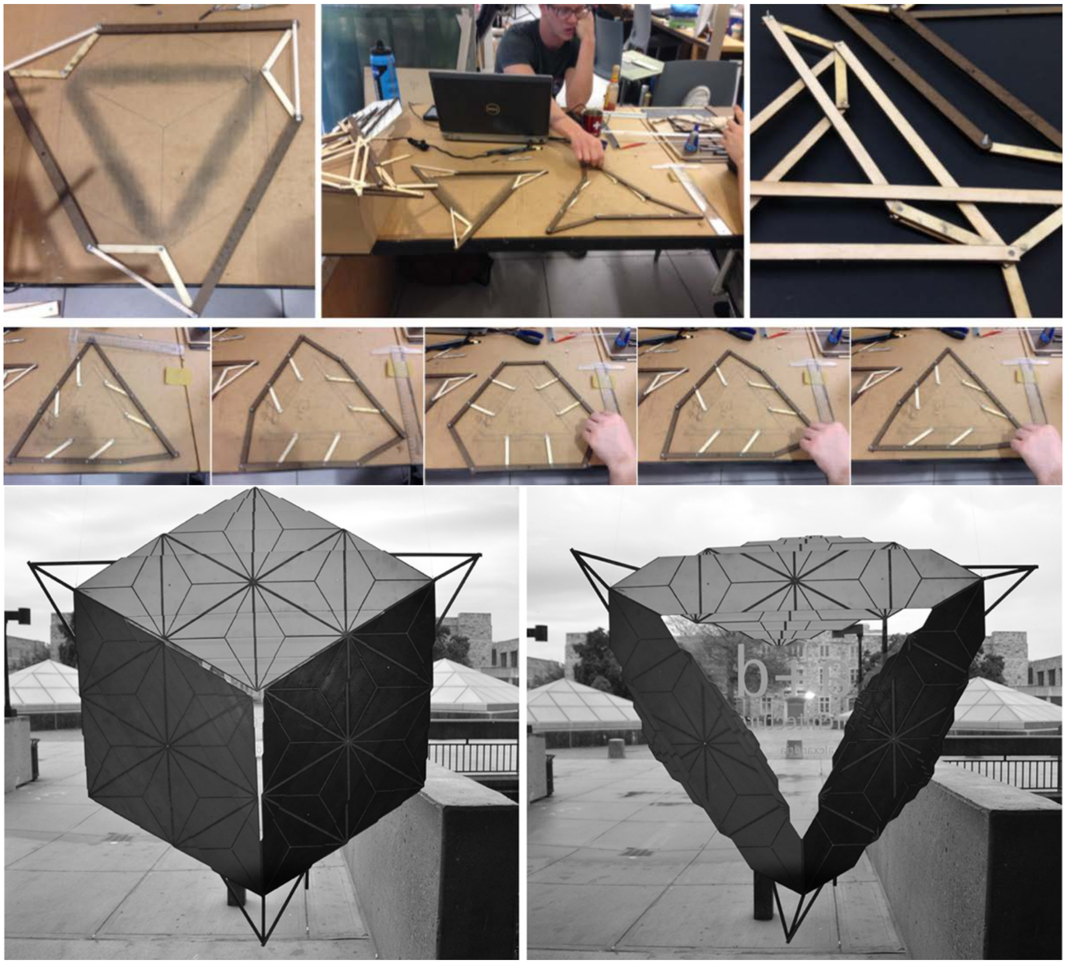


Figure 156: Transformable shading system. The top images show the process of designing mechanical arms that could control individual modules. Bottom: the mechanical arms show the hierarchy; the Masonite controls each individual module while the steel controls the overall movement.

In both design studios, students came up with a range of different design approaches. For instance, one student in tranSTUDIO designed a self-transforming screen that could stand still at any desired point. As a foldable device out of thin material, this shading system was compressible between two planes of glass. The fold system flattened out and covered the entire opening. Elastic fabrics were laminated between two layers of veneer to provide a hardware-free hinge for the fold system (Figure 157).

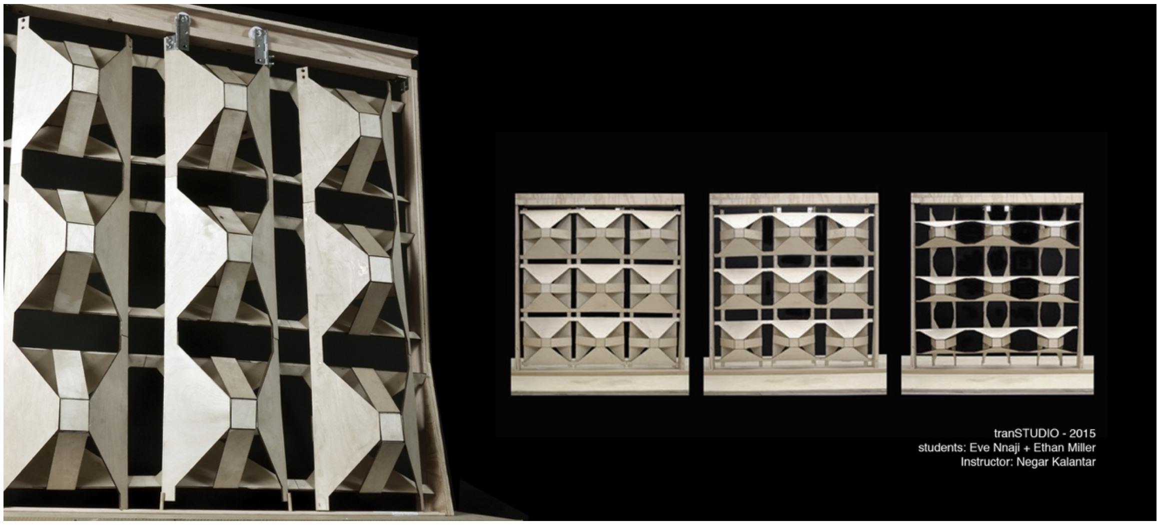


Figure 157: A transformable shading system. The fold system flattens out and covers the entire opening. Elastic fabrics were laminated in between two layers of veneer to provide a hardware-free hinge for the fold system.

Another student in transLAB designed a modular transformable shading system. In his system, each individual module was 1 foot × 1 foot. The whole system expanded to a depth of 1 foot. The back frame was attached directly onto the window mullions while the front frame remained free to be manipulated into position by the user through the use of a linear actuator (Figure 158).

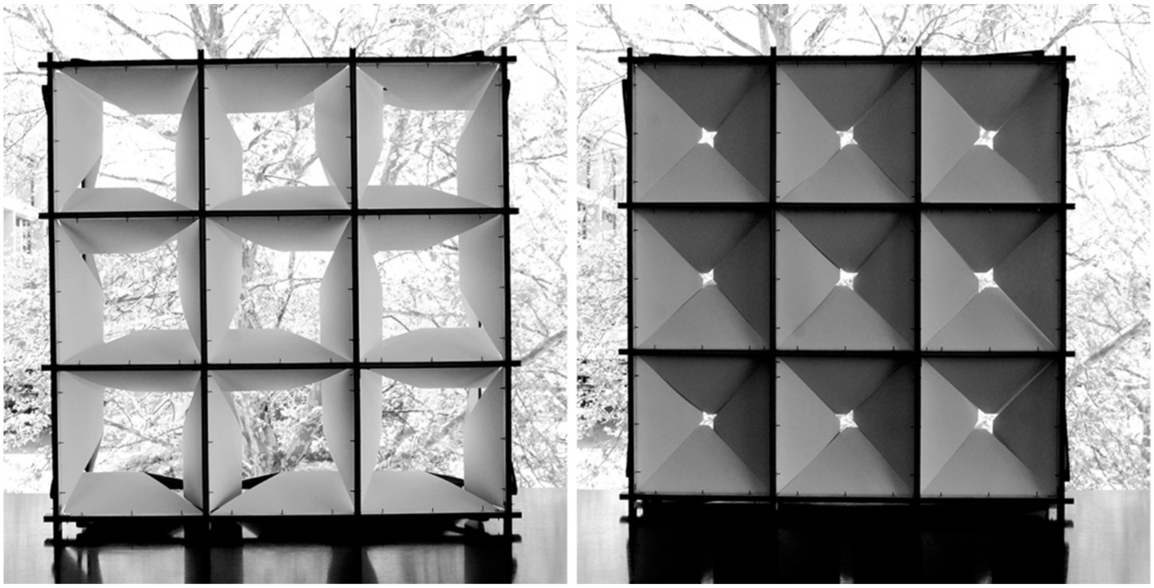


Figure 158: In transLAB modular transformable shading system was designed and manipulated through the use of a linear actuator.

5.12.5 Essential Basic Kinematic Knowledge and Mechanism Design Process in Students' Projects

Motion is often confused with mechanism in motion-related courses. Moreover, the design of a mechanism required to drive a specified motion is considered to be of minimal technical significance. What is necessary is a shift in sensibility from the linearity of technological advancement to the complexity of contemplative engagement with what the mechanism might offer to the grater design process. For instance, technical aspects of a proposed mechanism could be addressed in a way that all its parts brought into relation by motion operate to establish a cooperative sense of wholeness. In this case, students can think how to bring the motions of different components together in some uninterrupted rhythmic harmony or what might be the consequences of speeding up or slowing down the movement of different parts of a mechanism.

Due to the lack of engineering background, the principle or methods of a desired mechanism often remains intact in design studies. Thus, design students who want to design transformable design frequently find it difficult. In place of a vaguely informed guess of how a proposed mechanism might perform, the lack of comprehension regarding motion design principles can lead to failure. Some students may have a grasp of basic motion design concepts, but are unable to apply them to the more complex systems. Mechanical approaches to design motion can fall within a number of considerations. Table 25 demonstrates main components of movement design.

Table 25: main components of movement design

Mechanical Strategy	Methods for the actual movement of components (Mechanism)	Such as translation, rotation, scaling, and motion through material deformation.
	Methods of performing movements	Such as hinged, scissor hinged, ball and socket, and linear actuate.
	Methods of actuation	Such as actuated cylinder, magnetic systems, shape memory alloys and chemical systems.
	Methods of control	

Both studios educated students who did not have any background knowledge on the topic of kinematic to design different mechanisms to address a range of projects. In students' designs, different parts worked for and against other parts causing the whole system to slide or rotate. In transLAB and tranSTUDIO, the primary method of designing such mechanisms was to ask students to begin with a relatively simple yet rich kinetic concept, and gradually add levels of complexity. Students realized how the complexity of their design could emerge from very simple rules of rotation and translation. Therefore, as students' design proposals grew in complexity, students became able to maintain the simplicity of their designs within the governing rules of motion language. In the conceptual design phase, students sometimes required an abstraction of concrete reality (such as the technical complexity) to rapidly explore and refine their ideas.

Because the kinematic method was new to students, it was an opportunity for the instructor to facilitate their discovery of mathematics and the principles of geometry in an unfamiliar context. Through a number of simple models of AURA, the author presented the application of motion generation problems to the design of certain simple mechanisms. Of course, at this early stage, the only objective was to teach solutions to the problems associated with motion generation. Then, students tried to apply this knowledge to the design of thoughtful mechanisms for their design assignments. For example, in the underlying geometry of an AURA's model presenting a desired set of motion, students understood that distances between some points were supposed to be unchanged as the other parts move. In AURA's models, the relative movement between points was assumed by the simple assumption that the material devoted to a specific design did not deform under the action of applied forces. Moreover, in studying of underlying geometry of AURA's models, students could see how pure rotation without any constrains, pure sliding without any stick phases or frictions, as well as pure rolling without slipping were considered.

To combat the lack of supporting background information and experience in the field of motion design (which are the major obstacles to students' progress), the pedagogy of motion aims to give architecture design students the ability to understand, design and make simple but advanced mechanisms through a cyclic process of physical and digital modeling, examining, and refining of the design. Whereas, the amount of time given to develop their design was a battleground for most of students without knowing the language of motion. In both studios, quickly made of appropriate materials, a number of scaled-down models were developed and evaluated to apprehend how a certain type of movement could be accommodated. Until students' designs arrived at the desired shapes and perform well, students were encouraged to improve their designs through developments in their arrangement, size, and pattern, while also working with multiple prototype reiterations.

The general lack of experience with designing kinetic mechanisms in their previous classes opened the door for students to experiment with new forms and produce novel speculations within the transformable design field. Throughout one semester-long studio, students were prepared to exploit different kinetic mechanisms and understand how each one disclosed something lacking in the other mechanisms. By observing how each set of mechanisms gave rise to a different set of considerations, the studios encouraged students to push their proposed mechanisms' behaviors to their limits.

Both studios emphasized the simultaneous experiencing of environmental response and the application of conceptual kinetic mechanisms. Advancing an intimate awareness of the interplay between mechanical constraints and environmental requirements, students incorporated an abstract mechanism into a transformable shading device, allowing it to change its geometry in response to the position of the sun (Figure 159 and Figure 160).

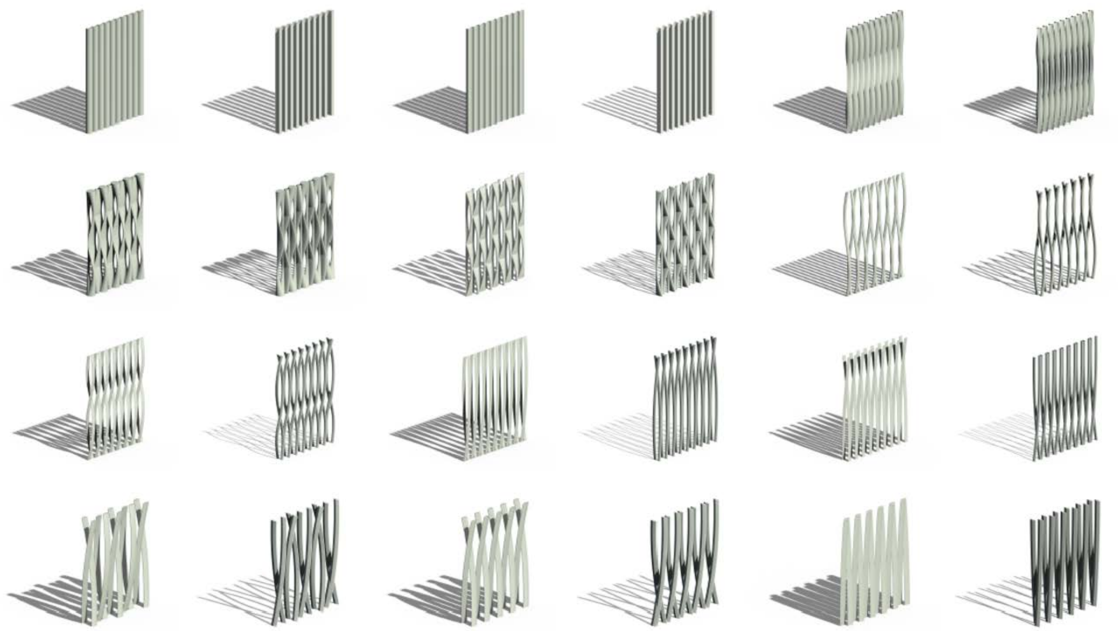


Figure 159: Parametric design helped student to develop their concept in response to the sun position.

For the sake of better understanding the design process and the relationships among internal and external factors that craft dynamic and responsive buildings, the studios helped students to understand a sequential design development of different mechanisms from a seed idea through the fabrication phase in which motion evolved into physical models. To this end, both studios attempted to be a mediator between ideas and reality. The link between an abstract mode of thinking about motion and the final intended reality of incorporated movable parts was best cemented by simultaneously executing both acts. Therefore, instead of simply illustrating the relationship between a proposed mechanism and its resulting fabrication, each student had the opportunity to directly examine it. By addressing the synergetic confluence of performance and appearance, transLAB and tranSTUDIO drew students' attention to creative challenges that turned their design concepts into reality.

Despite mechanisms readily available to activate shading devices, most students were eager to design their own and allot enough time to design the required mechanisms and figure out their complexities. In addition, most of the mechanisms that students found were not fully matched with their design intend.

From observations the author made in the studios, there were two main approaches to design a transformable shading device. In the first approach, a mechanism was studied to derive a concept for a shading device from it (Figure 161). The second approach was contrary to the first one, in which a mechanism was derived from a functional and environmental concept. Based on the experience gained in the AURA's design process, the author focused on ways to overcome the shortcomings was inherent in the above-mentioned approaches.

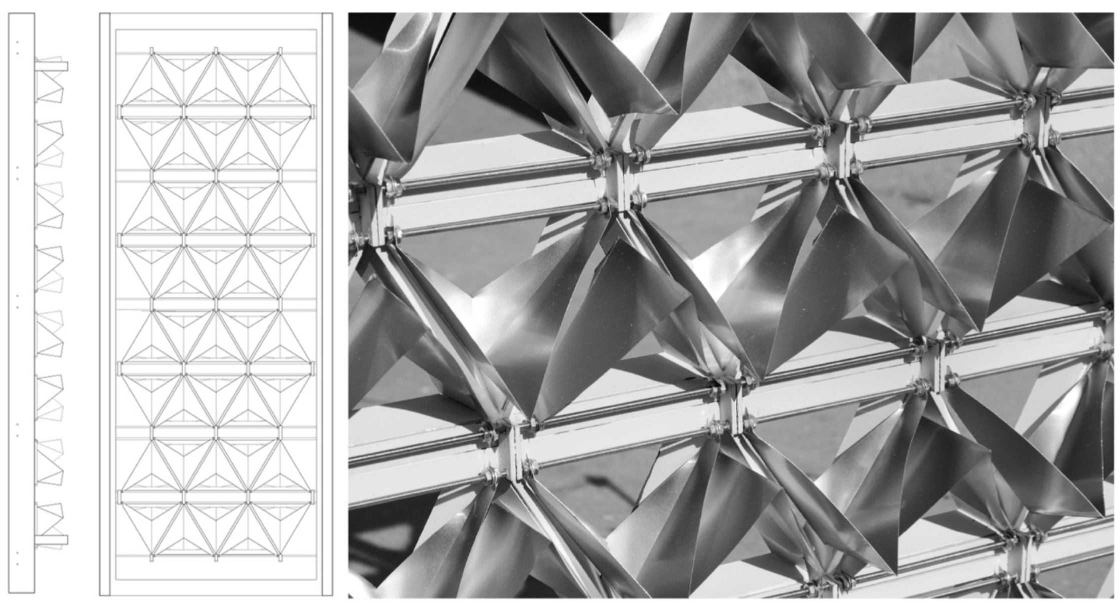


Figure 160: The pedagogy of motion emphasizes the simultaneous experiencing of environmental response and the application of conceptual kinetic mechanisms. In tranSTUDIO, an orthogonal grid of triangular prisms rotates along an axis to make a shading system. By rotating the prisms, the quality of light and shadow change.

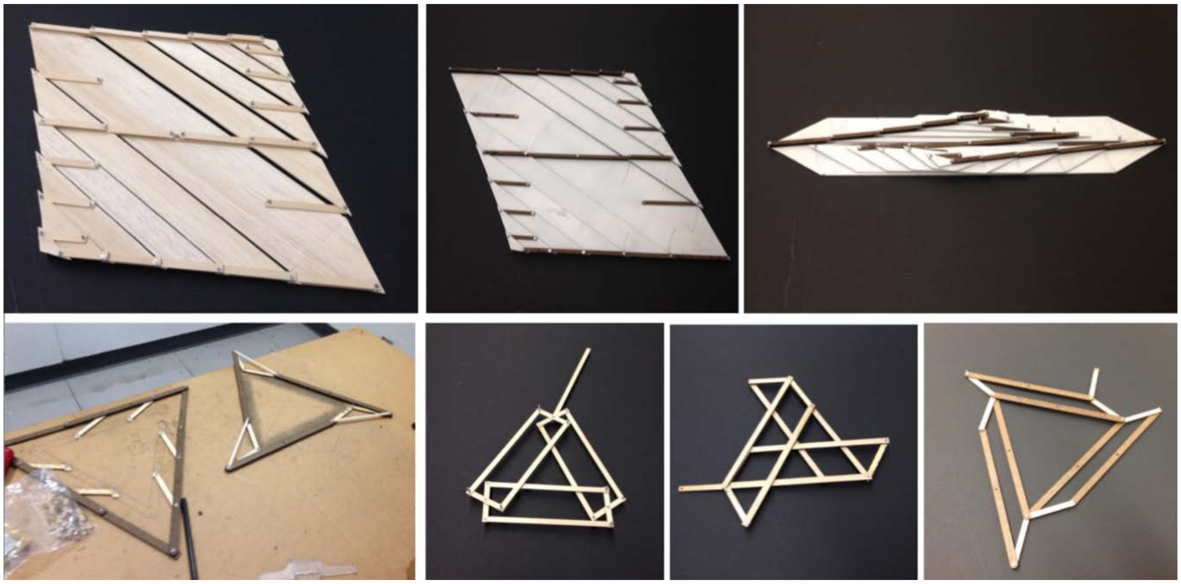


Figure 161: Start from existing mechanisms and extend it to the novel forms of movement

5.12.6 Essential Basic Structural Knowledge

Although the stability of the structural elements and the connections of movable components with other elements were very important in the design process, students were not mathematically concerned with the analysis of loads on their proposed systems.

During the design process of TSS, a designer should consider the connection of transformable design to the fixed parts of a structure. In both studios, there were groups of students who faced difficulties when attempting to connect their transformable shading systems to the fixed structures. For example, for his final project, a student in transLAB explored a transformable design concept for a TSS (Figure 162). He was not able to connect his kinetic modular system to a fix structural frame. Although the mechanism performed accurately as a kinetic module, the concept was not able to be adapted to a TSS. For the author, it was a lesson learned that integration of the kinetic system with the façade's structural system should be addressed during the early design stage.

Based on the lessons learned in transLAB at Virginia Tech, in tranSTUDIO at Texas A&M the author emphasized on the importance of the interconnectedness of the fixed and transformable parts of a proposed TSS design. Therefore, the second group of tranSTUDIO students was able to more deliberately pursue technical solutions for connecting their TSS designs to the fixed structures on their sites. Students were then able to revise their concepts based on further critiques. For example, one group in tranSTUDIO had difficulty to connect their design to the fixed boundary. Based on the experienced gain through transLAB, the group in tranSTUDIO was advised in the early design phase to seriously study the connection of the transformable designs to the fixed parts of the structure. As a result, this group was able to revise their concept and embed a triangular structure in their design concept. 3D printing helped them to fabricate their joints (Figure 163 and Figure 164).

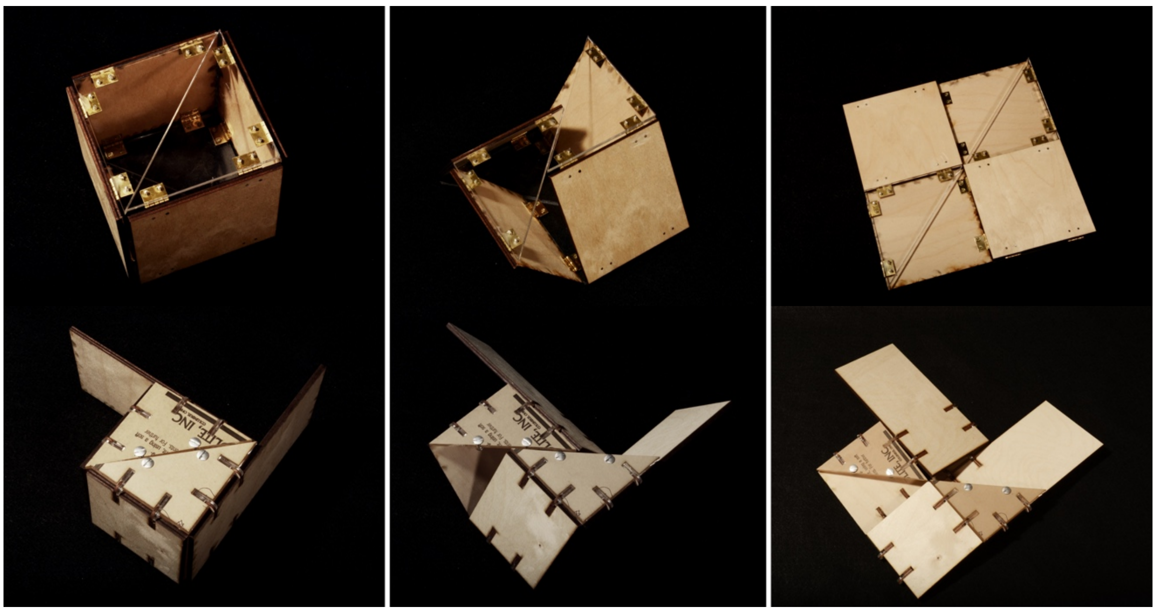


Figure 162: In transLAB, a student straggled to connect his kinetic modular system to a fix structural frame.

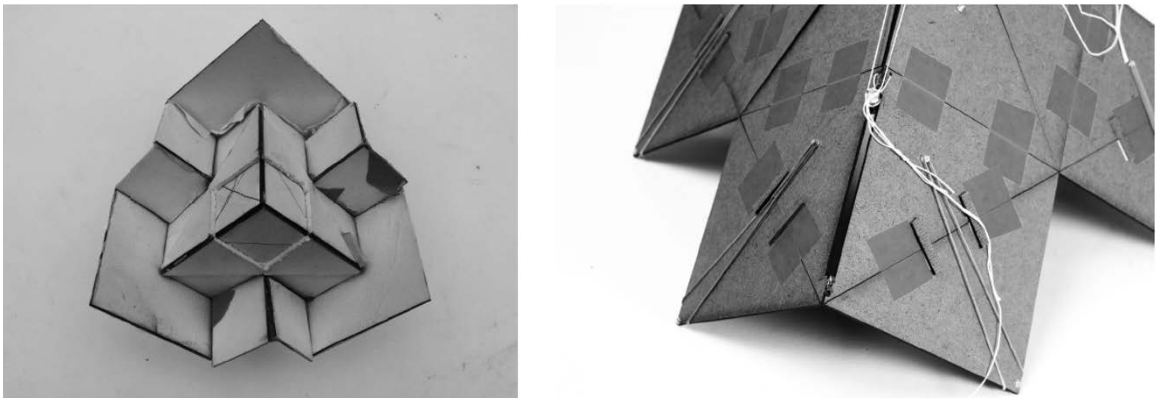


Figure 163: In tranSTUDIO, one group designed a modular system that was difficult to attach to the structural frame.

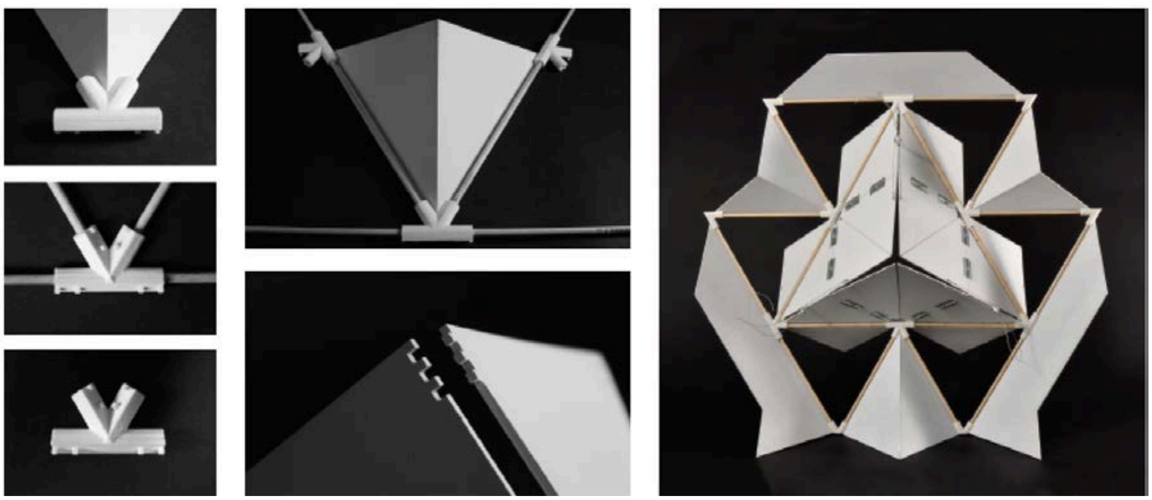


Figure 164: Students in tranSTUDIO considered the connection of the movable design to the fixed structure more deliberately.

5.12.7 Focusing on the Geometry of Motion as a Sub-syntax of the Language of Motion in the studios

No specific transformable design concept could be implemented without a strong awareness of geometry of motion. In short, in motion pedagogy, geometry is the determinant of motion. By taping into motion geometry as a sub-syntax of the language of motion, the pedagogy of motion comes to rely heavily on motion geometry for the structure of its instructive method and harbors the precise geometric elaboration of a sequence of movements that occur over time.

On one hand, one of the goals of both studios was to define what utterly constitutes language of motion. On the other hand, the language of motion involved defining the attributes of students' proposed mechanisms. In this way, the language of motion grounded the studios considerations within a broader context of vocabulary and syntax.

Both studios intended to pay attention to both vocabularies and syntaxes of motion language. Among the sub-syntaxes of the motion language, the geometry of motion was wrought intentionally and applied in terms of its pedagogical implications. In the studios, exploring motion geometry caused a drastic change in the way that motion is understood by students. Developing geometric thinking of motion assisted students to further predict, describe, visualize, and imply motion.

Since, the design study of AURA emphasized on the importance of geometry as fundamental to designing a transformable system, both studios proved that the performance of proposed mechanisms of students were depended on the underlying geometry of motion.

Based on the design process of AURA, students got benefit of graphical approaches to visualize the geometric relationship of the mechanism components during each stage of the transformation. These graphical approaches helped students to analyze the best possible course of movement of the whole mechanism.

Using sub-syntax of geometry as the basis for increasing the rigor of the design process of transformable architecture helped students gain a consciousness of the potential malfunction or failure of their design because of geometric interference among parts. Most of student model failures were due to the fact that students needed to resolve conflicts between geometric dimensions of components and their corresponding movement paths. Since a motion composition can be formed by constituting the geometric relations of movable parts, in conjunction with material behaviors, fabrication techniques, and control processes, all of students' failures were not traced back to unsolved motion geometry problems, but were due to fabrication inaccuracy, measurement errors, or material flaws.

Guided by empirical investigations drawn from areas such as application and knowledge of materiality and fabrication to tackle environmental, structural, and mechanical behaviors of their design, students took into account how the control of motion geometry could govern precision and communicate intentionality.

During the early weeks of the semester, some students were preoccupied with the desire to focus on results rather than the process. They overlooked the underlying geometry from which a mechanism originated. They did not have a clear cognizance of what the geometry of motion was from the very inception. Being the risk of imitating an existing mechanism informed these students the important of both underlying geometry and overlaid pattern that intricately connected to designing motion. Gradually, the students understood that both geometry and mechanism come from the same hand. Towards the end of semesters, by proposing more complex mechanism, where the geometry could push their design, these students viewed motion geometry as an expansive approach that contained insightful analysis to accomplish the intriguing aspect of their proposed mechanisms. The need to pay attention to the geometry of motion helped students to examine how complex mechanism were generated and occasionally be surprised at the simplicity of the underlying geometry of some of them. Students realized that the starting point of transformable architecture could be to understand its geometry of motion.

In the final studio assignment, students conceived their design as an advanced geometry in motion where environmental considerations bound the movement of various parts. In the interplay between environmental objectives and transformation of shading devices, students realized that their anticipated motion of their devices should obey geometrical laws. During designing transformable shading devices, students experimented how the underlying geometry of their designs could remain self-transforming in terms of their shapes whenever the shading elements would move laterally or radially across the building envelope. To this end, the final assignment showed the application of motion geometry-based approach to design exploration of different environmental and functional motion compositions sets and scales.

5.12.7.1 Using the Principles of Geometry in both Movable and Static Objects

Proposing a proper mechanism to provide specified motion apparently necessitated a determinant use of geometry. Most of students' final projects were designed by making use of geometry. Beside the use of motion geometry to change the position of different components of students' design, the geometric look of students' designs was important. Exerting geometry was not only limited to design a basic movable module. Students understood that the repetition of their basic modules could exhibit a three-dimensional geometry in the form of volumetric pattern as well. In addition to imply geometry as a great tool to motion-based architectural design and its representation, using geometric metaphors were deeply ingrained in the studios to give a clear sense of direction on how to analyze and develop design approaches.

To represent the geometric relationship of their design, students worked through techniques involving a range of media including hand drawings and digital media. Students dealt with several prototypes to represent and manipulate with both motion and static geometry in three-dimensional format. For instance, to design, model, and fabricate an intriguing concrete module for a building envelope, a team of two students in tranSTUDIO explored a number of studies on the underlying geometry of a tessellation grid for quad-dominant three-dimensional tiles. These modules were joined with adjacent modules, but only at their external edges. By dividing each edge into five unequally-spaced sections and cutting freeform shapes of varying sizes between the divided points, the students came to understand how a smart design for a tiling system can generate diverse patterns in an almost seamless fashion. By adding a third dimension to the curves, this team attempted to design a self-continuous module that was able to create a more intricate and continuous movement from the local module to the entire modular propagation. In parallel, the team tried to identify generative rules for and the overall aesthetic appearance of a self-interlocking pattern that could be further manipulated through the fabrication process. The team made different 3D-printed models as formworks and poured them with concrete. After facing some difficulties in detaching the concrete from the formworks, the group decided to use a machined mold of firm, high-density foam coated with Vaseline instead of a 3D-printed mold (Figure 165 and Figure 166).

Figure 165: Concrete self-continuous block

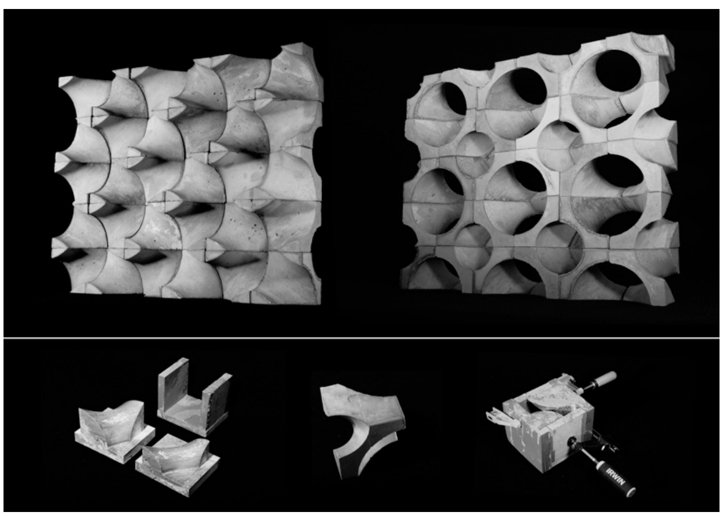


Figure 166: The aggregation of an individual concrete module was studied in transLAB. The use of two 3D printed pieces, combined with a plywood mold, allowed for a 4-piece mold for concrete blocks to be poured.

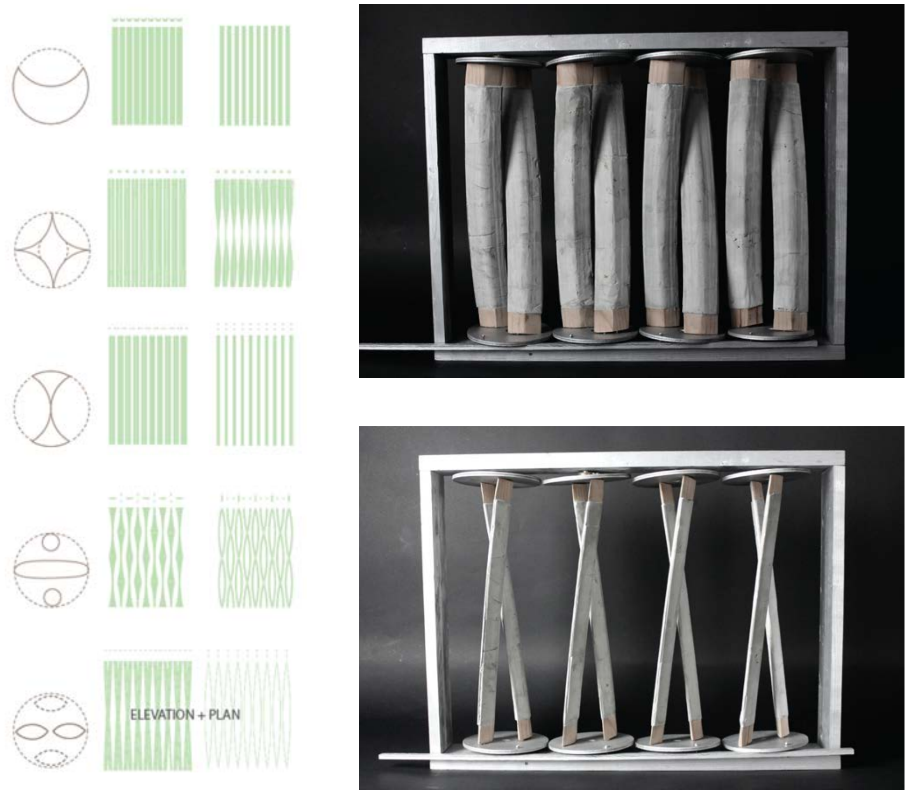


Figure 167: A concrete transformable shading system. The geometry governed the form finding process of the louvers.

Another example of the role of geometry in shaping students' design minds is the modular transformable concrete louver-like system. By making subtractions from a cylinder, the geometry of each module assisted in providing different levels of shading. This process evolved through a formal exploration into a set of two helical louvers moving on the same axis of rotation (Figure 167).

Geometry played a critical role in one tranSTUDIO student's design for a transformable door. In this design, as an interior ring rotated, two discs translated and revolved toward the center of the door's opening, eventually sealing the aperture (Figure 168).

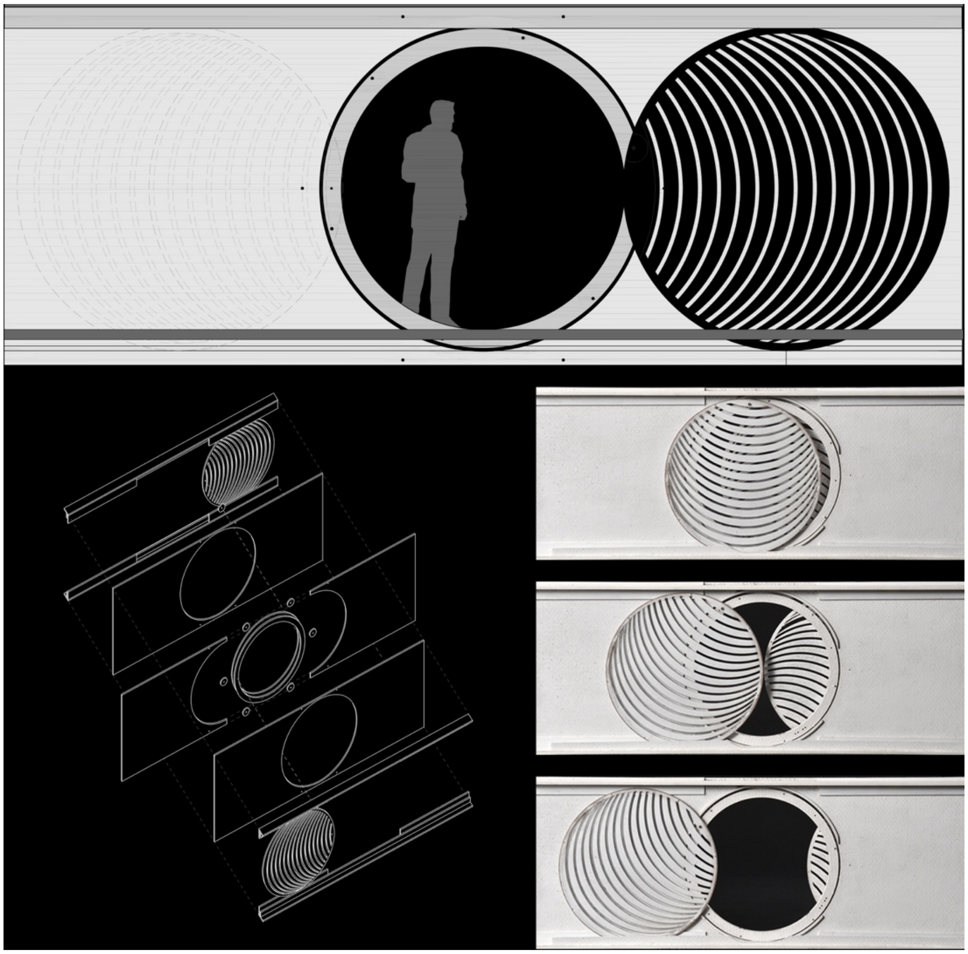


Figure 168: In tranSTUDIO, students attempted to explore movement itself by designing a transformable door. By experimenting with the effect created by pinning two discs at opposite ends of the diameter of a ring, this door explores possibilities beyond the traditional pocket door. As an interior ring rotates, the two discs translate and revolve towards the center of the door's opening, eventually sealing the aperture.

5.12.8 The Collaborative Design Process of Transformable Architecture

Too often, design education is not comprehensive. Within this educational discipline, the natural tendency is to elevate one agenda at the expense of another. Consequently, students are often left to their own devices to bridge the gaps between different modalities of thinking (Carraher 2015) (e.g., applied versus abstract), skill sets (e.g., practical versus conceptual), or toolsets (e.g., analog versus digital). Confronting the engineering challenges of a designing motion, design educators should involve considering a diverse knowledge spread out across multiple disciplines and unprecedented scales, all needing to be integrated into the fuzzy, ever-evolving design process for a transformable architecture.

Design educators should endeavor a better understanding how an exploratory concept of motion can be constrained to suit different technical, economic, and cultural considerations. To foster a complex fabric of new relationships that both directly and indirectly impacts design decisions across the spectrum of transformable design, design educators should attempt to re-contextualize a number of discourses that are outside of architectural education.

A transformable project is a complex collaborative and collective process. It is important to draw students' attention to the importance of collaboration with broad multidisciplinary teams of academic, scientific, and industry partners in order to achieve a deep and informed approach to an integrated design project.

Transformable architecture forges a new relationship with material, mechanical, electrical, industrial, and environmental engineering through a multi-dimensional design research opportunity. Since the field of transformable architecture is inherently multi-disciplinary and, thus, requires the knowledge of many specialists, the education of future designers should underscore the shift from back-end approaches to a more integrated front-end approach. Transformable architecture is a knowledge domain where proximity and connections among design factors such as functionality, reliability, and simplicity and the complexities of implementation, scalability, maintainability, cost, and comfort should all meet one another. Among the challenges faced in the study of motion is how to transgress discipline-based borders to search for intersections. To this end, motion pedagogy should allow interconnections among the environmental, technical, material, cultural, economic, and aesthetic spheres.

Since the nexus of art, architecture, engineering, and science fuels transformable design, one of the primary goals of the studios was to cross-traditional discipline-based boundaries by addressing transformation in schools of architecture. By opening up new avenues of design thought and opening lines of communication between architecture and other disciplines in order to harness knowledge and skills that can be transferred from "outside" fields, transLAB and tranSTUDIO traversed a diverse landscape of expectations, possibilities, and investigations in the field of architectural education. This Pedagogy encourages students to intervene in the evermore-complex series of necessary subjects that are currently understood to be outside the purview of conventional architectural education.

For the design process of transformable architecture, some aspects are knowable while other aspects are not. The pedagogy of motion is concerned with what is knowable as well as commonalities across specific projects. Design students may not have to know all the required knowledge by themselves to proposed a transformable design, but they should know what they need to know and when do they need them. Sourcing expertise wherever needed is a key element for tacit understanding between the designer and other disciplines when working on a transformable proposal.

Specifically, by providing multifaceted motion design experiences that developed over time to suit different circumstances and requirements, the studios introduced students to the interdisciplinary nature of transformability in shading devices. To consider a wider scope of opportunities, ramifications, and concerns for students' design concepts, in both of these mindfully diverse studios, the ultimate goal was to blur the conventional boundaries of the adjacent fields of architecture by helping students obtain a more profound understanding of the ongoing advancements being made in other disciplines. The ultimate goal of both studios was to integrate and fuse together different knowledge domains across disciplines ranging from architecture, building construction and management, mechanical, electrical, computer science, material, and industrial system engineering.

To lessen the distinction between different disciplines related to transformable architecture, several domain of knowledge such as fabrication, assembly, systems integration and actuation must be balanced with appearance in design and implementation phases (Kalantar and Borhani 2016b). Each phase should come from thinking through how the final system might be built and how technologically, functionally and aesthetically it would be assisted.

The design process of a transformable design should take many influential factors into account. While addressing emerging theories and technologies related to transformation, the studios dealt with many of the conflicts caused by the opaqueness of the discrete topics from different disciplines that continuously play a vital role in the design process of transformable architecture. Therefore, several curricular area specialists participated in the studios as guest experts. These special speakers helped students to transgress the boundaries between academic research and practice. In addition, to conduct design research concerning transformable shading devices, these two studios relied on the feedback from experts immersed in the design process.

Meanwhile, the main focuses of the studios were on motion design knowledge. The studios included a series of lectures and workshops that introduce students to principles that underlied the discipline of transformable design. Lecture topics included introduction to mechanisms theory, classification of transformable structures (typologies), design methods for different typologies, practical construction techniques, design strategies for physical behavior and interaction, and strategies for control. These lectures served not only to promote cross-disciplinary fusion, but also to encourage students to intervene in the ever-more complex series of necessary subjects outside of the classic field of design.

Although the main focus of these studios was on motion design, the studios enticed students to cross pollinate across a series of disciplines for taking a broader collaborative[81] and multi-disciplinary approach to design thinking that might provide an understanding of a design proposal within the context of larger systems. By taking a broader contextual view to apply critical thinking skills to students' future design works and maintaining curricular and professional relevance, both studios were organized several workshops. From the allied fields of construction, mechanical and structural engineering, material science, additive manufacturing, and robotics, different experts visited the studios to share their knowledge in how architects can use motion within the building arts (Figure 169).

[81] Although by its very nature architecture is a collaborative endeavor, the culture of architectural research is not fully collaborative. Based on Keith Green's study of architectural faculty research published in the Journal of Architectural Education, "architecture faculty members are largely disengaged from design research and almost never collaborate with colleagues in other disciplines". (Green 2006)

Figure 169: Exchanging knowledge and experience between students, instructor and guest experts across a series of disciplines, tranSTUDIO-2015, Texas A&M.

Pedagogically speaking, the author believes that within the context of design activities, it is necessary to explore the significance of integration across a breadth and depth of disciplines. Through lectures, workshops, case studies, and various different assignments, these studios introduce students to an intricate and exploratory interdisciplinary approach as early as possible. Hence, most of students emerge well-versed in this process and are able to use that knowledge as they progress in their technical and intellectual abilities throughout the semester. By bringing together digital and analog fabrication workflows across different scales, these interdisciplinary studios broadly investigated the potency of transformable design principles, helping to create adaptive designs and building components that changes the quality of space and the connection humans have with their environment.

In the studios, students understood how to not only gather information from different disciplines but how to integrate different information and connect various point of views to understand the complex nature of their design concepts. Instead of just pointing to existing information, students were asked to discuss a direction that can inform their design processes or workflows. Accomplishing this required more than technical tinkering, such as specifying movable components or employing one mechanical system over another.

In transformable architecture, working collaboratively is becoming an increasingly important concern. Specially, the collaborative effort of multi-disciplinary teams with a range of expertise and knowledge is the linchpin of a prospering transformable design project. To this end, students were encouraged to work together. For example, in the final assignment of tranSTUDIO, a diverse array of digital models, prototypes and environmental analysis were developed by organizing groups of two people. In the studios, the relationships between students and other students was an important consideration in better understanding of the nature of transformable design practice. The level of collaboration between students in both studios was generally high. In specific, tranSTUDIO gave rise to collaborative learning scenarios that foster mastery of not only "group work" when students working together on individual assignments, but "teamwork" once they collaborating on the transformable wall and the fifth wall assignments (Tucker and Abbasi 2012). In this way, numerous facets to team and group design activities were considered outright in the context of the transformable design disciplines. In their final project, students were able to follow their own interests while working in groups.

5.12.9 Tolerance as Critical to the Design Process of students

Designers usually prefer to work with exact dimensions. This is because design software uses precise values for the dimensions of geometric entities. Before a transformable design can be manufactured, however, tolerances must be specified regarding all linkages and joints, because no fabrication process can make exact parts. Tolerances are also significant because they determine the manufacturing processes that can be used. This directly affects the cost of the finished part.

In both transformable studios, students didn't understand how much tolerance was important to a kinetic design system. Even when their systems failed, they were not equipped to recognize how the lack of appropriate tolerance could cause an entire system to fail. After having a discussion about the notion of tolerance, in the self-evaluation questionnaire distributed after their first transformable project (door design), 75% of the students at Texas A&M mentioned tolerance and friction as primary challenges to their design process (Figure 170,

Figure 171: In the fourth project – Spatial Exploration as Architectural Intervention: Design a Fifth Wall – students at Texas A&M University carefully explored the level of tolerance in their specific projects. They experimented with situations in which the parts did not suit their intended function (when manufactured without tolerance). Incorrect tolerances can cause unforeseen effects, such as interference and unnecessary play. Since these problems usually involve more than one part, they are often discovered late in the product cycle, possibly after the product is put together and during the performance of motion.

and Figure 172).[82] For novice designers, it is often a matter of what the limits of tolerance define and how those limits are determined. By gaining fabrication experience, students will gradually come to understand how they can achieve the proper level of tolerance when they work with different machines such as a CNC, lathe, mill, and even a drill press.

[82] Based on the questionnaires and self-evaluation forms filled out by students.

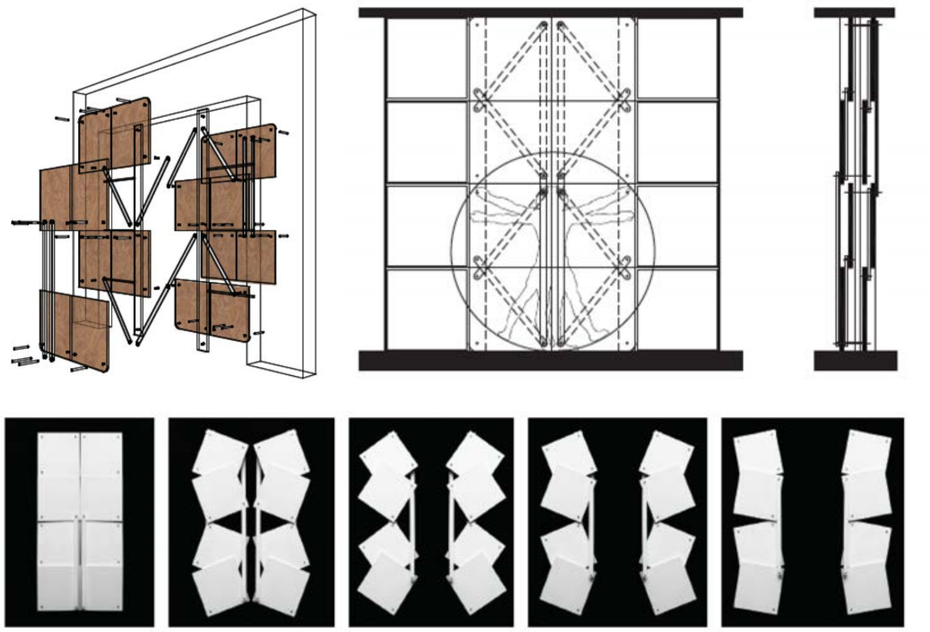
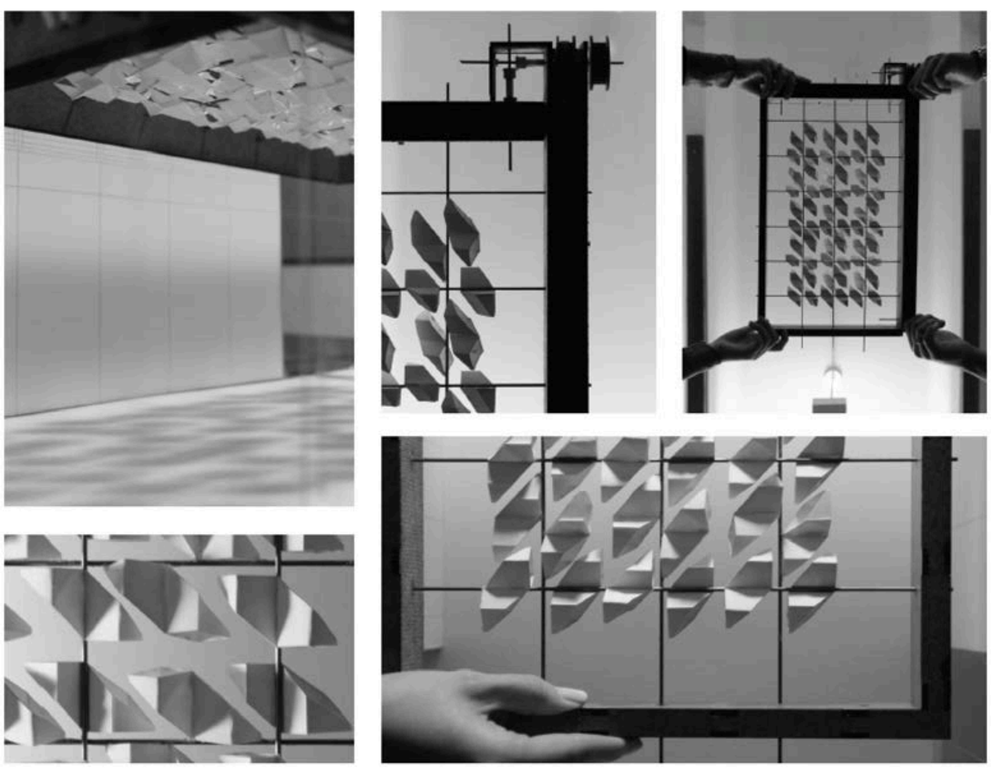
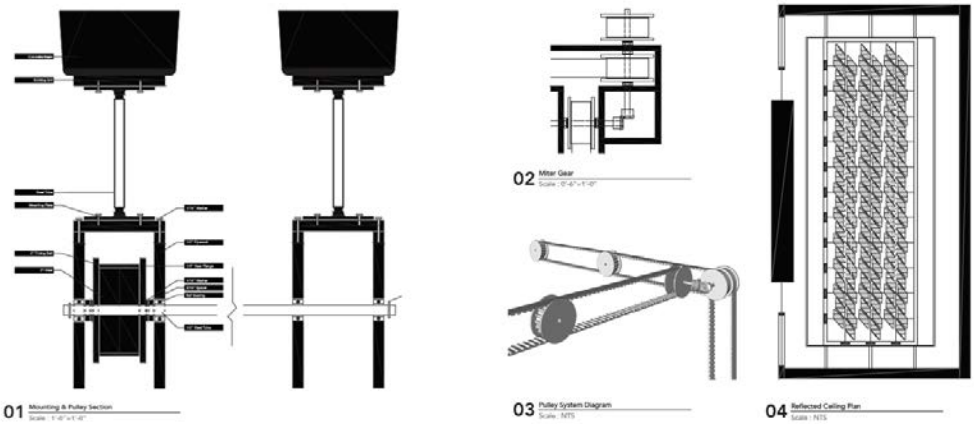


Figure 170: Precision and tolerance were the major challenges faced by students in their first design project, the creation of a door design.





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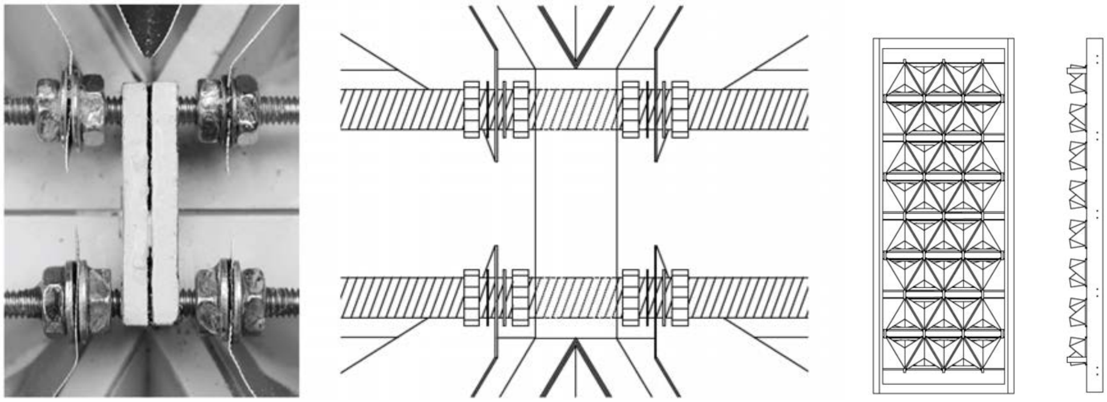


Figure 172: In her final design self-evaluation form, student T-12 mentioned “precision is everything. If one piece is not positioned in it’s exact position, the whole system might fail. Folding the fins becomes incredibly crucial to give enough tolerance for the fins to pass through.”

5.12.10 Essential Knowledge and Skill to Address Fabrication and Technical Aspects of a Transformable Design

Practicing and teaching from inside the discipline of transformable architecture, rather than from the more limited viewpoint of an outsider, the author dealt with the challenge of balancing the overwhelming amount of technical knowledge and fabrication skills required to scaffold a motion design concept toward a deliberate performance stage.

A transformable design is not about mere mechanical or electrical components, for which an artless technical or production approach might be sufficient. If done with proper care and attention, technical and fabrication sides of transformable architecture can challenge students to find themselves moved toward a place of more understanding about the role of technology in empowering motion to attain its performance goals. At its best, the technical solution that is offered in a transformable design should bring into question the reliability and integrity of a proposed transformable concept. In addition, technical aspects can become an instrument for the expression of motion including immediate, gestured, metaphoric, or symbolic one.

To establish a pedagogical strategy for the development of transformable architecture that is driven by design intent rather than technical specifications, as both the AURA’s design process and the studios demonstrated, the design of technical parts should not be disengaged from the overall design process as a task done prior to or in the last phases of design.

Paying attention to technical aspects in motion-based courses should address different priorities ranging from more tangible concerns that aim to minimize possible errors or expedite production, to those who intend to stimulate students' minds, provoke their imagination and ways to deepen their understanding of motion.

Students in both studios gained knowledge in the core competencies of established and emerging technologies that are essential for inventing new futures and bringing more transformable designs to fruition.

Since many advanced technologies have failed to realize their potential in many transformable projects, the studios aimed to open up the dialogue between emerging technologies and transformable architecture. In its use of technology, by incorporating numerous technological innovations in both transLAB and tranSTUDIO, the studios were able to constantly update themselves. In tranSTUDIO, mechanical and non-mechanical design approaches coexisted. In this studio, these approaches were adapted to specific phases or the whole process of some students' designs. For instance, in tranSTUDIO, one group in the final semester assignment used shape memory alloy actuator wires[83] to generate and control the movement of a transformable shading system (Figure 173). In this design, although the shape memory alloy wires could contract for only 2% to 5% of their length when heated, the movement of wings was incredible. Upon heating, the wire let a wing to be opened. When the wire cooled again the wing returned to its original. This design could be conceived as self-contained system. With a strong sense of autonomy, the wings could change their degree of openness in response to the outdoor temperature through the day.

[83] Such as Flexinol

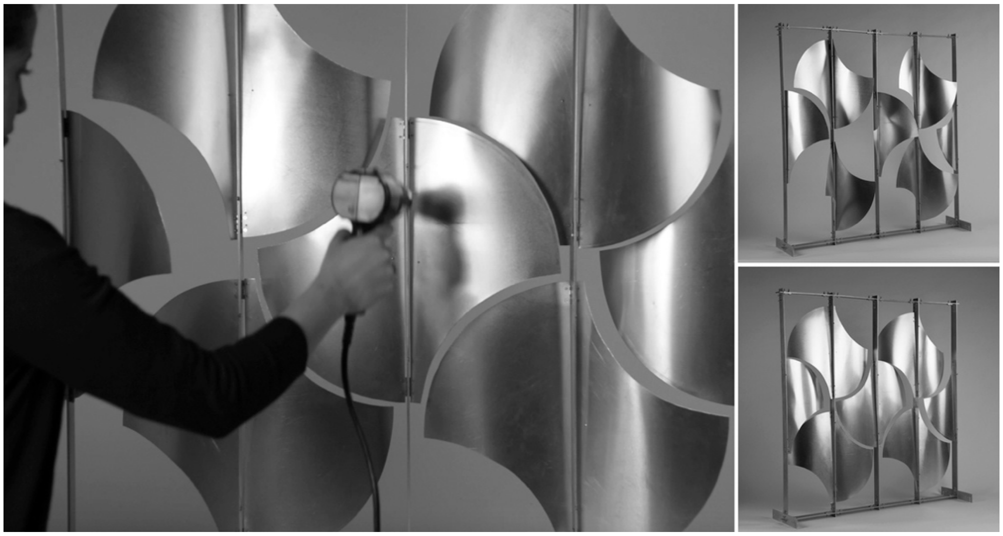


Figure 173: Experimenting with Flexinol to generate and control the movement of a transformable shading system.

Drawing from students' toolkit to incorporate the possibilities of emerging technologies and the requirements of a transformable shading system, the studios tried to bring together what was technologically possible with what was permissible with respect to designing a transformable design.

5.12.11Material Properties in the Early Stages of the Design Process

After making several models in their early design stages, student profoundly realized that the choice of the proper materials can impact on the success or failure of a transformable design. Throughout their prototyping processes, students understood that having less appropriate materials could create undesirable friction that caused a proposed mechanism to fail.

By making working prototypes, students understood that their movable design components were subject to gravitational force. In both studios, several students noticed that choosing an appropriate material that be light enough to be set in motion could minimize the energy required to move their prototypes. In some of student's models, due to the lack of appropriate materials that provided high strength and stability yet light weight, the internal stresses of dead and live loads led to material deformation.

Due the limited time of a semester, students' working prototypes were not ready to be installed outside of a building and perform for a while to study how temperature differences could cause changes in length or material deformation or how material might become brittle when they were exposed to extreme cold. In both studios, students did not have a chance to study the reaction of their prototypes and the applied materials within their ambient environment that might lead to some challenges such as corrosion.

Since the choice of appropriate components for a transformable structure such as hardware, or accessories needs special consideration, there was a constant struggle for students to find them locally. The result of both studios and the author's motion design experiences emphasize to draw up a catalogue of appropriate resources for transformable design which suitable materials, hardware, tool, and accessories need to fulfill.

5.12.12 Spatial Quality Offered by a Transformable Design

In architecture, space and time are fundamentally entwined. The interlacing of time and space holds a key to understanding how the motion pedagogy aims to improve the status of the existing architectural curriculum. By accentuating the nature of motion as change of position occurring in time and space, the pedagogy of motion gives rise strong links with the core of architecture discipline – the experience of space and time.

In transformable architecture, the gradual shift of moving components in time and space thrives on the tension between before and after, between now and then. The tension between these dichotomies leads to a recognition of architecture as time-like entity. In this way, the polymorphic core of motion pedagogy is nested in a context of space and time.

The way that people live their lives is bound by the quality of their built environment. To tangibly link motion and the consequent changes in how space should be ordered, both studios promoted students to think in an architectural mind frame for addressing the time-like environment by mediating between space and time.

transLAB and tranSTUDIO provided foundations for students to become more design oriented. Within the context of studio practice, students were informed that their projects should emerge from a spatial concept, even if rough and inchoate, and that conception should serve as a foundation for the entire final work. Indeed, as students realized, transformable architecture invariably is as much about mechanism and performance as it is about space and form. Accordingly, students and the author as the studios instructor explored motion in both its technical and spatial aspects, as an armature for architectural thinking.

5.12.13 Representation and Documentation of Motion as a Way to Narrate the Notion of Change

In pedagogy of motion, movement denotes action, actuation, vitality, adaptation, change. In this pedagogy, by substituting fixed, and static architecture to adaptable and transformable one, the apparent movement of the architectural elements takes precedence over their immobility.

The outcomes of architecture students' design activities often are limited to illustrations viewed as single images. In the studios, in order to demonstrate the motion and changeability of transformable shading devices in relation to their surrounding, students were encouraged to present a series of images. This conveyed new understandings of the conventional types of architectural representations and shifts the trajectory of these representation methods, releasing them from the confines of a solitary moment, a single referential template, or a single viewing position. This method was a stimulating narrative about creative impulses expressing themselves to capture and reveal the essence of motion through the interaction of force, motion, and geometry.

As motion involved to think about a project in terms of a process, students understood that their designs should have a fourth dimension: Time. Through encouraging a shift in sensibility from the spatial to the temporal, students understood how the necessitated time to move their transformable design parts could build their perception of movement.

Since the perception of motion is based on a poetics of representation, the lens of media is of the utmost importance when pushing the boundaries of students' imagination, knowledge, and sensitivity regarding motion and space. Thus, both of the studio's inquiry was pursued through innovative, analog-digital media migrations as vehicles for zooming in on, studying, and generally advancing transformable architecture. Students in the studios exploited different representational forms[84], and come to understand how each discloses something lacking in the others.

Each mode of representation in transformable architecture gives raised to a different set of considerations when overseeing the relationship between design and reality. For instance, by offering an immersion in the work, sketching was an act of design discovery. Each sketch, a snapshot of evolving design iteration, was not a representation of an artifact, but rather an early representation of a transformable idea. In this case, students' sketches, first and foremost, rapidly conveyed their ideas about development of a mechanism, form, or space that changes its size and shape (Figure 63).   A concern with the latent potential of these sketches was that they allowed for fluid interpretations of movement.

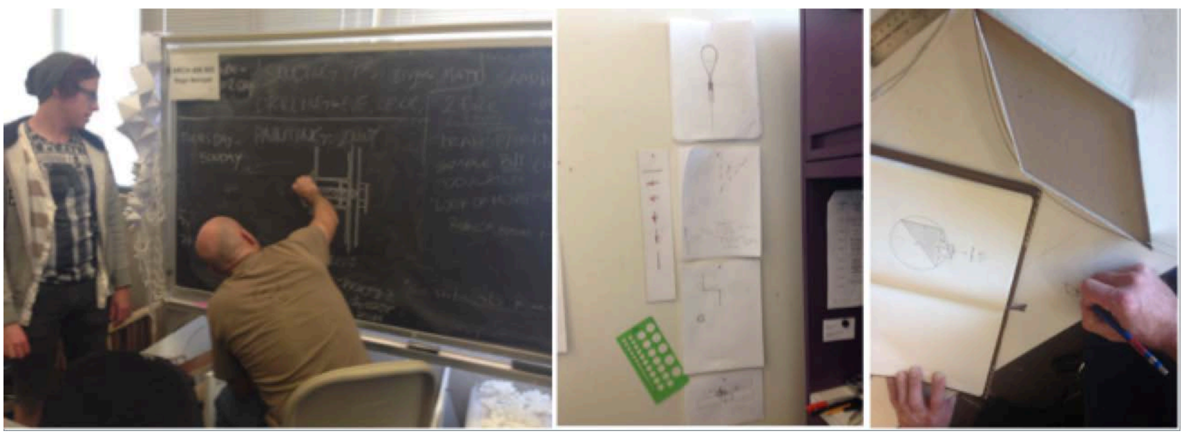


Figure 174: Sketching is an act of design discovery. Each sketch, a snapshot of an evolving design iteration, is not a representation of an artifact, but rather an early representation of a transformable idea.

Upon being exposed to a variety of media techniques and methods for reflecting their ideas about transformation of objects and spaces, the main challenge was to ask students not to lose hold of these representation methods while, at the same time, not grasping them so tightly as to miss the potency of their ideas.

Students were encouraged to explore the effects each media or method might have upon their design decisions. In the course of their explorations, they were asked to try their

[84] Such as hand sketches, digital models, scale models, and prototypes (full scale models)

hand at various modes of architectural representation, spanning the spectrum of imaginary to photo-realistic imagery. Focusing on the creative and inventive significance of each mode, such representations were characterized by their expression of the concept of movement within a space that is in constant flux.

To uncover processes inherent in the interpretation of a mechanism, imitation of a form, imagination of a spatial order, and realization of a transformable shading system, students were asked to begin representing their work while their projects were still actively in the ideation phase. In the context of the studio, a student's graphic dexterity was not employed simply to passively record, but in fact, through the different pictorial representations they are asked to create, students attempted to address moments of invention pregnant with creative possibilities (Belardi 2014).

Beyond the physical relationships of cause and effect, students were asked to exploit the concept of transformation in their design, not only in terms of usability, but also in terms of dynamic aesthetics of physical motion. In both studios, different means and methods of representation were vehicles for exploration and expression, rather than demonstration. By opening windows for us through which we might view their projects, students' representations both framed their design intent and structure their design process. Students elucidated both their visions for their final designs and their organization of their ideas and possibilities. In this manner, representations took an ambivalent position; they became more than just a form of depiction. Students rendered their ideas visually and physically, as a form of thought. As Greg Lynn indicates "the introduction of time and motion techniques into architecture is not simply a visual phenomenon (Lynn 1999)".

The growth of the student designs should be seen not only in the final models or their final digital representations but rather at every step in the evolution of their design process, from their back-of-the-envelope sketches through the performance analyses and practicality of their study models. To this end, each of the studios had their own weblog (Figure 64). The studios' weblogs opened not just new possibilities for reflection of transformable design experiences by putting notable students' works on display, but also an opportunity for students to explain their inspiration and point of views. To this end, these weblogs were both a document and proposition that make available a visible and straightforward record of how students' designs were at work. In both studios, the weblogs, students' sketchbooks and journals, among others means of presentation reflected the evolution of students 'works and disseminated how students' knowledge were generated.

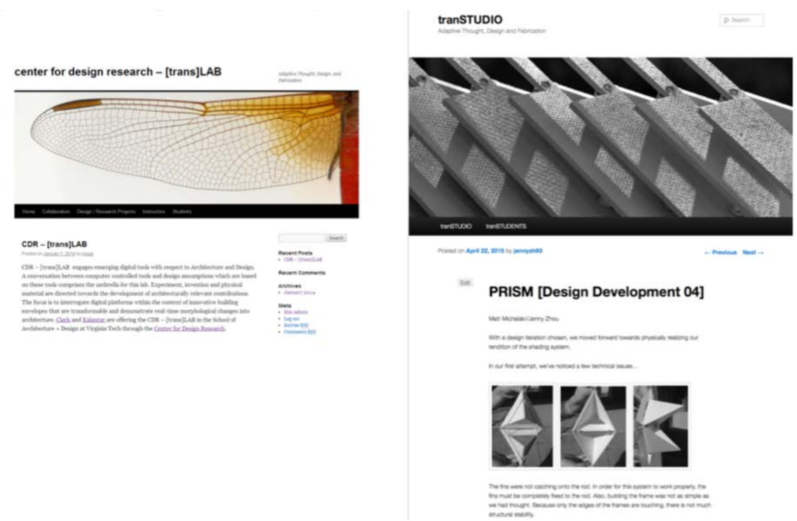


Figure 175: Weblogs were a way of reflective note-taking. http://blogs.lt.vt.edu/translab/ and thetranSTUDIO.com

5.12.13.1 Between Formal Representation and Iterations

To design motion, students realized that they should address sequences of motion. The most common technique for presenting motion was to introduce it through the sequencing of static snap-shots and therefore dynamic. Through conceiving motion as a sequence of frames, students attempted to represent a linear indexing of time when their designs transformed in a continuum.

Although the ability to animate renderings and transform surfaces that do not yet exist can offers new perspectives of looking at motion in architecture, it can aspire students to persuade completely insubstantial transformable designs. Yet this less reality-oriented motion collides with reality at a point when students want to make a working prototype of their design. In other words, beyond rendering images on the screen, the main challenge is how to merge students' understanding about transformation brought on by motion-related courses into the physicality of architecture. Unfortunately, in some of motion related coerces, movable forms are conceived in a space of virtual movement rather than within actual models.

The performance-oriented nature of transformable design incorporates experimentation and thinking through making. In the studios, as students learned to think with their prototypes, they begun to challenge the territory between formal representation and physical iteration.

From a pedagogical perspective, the prototyping process was essential to an evolving architectural expression of students' concepts. The studios called for a consideration of the vigilant development of actual physical models, as the main medium of students' activity, to realize the imagined condition. Prototypes remained the dominant form of communication in both studios (Figure 176). The end results, then, could be evaluated for what they actually are, and not for what a representation purported them to be (Gore 2004). In this manner, by forecasting and analyzing future and current prototyping successes or failures via varying parameters, students became more reflective and self-critical. As students' drawings begun to give way and yield to reality, a dynamic array of variables that normally was driven by conjecture and rough approximations begun playing out. In short, discovering the failure aspects allowed these prototypes to be studied more purposefully with regards to how they might perform over time. It is worth to mention that the trial-and-error nature of prototyping or the lack of an appropriate tool sometimes resulted in imperfect implementation of associated motion.

In addition, by blurring the separation between design and implementation, prototyping emerged as the most frequently used vehicle of communication between the author and her students, and more importantly, between her students and their peers.

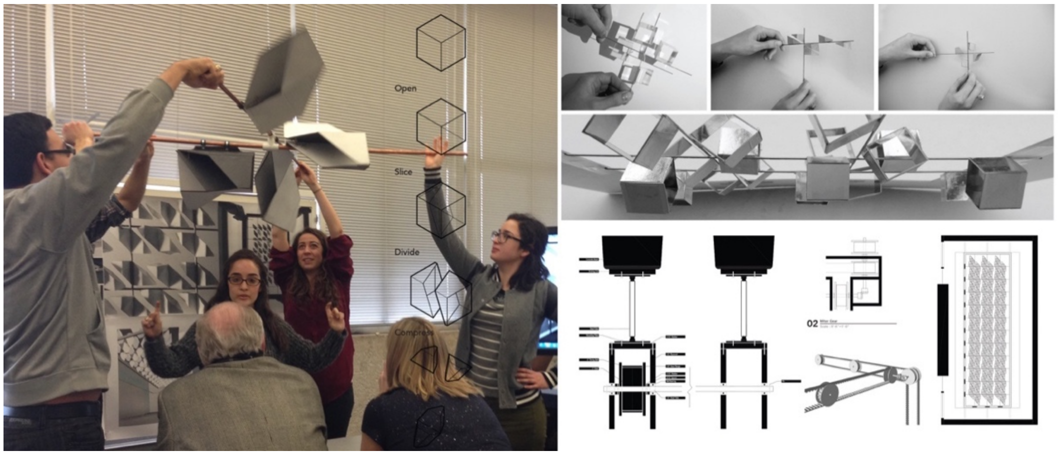


Figure 176: Different means and methods of representation as vehicles for exploration and expression, tranSTUDIO, Texas A&M, Spring 2015

5.13 Pedagogy of Motion in a Freshman Studio

Although the introduction of motion is advantageous at both the early and more advanced stages of architectural education, beginning design students who have less exposure to traditional static forms in architectural education can use such exposure to motion to foster a new, emergent form of design knowledge, which is not inert but rather evolving, and in that way is transformable. The development of this new body of knowledge as an alternative method of architectural thinking could recast the architectural design process and transmutes the landscape of how we do architecture.

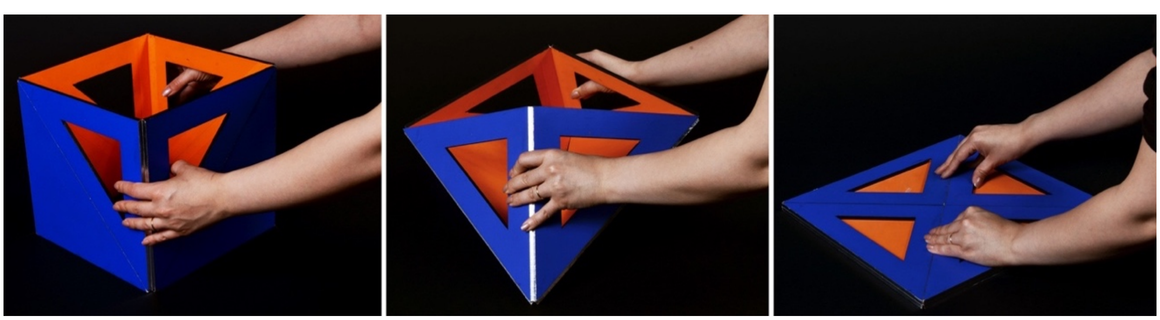
To assimilate the principles of motion design into the existing knowledge structures of a foundation design studio at Texas A&M University, two motion-related assignments were offered in the first four weeks of the spring semester of 2015 (Figure 177). These two assignments called “Opening a Cube” and “Portable Research Laboratory[85]” (Figure

[85] In their second assignment, Portable Research Laboratory, freshman students were asked to relate their motion experiences to a specific design context: designing portable and versatile field-ready research laboratories in deserts across the globe. By maintaining a capacity for rapid deployment and removal, the lab’s structure was intended to be easily erected by researchers at locations where less nimble facilities would be impossible. The lab was intended to be moved frequently, as the research required.

178 & Figure 179). At Texas A&M University, by letting freshman students become familiar with the fundamental geometric thinking supporting the concepts of motion, these assignments built on the idea of how a novice designer could explore time as a geometric parameter that is not stagnant.

Besides freshman students at Texas A&M, as mentioned before, the “Opening a Cube” assignment was offered to fourth year students at Virginia Tech University in the spring of 2014 as well. To keep the consistency of the text, this dissertation concentrates more on the “Opening a Cube” assignment than the second assignment of the freshman studio. The outcome of comparing these two studios can be a vehicle for evoking evidence of the possible Pitfalls and potentials architecture programs face in addressing motion-related courses.

Figure 177: Two motion-related assignments were offered in the first four weeks of the spring semester of 2015



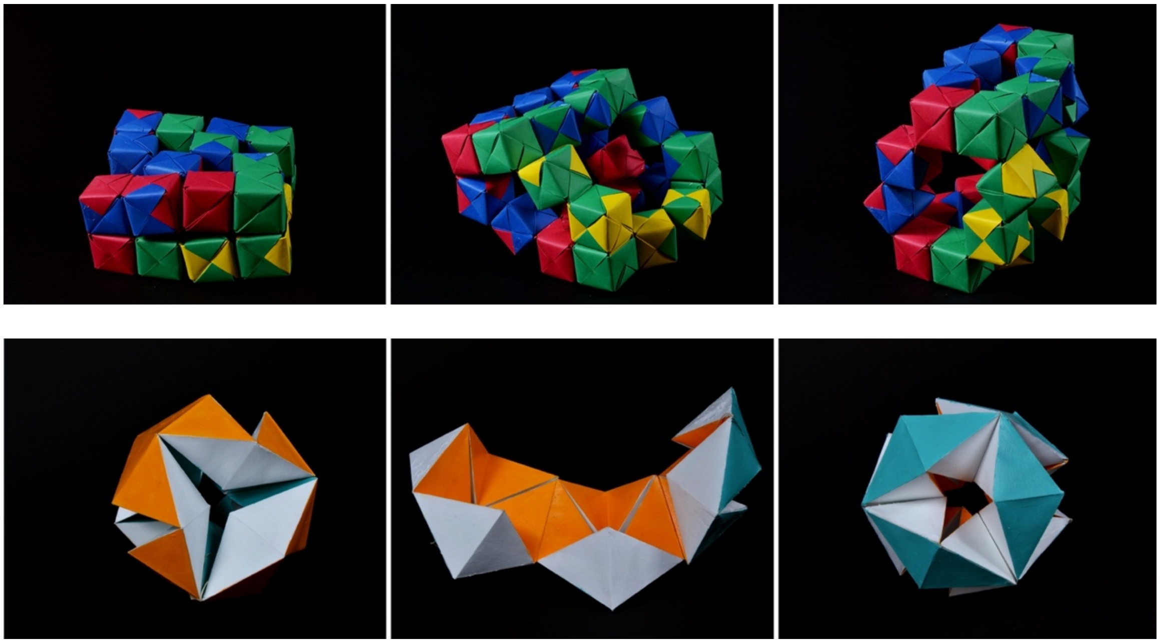


Figure 178: Opening a cube, Students projects

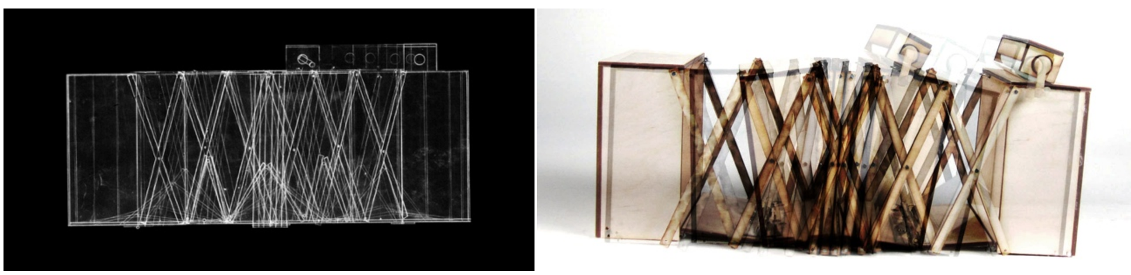


Figure 179: Portable Research Laboratory

Opening a Cube

In the freshman studio, the Opening a Cube assignment was explored first. The intent of this first assignment was to investigate ideas of openness and closed-ness, according to two basic movements: rotation and translation. To do so, students attempted to transform a 10”X10” cube by building physical prototypes that could gradually be opened and closed. By transforming a cube, students were encouraged to foresee, form, and interact with motion. Here, motion was abstractly considered; it served as an introduction to motion design principles.

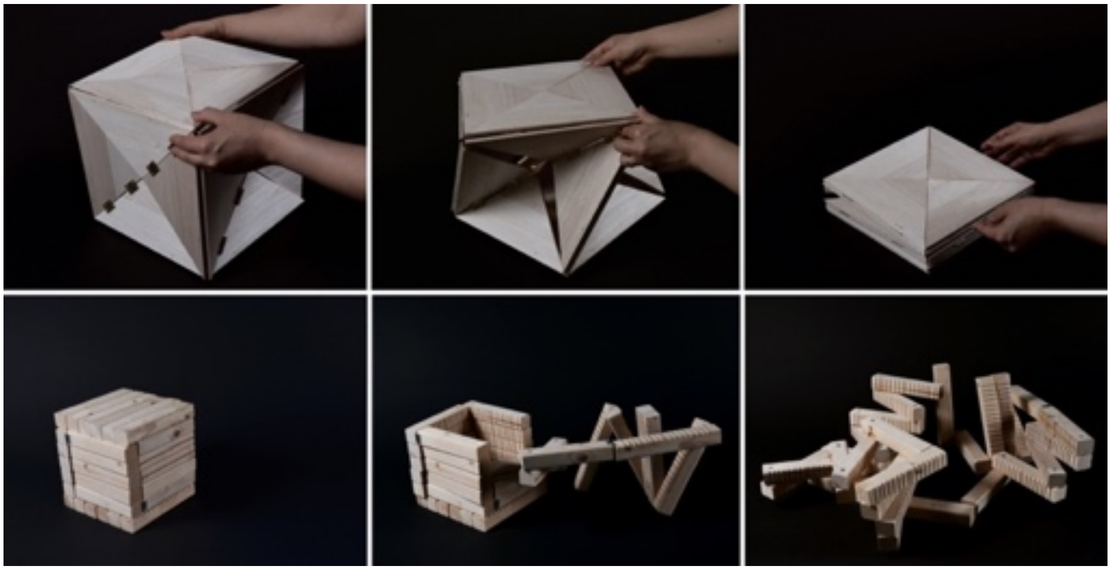


Figure 180: Opening a Cube. Examples of students' projects

In the Opening a Cube assignment, students were asked to consider how the movement of their proposed designs and/or sequence of its components' positions could be introduced through drawing, making, recording, and photography. Specifically, students were asked to reflect their inspiration, foundational concepts, challenges, and learning experiences through written documentation such as design statements and self-evaluation forms. By facilitating the construction of students' knowledge, these written documents offered students the opportunity to analyze what they had done, and predict what might be accomplished going forward. The documents also provided the author, as the studio instructor, with a useful window into what the students did and did not know. As a means of providing evidence for the arguments it posits, this study incorporates examples of those students' written feedback.

Before engaging with the first assignment, students were given several verbs such as expand, collapse, pivot, swing, spin, revolve, glide, and slide. The intention was to inspire these students to consider the different types of movement that could transform a given object. To encourage brainstorming and promote creativity and critical thinking, students were encouraged to select and familiarize themselves with one or two of the suggested verbs. For example, one student wrote: "I used [several] verbs and began to draw ways a cube could embody [them]. It resulted in my cube swinging in an accordionlike manner[86].” The main goal of this activity was not only to spark students’ interest and increase their involvement with the diversity of motion in their daily lives, but also to encourage them to become fully engaged with the potential of motion.

Complex combinations of very simple transformational actions – for example, rotation and translation – can deliver a gradual transition from a closed to an open state. A variety of different ideas emerged; different students developed different ideas to infuse their cubes with movement and excitement. After the desired transformation of form had been accomplished, almost all of the cubes were able to return to their original state.

In the first assignment for both freshman and senior studios, students began with simplified study models in order to facilitate a clear understating of the principles of motion design. In the first step, students attempted to predict what motions could be achieved, and their connection to simple pull, push, and rotation mechanisms. Then, they were encouraged to describe how their applied mechanisms led them to orchestrate their design processes.

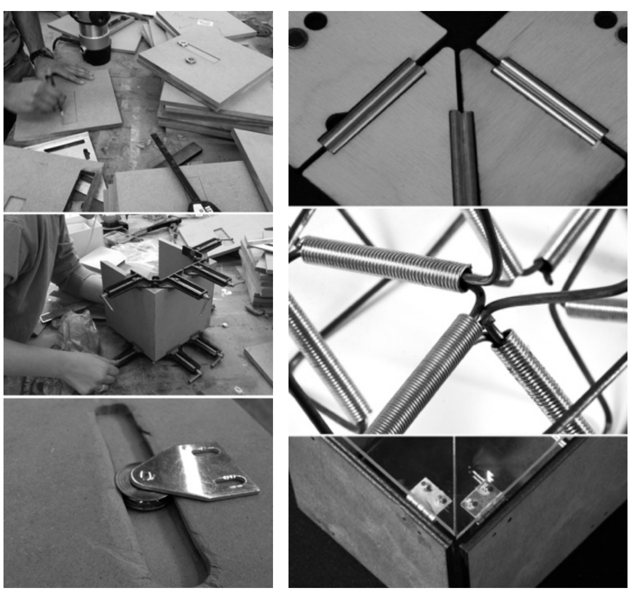


Figure 181: New design challenges caused by changing materials and scale of the cubes. To achieve the desired motion, students designed and fabricated their joints.

[86] Reflected in a design statement of work, a freshman student at Texas A&M.

Although several students tried to transform their cubes from being completely open to almost entirely closed, one of the student's designs moved the cube from a controlled, six-sided state, to a chaotic collection of jumbled, chain-like wooden pieces connected together by hinges. Another folded a ten-inch cube into a two-inch prism. Yet another design transformed and multiplied one cube into three, as it was unfolded. Another cube was broken into nine smaller cubes, with magnets holding the various pieces together; this allowed the pieces to slide horizontally and be organized into various shapes (Figure 180).

Some students found this assignment challenging, and concepts of motion troublesome to design. Before using drawing to study the geometry of pure motion, students endeavored to perfect their understanding through trial and error. Even after addressing the geometry of parts in motion and drawing it on a set of points, line segments, or surfaces representing their trajectory through space, it was difficult for students to analyze certain forces that they could not predict, such as friction, surface tension, inertia, and gravity. While making their prototypes, some students discovered that there were too many unpredictable forces to allow for proper movement. As one wrote: "my largest challenge was trying to get the pieces to move once I discovered that there was too much friction between the rail and track[87]."

[87] Reflected in a self-evaluation form of work, a freshman student at Texas A&M.

Figure 182: *Costume made hinges.*

Due to unpredictable technical flaws, most students faced random errors that impeded the clear expression of their concepts. The author attempted to promote the students' ability to think ahead and plan over time, and cultivated an awareness of what should be taken into account to ensure the operation of the desired mechanism. As the fabrication outcomes highlighted, whatever was planned at the beginning of the design process was not always possible, at least not by adhering to the original plan. For instance, once students moved from their primary study models (made mainly of Bristol board) to more progressive prototypes (constructed from stronger materials such as chipboard, plywood, or Plexiglas), the added thickness occupied the space previously dedicated to motion, which caused performance problems. Moreover, the transition from a thin planar sheet material to another medium did not allow the cubes to be closed or opened as completely as desired.

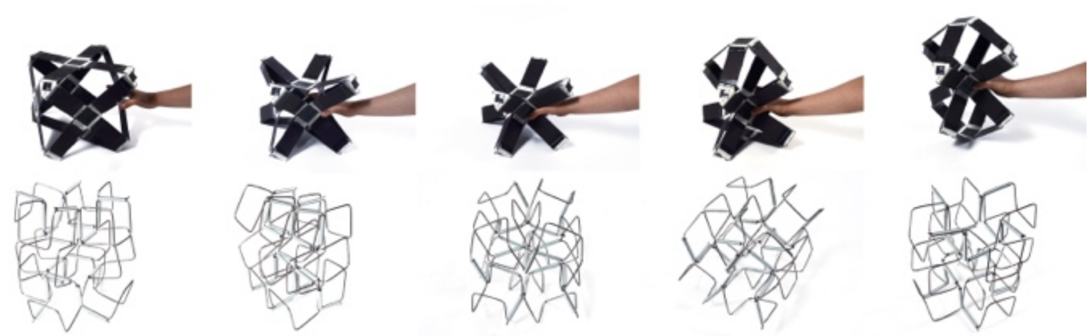


Figure 183: Fabric and spring hinges in transformable cube design.

The lack of proper accessories (such as hinges or rails) that would allow parts to move only in desired directions or create a hierarchy of movement was one challenge preventing certain students from realizing their designs. Mainly, it was hard to find the right hardware or accessories locally. Other challenges involved the size and cost of such accessories. One student wrote: "some challenges were finding the right type of hinge to use because my project required a lot and too small of a size, so searching for an easier and more frugal option was difficult[88]." Fortunately, some students overcame this challenge by creating their own hinge mechanisms (Figure 181 & Figure 182). For example, in fabric hinge design, students used strips of fabric that were laminated between the flat panels. These hinges allowed the joints to lay completely flat when opened (Figure 183). In some cases, these fabric hinges permitted the pieces to pivot smoothly and the cube to collapse to be completely flat.

As mentioned above, to help catalyze the development of transformable design principles for the education of future architects, the "Opening a Cube" assignment was offered to both freshman and fourth year students (Figure 184). This assignment served as an attempt to draw comparisons and contrasts between novice students and their experienced counterparts; it exemplified how students' awareness of the principles of motion design in a foundation design studio was comparable to a fourth year student dealing with motion. For both group of students, the assignment was intended to serve as an introduction to motion design. Interestingly, the freshmen and senior students' levels of knowledge about

[88] Ibid

motion were remarkably similar, irrespective of their ability to represent their thoughts or skill in developing a design process. In spite of their intuitive notions about Opening/Transforming a Cube, both groups of students had the minimum knowledge and experience necessary to apply their concepts to their designs and develop their motion compositions.

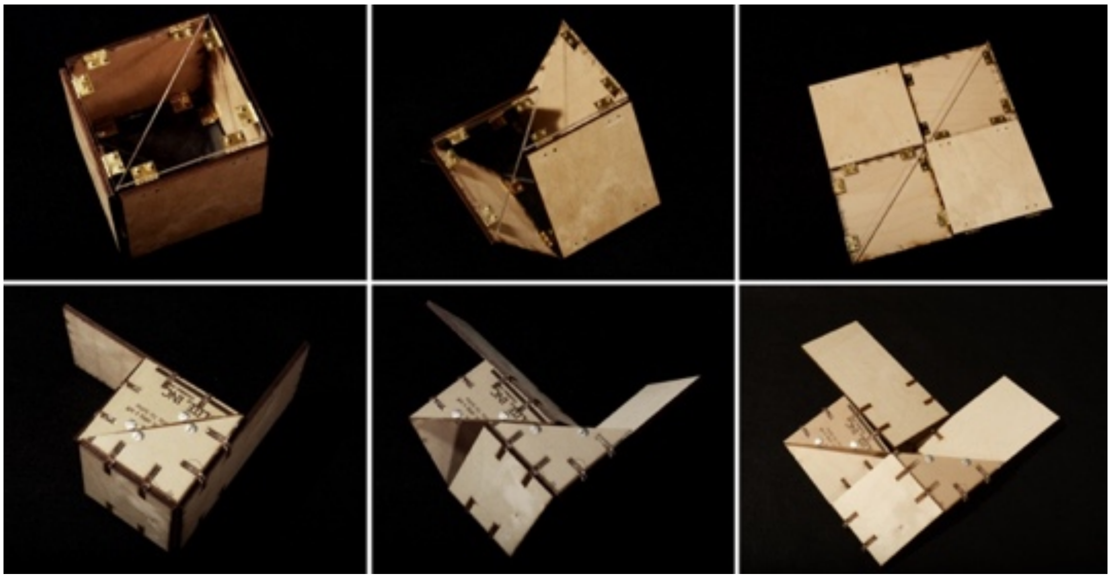


Figure 184. Forth year students' projects at Virginia Tech, 2014.

Rarely was a model built exactly per the first intuitive concept[89], but most of the students at both the freshman and senior levels showed that they had instinctive but unclear and unspecific ideas about concepts related to motion. For both groups, there was a trial and error process wherein they clarified their intuitive ideas about motion. In this assignment, the unfortunate truth was that the senior architecture students still lacked the experience and confidence to quickly turn their motion-based concepts into transformable cubes. As was expected, however, the seniors were still able to develop their designs in less time than the freshmen. Within the first of the semester, opening a Cube was, on the whole, exciting and abstruse for both groups of students, leaving them wanting to learn more

[89] Material properties, means and methods of fabrication, availability of the required fastener and accessories, proficiency in software, and changes in opinion all played a part in shaping the final designs for this assignment.

about the principles of motion design. It is worth mentioning that at the end of this assignment, nearly all of the students from both groups had a sense of the path to being a better designer. By employing the concept of transformability as an exquisite design tool, the value of this assignment was to introduce new ways of thinking about design itself.

5.14 Conclusion

Although motion has long been part of the architectural repertoire, little thought has been given to motion studies in architectural education. By showcasing pedagogical changes in order to integrate motion pedagogy into the curriculum, this chapter discussed how architectural education could be transformed to reflect current and upcoming changes in the building industry.

To the author' mind, there are less comprehensive guidelines or frameworks that seem to exist that articulate the design rules students should follow from conception to realization of motion in architecture. There are a few precedents that can serve as guides for designing transformable structures, but there is even less evidence establishing a design methodology for this kind of architecture (El-Zanfaly 2011). Most of these precedents only identify the types of motion and components found in such structures without clarifying the process of designing a change from one state to another.

Yet, the role motion plays in forming architecture is hardly at the center of the way in which future buildings are designed and future architects are educated. To understand why the richness of motion in architecture is not appreciated in the education and practice of architecture requires a considerable amount of research that can be done through in-depth observation and participation focusing on design process, fabrication phases, installation procedures, and maintenance of transformable architecture.

Incorporating two architectural programs throughout the U.S., to gather direct input on why schools of architecture are currently not motivated to offer transformable design-related courses, the author strived to study and challenge the conventional pedagogical approaches to architecture education through the lens of the motion design pedagogy. By offering scholars the opportunity to evaluate the current picture of motion pedagogy as it appears in two schools of architecture, the author is hopeful that the pedagogy can open new possibilities for reflection and experimentation regarding the different aspects of transformable architecture.

To position the study of motion design within the wider context of the role that motion pedagogy should play in the education of future architects, this chapter was an attempt to analyze the challenges and opportunities architecture programs might face in addressing the application of motion design principles as an element of architectural form-giving.

This chapter explained how motion language was introduced into a design studio as an element of architectural form-giving. The language of motion was not assumed to be a closed system of predefined instructions, but rather an open-ended form of guidelines associated with a student's exposure to a number of topics and basic wellsprings of knowledge significant to an understanding of motion study. Engaging architecture students at Virginia Tech and Texas A&M with direct and hands-on experimentation with the design of movement through the language of motion has led to a realization regarding the capacity of the pedagogy of motion as it can be applied in architecture programs. By providing multifaceted transformable design experiences that develop over time to suit different circumstances and requirements, the pedagogy of motion enables beginning designers to consider the use of motion as a strategy in design, rather than just a design in itself.

In the studios, although the general premise was to help students expand on their current proficiency through incremental levels of progression, from the basic to the advanced, the introduction of transformable architecture was not only critical to students' ability to develop a greater level of conceptual rigor, but expand their ways of seeing and practicing architecture. As an educator, in many of the author's in-house discussions and reviews, what became apparent was that transformable architecture was an effective means of bringing students' design talent, constructive awareness, and curiosity to fruition.

The studios, in spite of indicating a reasonable level of diligence and efforts of students on a five credit design studio, was not an exclusive silo of knowledge around transformable design. it was not expected that students could span the full spectrum of transformable shading design in their first transformable design experiment; however, it is fair to say that the studio environment helped almost all of the students express their design thoughts and mindfully convey their design concepts.

This chapter mainly reviewed how both studios could help students to gain the required knowledge, information, and skills for designing motion in architecture. In addition, the chapter discussed about the followings:

- Making as Way of Knowing
- Multidisciplinary Approach to Motion Design:
- Representation of Motion

Making as Way of Knowing:

To make their idea a reality, intensive use of prototyping was being made in the studios. Although some students failed to conceptualize prototyping as a search for understanding their design concept, the processes of prototyping were a great way to seize design intentions, ideas and ambitions in the form of physical artifacts. In this case, Physical and even digital models were not necessarily representational model.

In the studios, the translation process from drawing to transformable devices emerged from a constant oscillation between thinking within the scale of a concept and an involvement with the constructive process of the work. In both studios, students' works ranged from the implementation of advanced motion geometries, to small-scale intricate 3D-printed joints, to prototype-based research in transformable architectural components, and to full-scale operable shading devices.

Most of the immediate needs of students were addressed with a full toolbox of analog and digital[90] methods of production, providing an extension of their thinking throughout the fabrication process. In the studios, the general premise was to help students expand upon

[90] By using the most common subtractive tools in CAD/CAM technologies (such as CNC Router and Laser Cutter) and Additive technology.

their current skill sets by selecting, using, assessing, and customizing appropriate fabrication methods that also match their backgrounds, concepts, and budgets.

Multidisciplinary Approach to Motion Design:

It is obvious that the integration of motion into the built environment requires a continuous search and open communication across several disciplines. Navigated in between, away from and towards a range of topics, the offered studios were an attempt to bring together seemingly disparate yet inter-related bodies of work in various disciplines into a coherent area of different design-research activities. Therefore, by introducing students to exploratory interdisciplinary approaches, the studios included a series of lectures and workshops that introduced students to the principles that underlie the discipline of transformable design.

Representation of Motion:

By conceiving motion as a sequence of frames represents a linear indexing of time, the studios also underscored the importance of different design and representation tools. These tools included physical prototypes and both digital and analogue design media simultaneously letting students' designs move and represent in a continuum. Through a set of lavish drawings, videos, and prototypes, students investigate the variety of means by which the motion of their design could be presented.

5.14.1 Design Process Model for the Future Transformable Design Studios:

Four years of self-immersive AURA study were used to establish a provisional TSS design process model that was then used as the theoretical framework for two transformable design studios:

1- transLAB 2014 at Virginia Tech
2- tranSTUDIO 2015 at Texas A&M

These additional two years of self-immersive study, along with continuous observations of the studios' progress, reframed this TSS design process. During these two studios, 22 young designers were exposed to the provisional TSS design process, and each individual experience added to the greater TSS design process model.

As previously discussed in the Structure of the Research section, an important goal of this research was to improve the researcher's understanding of the TSS design process. Design problems are "wicked" and notoriously difficult to structure; the way this research dealt with these wicked problems was to consider the TSS design process as a cyclic map. With this configuration, each cycle of the solution formulation reveals a new understanding of the problem. This means that the more one practices in this domain, the better one understands the problem. Design not only follows a sequential overall process, but also a system of cyclic feedback occurring in the sub-processes. The developed design process model includes regular feedback loops to promote continuous improvement. The 22 young designers' experiences with the TSS design process improved the comprehensiveness of the model; however, this is an endless loop that needs to be continuously refined.

Based on these two studios, the following subjects comprise the main additional objectives of future transformable design studios:

1- The earlier students learn about transformation design strategies, the better they can implement them in their subsequent design projects.
2- The control aspect of TSS will be included in the transformable design studio.
3- The effect of materials properties in TSS will be included in the transformable design studio.
4- An educational motion kit (motion typologies models) will be designed, produced, and made part of the education package.
5- A network of professional experts in the field will be established.
6- Materials and fabrication process information will be gathered in an open-access source.
7- A glossary for transformable design will be developed for the transformable design studio.
8- A one-year studio is more suitable for the transformable design studio. The first studio should be more about foundational knowledge, skill, and information; the second should be a platform for the integration of TSS into the architectural

design process (the key to understanding the **relationship** between the **part** and the **whole).**

9- The history of transformable architecture and literature will be included in the studio.

10- The focus of the studio will be expanded from Transformable Shading Systems to include transformable architecture.

5.14.1.1 The earlier students learn about transformation design strategies, the better they can implement them in their subsequent design projects.

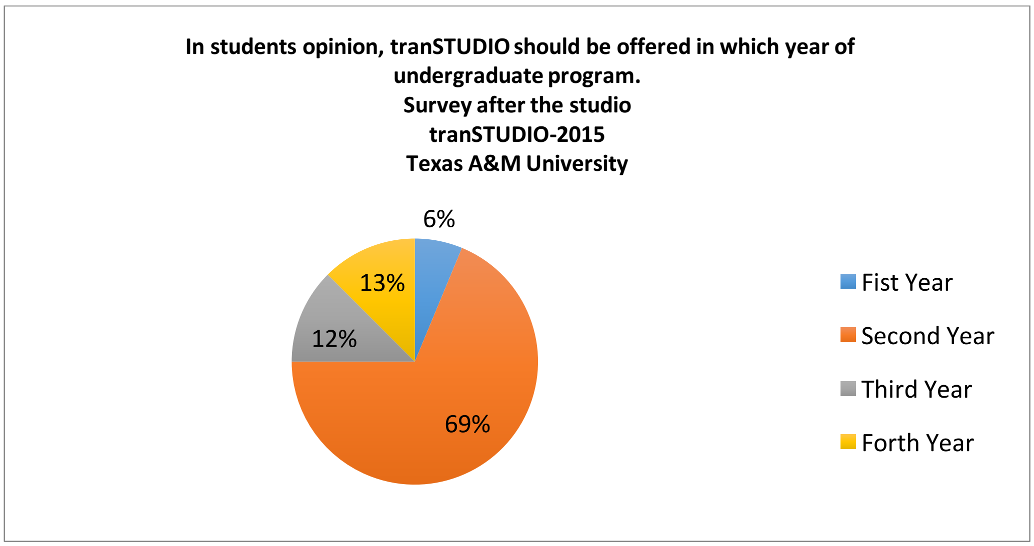


Figure 185. tranSTUDIO students' opinions on the best year to have a transformable design studio.

The final survey was conducted at the end of the studio (after the final presentation and exhibition); it included a question asking students their opinions regarding the best year of the undergraduate program to offer tranSTUDIO. Interestingly enough, the majority of students (88%) believed that it should be offered sooner than senior year. They gave the following reasons:

- The design process and principles taught in tranSTUDIO could have been utilized in upper-level classes and would have made their third and fourth-year projects better.

- They would have been less “tainted” by previous work, and thus more able to focus on new design ideas
- The more knowledge they had about transformable systems in earlier years, the more they could have integrated it into their upper-level projects.
- They learned new software, fabrication skills, and materials knowledge that would have been of benefit to them earlier on in their education.
- They explored a whole design process, from ideation to realization, and that would have been useful in earlier years.
- They could have dedicated more time to the projects.

The author has already begun implementing the principles of transformable design in her foundational levels. However, she will attempt to offer the transformable design studio as a second-year course, and compare the results with the fourth-year studios. This new experimentation is likely to further refine the TSS design process model and incorporate new components.

5.14.1.2 The control aspect of TSS will be included in the transformable design studio.

Out of the three basic aspects of motion design (the geometry of motion, materials, and behavior), the main focus was on knowledge regarding the geometry of motion. The materials knowledge and behavior aspects of the transformable system were not covered, due to time limitations. However, the behavioral characteristics of transformable design could significantly influence the TSS design process. In these two studios, the means of operation was mainly mechanical force, and usually the operation was manual. However, means of operation can open up new possibilities and design concepts (Figure 186).

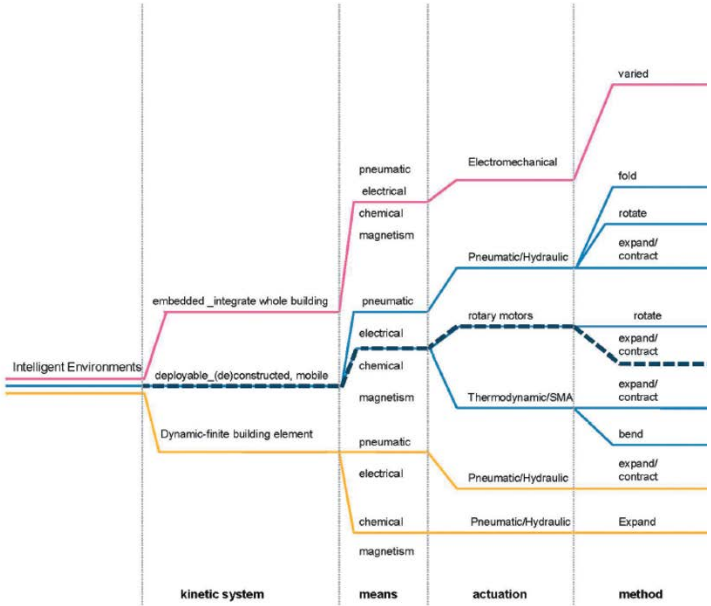


Figure 186. Different means of operation for kinetic systems (Ku, 2010).

5.14.1.3 The effect of materials properties in TSS will be included in the transformable design studio.

As we previously mentioned, a proper motion design would address three aspects: material, geometry of motion and behavior (control). In current studios, the main focus was on geometry of motion. The next evolution of this studio will expand the scope and address the three aspects of motion design including material properties and control systems.

5.14.1.4 An educational motion kit (motion typologies models) will be designed, produced, and made part of the educational package.

The proper teaching of transformable design requires tangible educational models that help students grasp the principles of motion. During these years of self-immersive research, the author designed and fabricated many models that were then shared with students in transLAB and tranSTUDIO. However, to share the Pedagogy of Motion, the author will also design an educational kit that will be supplementary to the TSS design process map. These physical models will assist students in tangibly understanding motion geometry and facilitate their overall learning process.

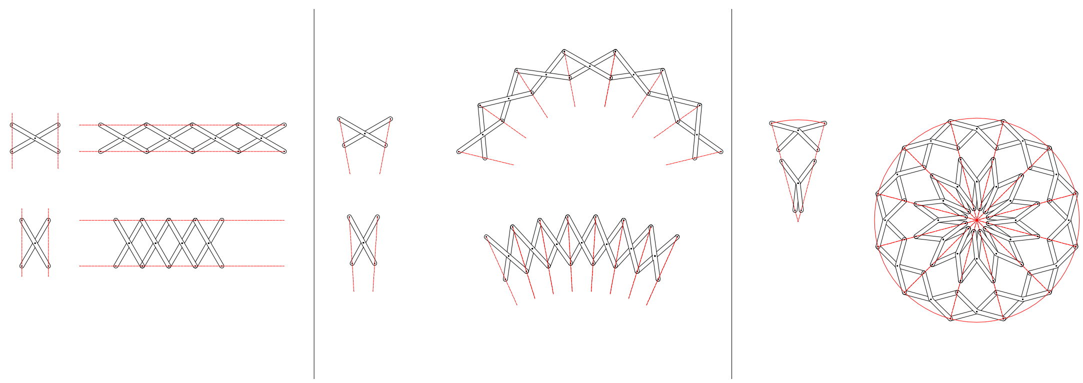


Figure 187. Three types of scissor structures.

5.14.1.5 A network of professional experts in the field will be established.

During the five years of this self-immersive process, the author established connections with different professionals ranging from structural and mechanical engineers, to environmental experts, fabricators, materials engineers, and façade designers; all had critical roles in shaping the TSS design process model. The author will establish an online library to create a network of designers and experts. This library will need to be regularly updated.

5.14.1.6 Materials and fabrication process information will be gathered in an open-access source.

Providing information related to where designers can access materials and other details (such as fasteners, spacers, actuators, etc.) would be very helpful to beginners. It is very useful for students to have access to the technical details related to their materials.

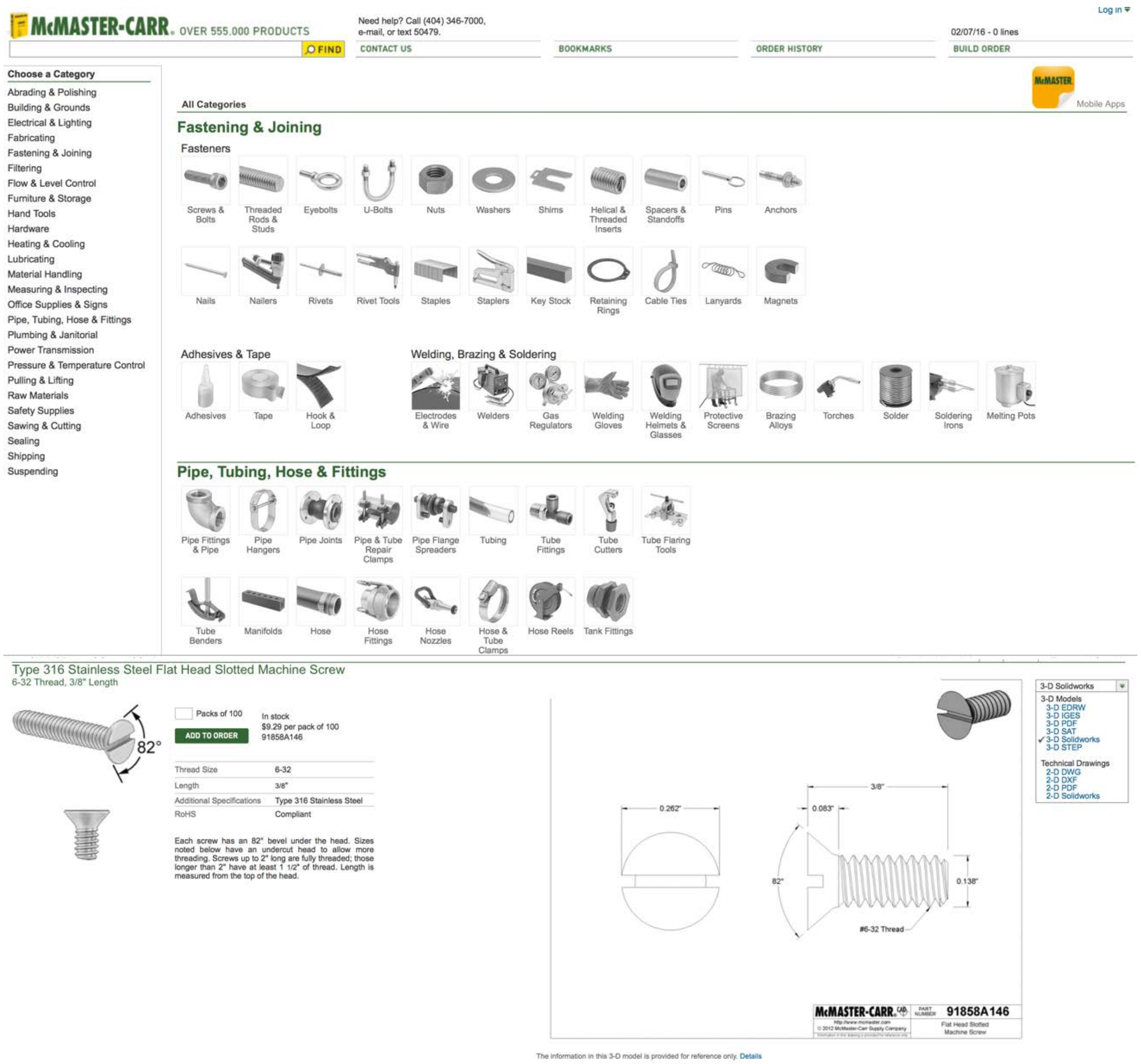


Figure 188. McMASTER_CARR is one the best and most reliable companies. Transformable studios would benefit from their library of materials and online purchasing (Screenshot form *http://www.mcmaster.com* on 02/07/2016).

The author has already begun gathering samples for materials exploration. This library will eventually gather together hands-on and in-depth materials useful for exploration and investigation into transformable systems. The entirety of this information will be accessible online. The website will include useful design tips and explanations of materials properties, as well as their technical properties.

5.14.1.7 A glossary for transformable design will be developed for the transformable design studios.

As has been mentioned, a lack of common language and terminology among students, fabricators, and experts was one of the main observations made during the studios. The author will investigate the existing glossary of terms used in kinetic design, the fabrication process, and materials subjects, and select primary terminology to recommend to transformable design students. This will be an online glossary intended to evolve over time.

5.14.1.8 A one-year studio is more suitable for a transformable design studio.

An effective education in transformable design requires at least two semester-long studios. The first studio should focus more on foundational knowledge, skills, and information; the second should be a platform for integrating TSS into the overall architectural design process (the key to understanding the **relationship** between the **parts** and the **whole**). The author will attempt to teach two semester-long studios with a focus on transformability. The final survey presented during the previous studios indicated that all students desired an additional studio (one year) to apply their learning. The first studio should be more about what information, knowledge, and skills they need to design transformable systems; the second should be about the integration of these three inputs.

5.14.1.9 The history of transformable architecture and associated literature will be included in the studio.

It is very valuable to research and teach the precedents in this area, as well as their results and challenges. Due to time limitations, in both studios the history of transformable architecture was limited to the introductory session. In a two-semester studio, there will be adequate time to expose students to the full history of this subject.

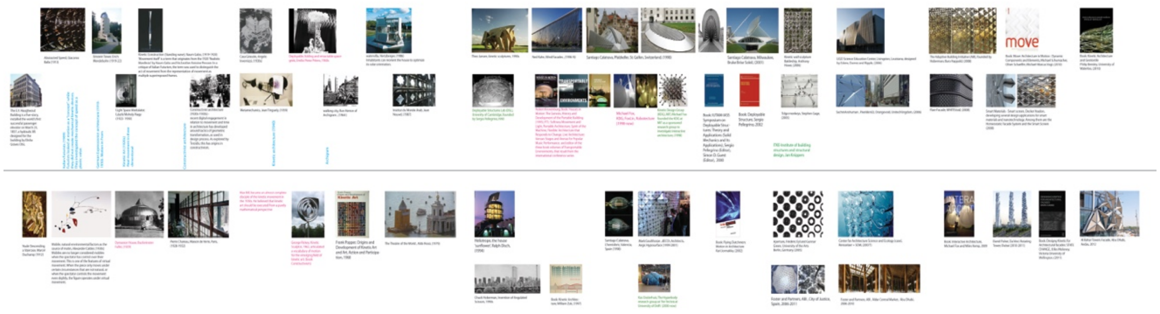


Figure 189. The history of transformability, as structured by the author.

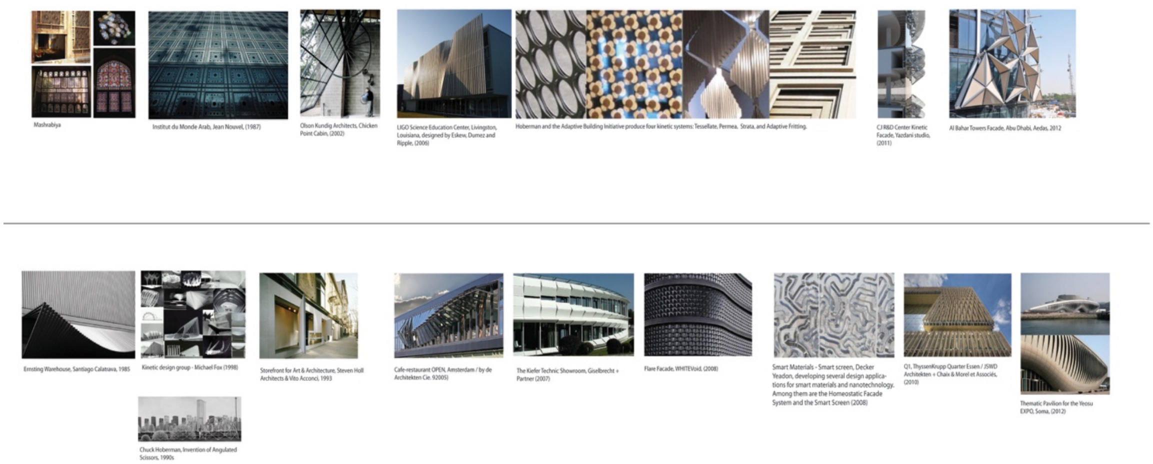


Figure 190. Transformable shading systems in modern architecture.

5.14.1.10 The focus of the studio will expand from Transformable Shading Systems to include transformable architecture.

The ultimate goal of two studios was to make students more knowledgeable about the design process of transformable shading systems so that they could become competent to design and fabricate a TSS. The next evolution of this studio will expand the scope and address the entire topic of transformability in architecture. Both studios featured assignments addressing transformability in architectural elements such as deployable walls, convertible ceilings, and expandable spaces. However, they did not address the entirety of architecture or what transformability could offer space.

5.14.2 Future intention to expand the captured knowledge and share it with a broader audience.

The following are additional goals for future transformable studios that will allow the knowledge gathered here to be shared with a broader audience:

1- An issue of a magazine will serve as a prelude to the longer-term objective of the first national conference on the pedagogy of transformable design. This conference will open up new possibilities for reflection and experimentation regarding the different aspects of transformable design pedagogy. Prior to this conference, this research will lead to several lectures and a series of conference papers.
2- An international conference will be arranged, the emphasis of which will be on gathering transformable educators, theorists, and experts to discuss the pedagogy of transformable design.

A book-length project on the pedagogy of transformable design will also be pursued.

6 Chapter 6: **Conclusion**

This dissertation is the product of several years of research into transformation design that was conducted in an effort to understand the innate characteristics of a design process dedicated to transformable architecture, and to resolve some of the limitations associated with the use of motion design principles. This work allowed the author to more deeply research the motion design process, a logical extension of her long-standing scholarly interest.

By employing the concept of transformability as an exquisite design tool in this dissertation, the goal was to introduce new ways of thinking about design itself and its related disciplines. To unify the seemingly paradoxical duality of static and dynamic architecture in view of transforming the existing education in and practice of architecture, this dissertation called for a new way of design thinking and reassessment of the conventional architectural design methods. This research was dedicated to leading readers through the principles that underlie transformable architecture by disseminating two main design research streams as "knowing in action":

- The AURA design process as an immersive case study; and
- Two transformable design studios as a method of knowledge capture.

6.1 AURA Design Process as an Immersive Case study

The dissertation intends to counteract the shortage of transformable design knowledge through demonstrating the design process of AURA. As a means of helping the author and other designers better understand the entire design process and the inherited challenges of the greater motion design discipline, the AURA design process was kept mainly process-centric rather than product–centric. Therefore, fabricating several prototypes, in itself, was not the foremost goal of the design process; however, better understanding the design process of transformable architecture that results in a well-designed space or product was the goal.

6.2 Two Transformable Design Studios as a Method of Knowledge Capturing

Transformation, though it is not a newly coined design term, has rarely been acknowledged as a critical component of architecture. Due to a relative lack of history regarding transformable architecture resulting from the dominant tradition of understanding architecture as a collection of static artifacts, motion study has not progressed to a place within the pedagogy of architecture, and the impact of transformable architecture on pedagogy has predominantly been underestimated. As opposed to the few architecture schools that have taken pioneering roles in architectural education, the average architectural school has lagged behind in both methodology and tools for designing transformation in architecture. A lack of devotion to motion pedagogy explains why we do not yet have many transformable buildings.

As discussed, existing approaches to practicing and teaching motion in architecture have shortcomings in terms of the nature of transformable design principles. At this time, there are very few institutional frameworks available to help tackle the lack of pedagogical effort being made under the rubric of transformable architecture. To help catalyze the development of transformable architecture, this dissertation was a vehicle for eliciting evidence of the challenges and opportunities architects face in addressing motion in their buildings. By investigating the role that motion-based courses play in architecture education, this dissertation created one of the first comprehensive studies of transformable design pedagogy. The author expects this work to be of interest not only to scholars working to educate future architects, but also to those who work in many related fields of education.

This dissertation discussed why motion study deserves greater focus within architectural pedagogy. Thus, the author attempted to position the study of motion design within the wider context of the role that motion pedagogy should play in the education of design students. The pedagogy of motion as an alternative way of thinking about architecture is built upon a continuous exploration of "what architecture can be," rather than a repetitive re-asking of "what architecture is."

By incorporating motion into architectural education, this study rethinks the role of motion design principles in restructuring the curriculum of transformable architecture. In this dissertation, the author presented the concept of motion pedagogy; this pedagogy serves as a proposal for developing new ways of thinking about the education of future architects, and also of practicing the discipline of architecture. To analyze the impact of motion pedagogy on an entire curriculum while also studying the skills/knowledge accumulated from the use (or lack) of motion design principles, the author outlined the notions of motion pedagogy within the context of two design studios for fourth-year architecture students. Serving as one of the first endeavors to structure the education of transformable architecture at Virginia Tech and Texas A&M University, the author's major effort was to place, examine, and promote the pedagogy of motion in its proper place in architectural education.

This study explores the incorporation of motion into the design process. Building upon the author's transformable design studios and AURA's design process, the purpose of this dissertation was twofold:

1. To understand the constrains, trends, drivers, and demand for design projects that interact with the environment through motion; and
2. To overcome the lack of a comprehensive design framework of transformable architecture that leads to either poor design decisions relating to the utilization of motion or the failure of a proposed design concept. Thus, this study provides a framework for the interconnections among the education of architects, and the professional competence required to design transformable architecture.

6.3 Capturing Preliminary Process Map During AURA's Design Process

To develop a comprehensive deign framework of TSS the author had two knowledge capturing platforms: AURA's design process and the transformable design studios.
A preliminary process map was developed during AURA's design process (Figure 191).
This preliminary process map was developed in a basic flowchart.
The preliminary process map was developed in 8 stages:

1- Appraisal
2- Early Design Studies

3- Conceptual Design
4- Design Development
5- Design for Fabrication
6- Final Controls
7- Fabrication
8- Post Fabrication

The main focus was to document all the process and observations during AURA's design process and structure them in a flowchart. Although the author was closely observing the process, the design map was not mainly concerned with the inputs (knowledge, skill and information) and outputs of each stage.

This preliminary design map was the primarily framework for designing the transformable design studios. During the studios this preliminary design map were validated, refined and restructure to include the whole learning outcomes of 1) AURA's Design Process and 2) The Transformable Design Studios. The outcome of these two knowledge-gathering phases is a detailed process map for Transformable Shading System.

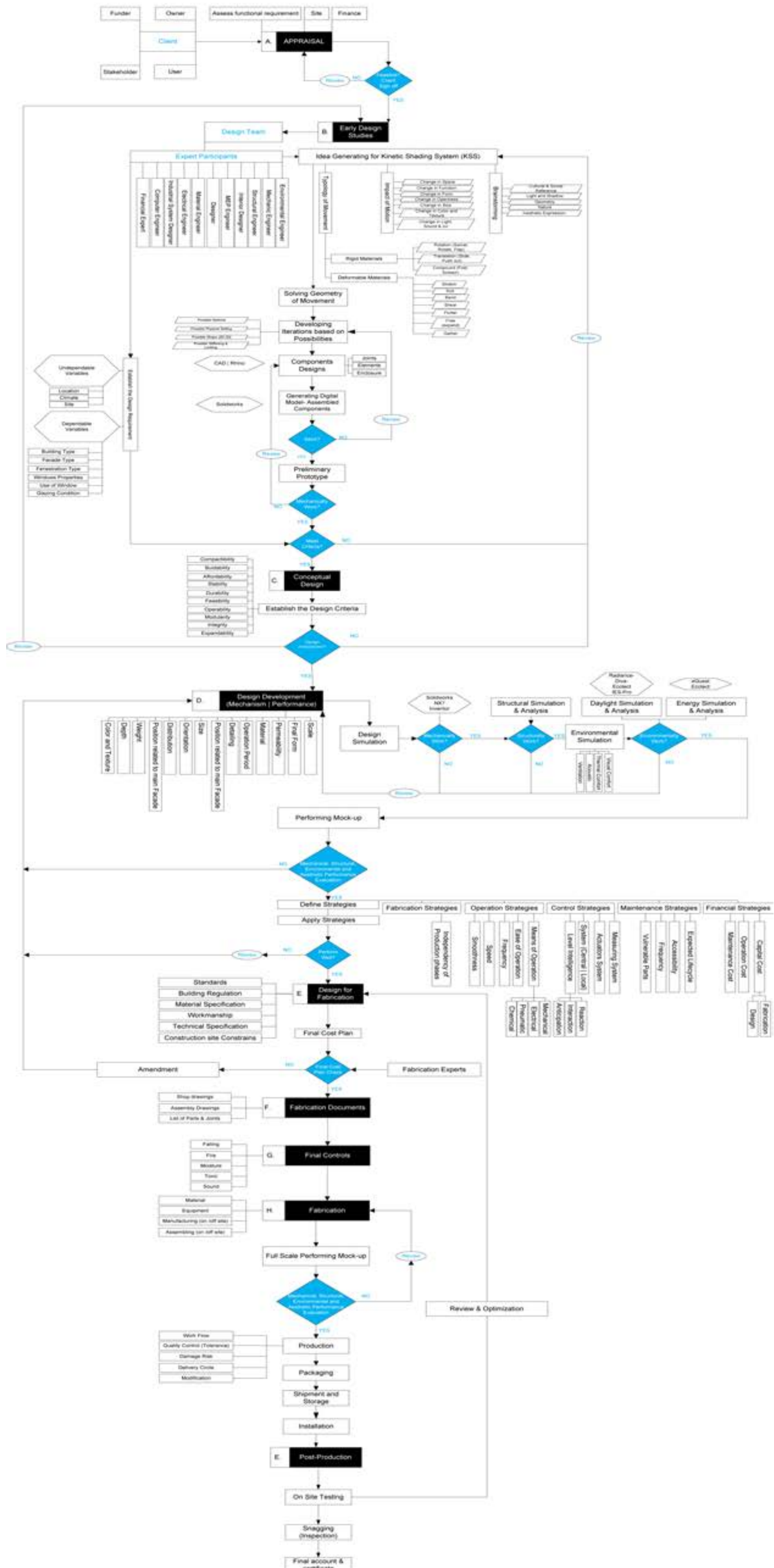


Figure 191: Preliminary process map of TSS developed after AURA design process

6.4 Capturing the TSS Detailed Process Map During AURA's Design Process and the Transformable Design Studios

To capture a TSS detailed process map, a number of steps have been taken during AURA's design process and the two design studios.
The following is a description of the required steps:

- Identify all related TSS design process phases in the overview map;
- Organize the TSS design process phases into the project sequences/activities;
- Determine the information exchange required for each sequence/activity;
- Determine the skills required for each sequence/activity; and
- Determine the knowledge that is required to make the best decision.

In the TSS overview process map, there are three major phases listed in sequential order; within each process is a swim lane.[91] These three phases are:

- Design;
- Fabrication; and
- Post-fabrication.

TSS design process map includes all three of the phases included on the overview map. However, it is worth mentioning that during this research, the author did not thoroughly investigate the fabrication and post-fabrication phases because the focus was on the TSS design, and specifically the motion design segment of that phase.

In a sequential order and within each process's swim lane, the following necessary steps should be taken:

- Design

[91] A **swim lane** is a visual element used in process flow diagrams or flowcharts that visually distinguishes job sharing and responsibilities for the sub-processes of a business system. Swim lanes may be arranged either horizontally or vertically.

- Early design studies
- Conceptual designs
- Design development
- Designs for fabrication

- Fabrication

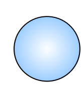
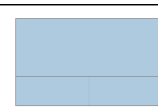
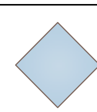
- Fabrication
- Assembly
- Installation

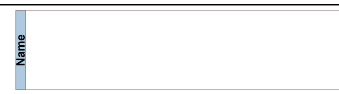
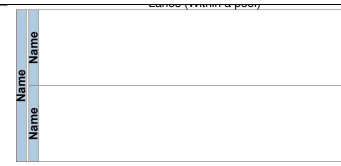
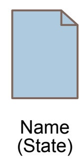
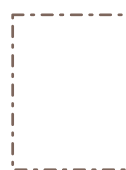
- Post-Fabrication

- Shipment, storage
- Operation
- Control
- Inspection
- Maintenance

Table 26 illustrates the symbols used in the TSS design process model.

Table 26: BPMN Standard Symbol Notation Used in Process Mapping

Element	Description	Notation
Event	An Event is an occurrence in the course of a business process. Three types of Events exist, based on when they affect the flow: Start, Intermediate, and End.	
Process (Activity)	A Process is represented by a rectangle, and is a generic term for the work or activity that an entity performs.	
Gateway (Decision Node)	A Gateway is used to control the divergence and convergence of Sequence Flow. A Gateway can also be seen as equivalent to a decision in conventional flowcharting.	

Sequence Flow	A Sequence Flow is used to show the order (predecessors and successors) in which activities will be performed in a Process.	
Message Flow	An association that is used to tie information and processes with Data Objects. An arrowhead on the association indicates a direction of flow, when appropriate.	
Pool	A Pool acts as a graphical container for partitioning a set of activities from other Pools.	
Lane	A Lane is a sub-partition within a Pool that will extend the entire length of the Pool, either vertically or horizontally. Lanes are used to organize and categorize activities.	
Data Object	A Data Object is a mechanism for showing how data is required or produced by activities. They are connected to activities through associations.	
Group	A Group represents a category of information. This type of Group doesn't affect the Sequence Flow of the activities within that Group. The category name appears on the diagram as a group label. Groups can be used for documentation or analysis purposes.	

6.4.1 Knowledge, Skill, and Information Gathered Through the AURA Design Process and Transformable Design Studios

Regardless of the particular scope of the TSS design, there is a common set of knowledge, skills, and information that all architects and designers should pursue to address the following: inquiring, integrating, analyzing, conceptualizing, abstracting, visualizing, formalizing, communicating, enabling, and assisting. However, there are some particular knowledge categories, skills, and information that influence the ability of an architect to design a TSS. During the AURA design process conducted for this research and two transformable design studios, the major knowledge categories, skills, and information (KSI) exchanged, gained, or generated were captured and are shared here. A KSI is a series of narrative statements required for designing a TSS. Moreover, designers must also know when and how they should target these knowledge categories, skills, and information.

In this research, knowledge in action provided a unique opportunity for the author to identify the main influential aspects of KSI during the AURA self-immersive case study; these aspects were then shared with the 22 architecture students who attended the two transformable design studios.

The major knowledge categories, skills, and information exchanged during the AURA design process and the transformable design studios can be categorized as follows:

1- Knowledge: the state of being aware of the theoretical and practical understanding of a subject.[92] Here, knowledge is a body of information applied directly to the performance of a function that supports the design and decision-making processes of a TSS (Figure 192). In the context of this research, there are two main types of knowledge: practical and theoretical. These two branches of knowledge contain the following:

Practical knowledge:

- General design knowledge;
- Environmental design knowledge;
- Motion design knowledge (including the required knowledge about materiality, geometry of motion, and behavior of a mechanism);
- Structural/mechanical design knowledge;
- Material knowledge;
- Fabrication knowledge; and
- Control knowledge.

[92] "Knowledge" [Def. 1]. (n.d.). *Merriam-Webster Online.* In Merriam-Webster. Retrieved September 1, 2015.

Theoretical knowledge:

- Aesthetics of motion;
- Poetics of motion; and
- Relationship between architecture and motion.

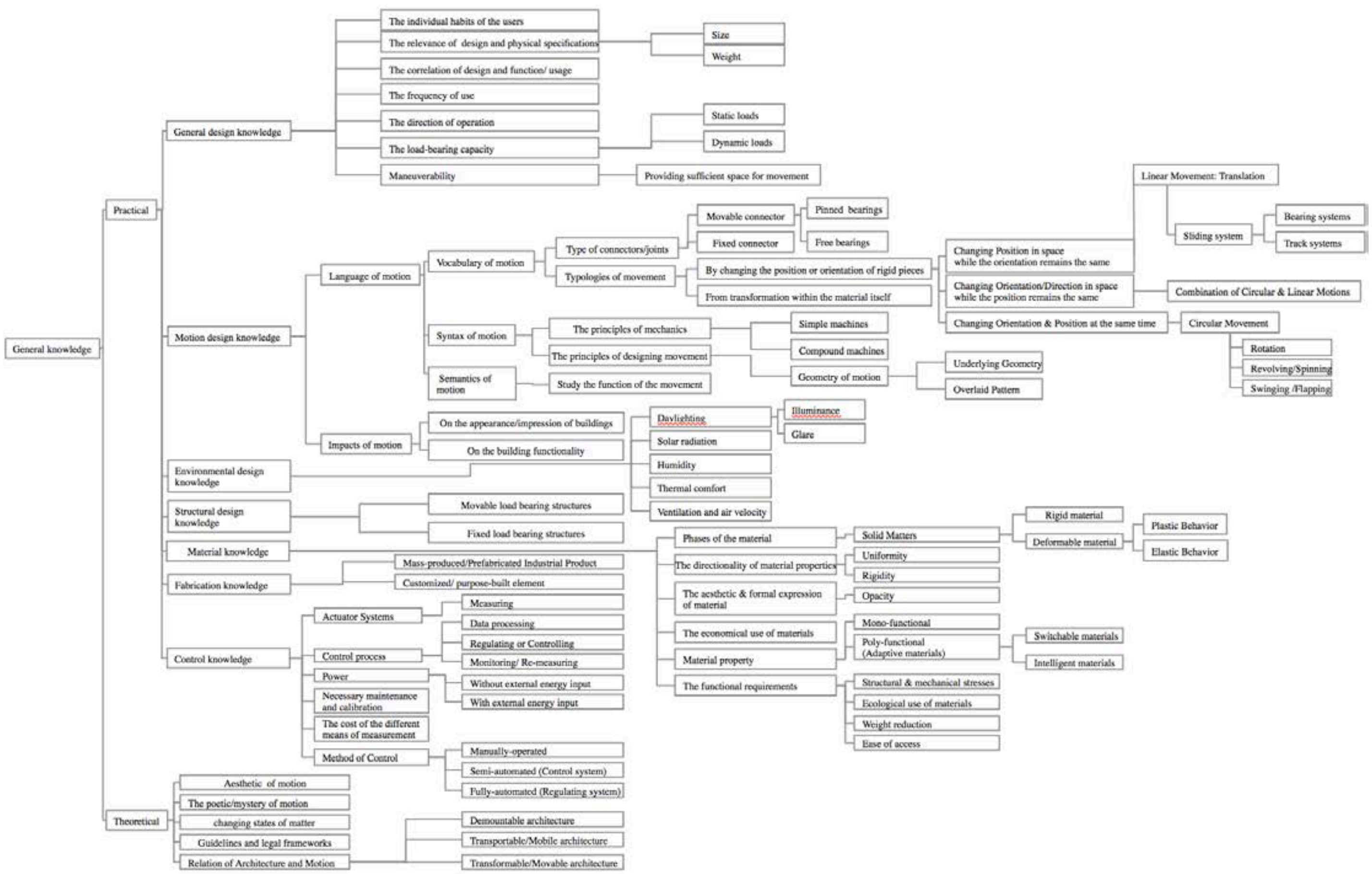


Figure 192. Knowledge required for the TSS design process.

2- Skill: the ability to do something that comes from training, experience, or practice (often non-contextual).[93] In the context of this research, this concept includes:

- Fabrication skills;
- Digital modeling skills;

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[93] "Skill" [Def. 1]. (n.d.). *Merriam-Webster Online.* In Merriam-Webster. Retrieved September 1, 2015.

- Physical modeling skills;
- Performance analysis skills for working with environmental analysis software to control glare, light, and solar energy; and
- Technical skills for working with mechanical analysis software.

3-Data/Information: raw material and facts/organized and processed data.[94] Generally, information can be classified into two types:

Quantitative information:

This is prescriptive information about which a designer is not required to make decisions. Mostly, this information cannot be modified over time (as is the case with building location and environmental information). In the context of this research, quantitative information includes three sub-types, as follows (Figure 193):

- Contextual information (such as site, building, envelope, and cultural or social information);
- Environmental information (such as air temperature, light intensity, solar radiation, humidity, air quality, etc.); and
- Technical information (such as material, structural, fabrication, mechanical, and installation information).

Qualitative information:

This is more descriptive information about which a designer can make decisions; this information can be modified over a period of time (such as level of comfort, security, and privacy). In this research, qualitative information embraces two sub-types, as follows:

- Functional information (such as performance requirements, level of security, and level of performance); and
- Economic information (such as fabrication budget, cost of shipment, and cost of maintenance).

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[94] "Data" [Def. 1]. (n.d.). *Merriam-Webster Online.* In Merriam-Webster. Retrieved September 1, 2015.

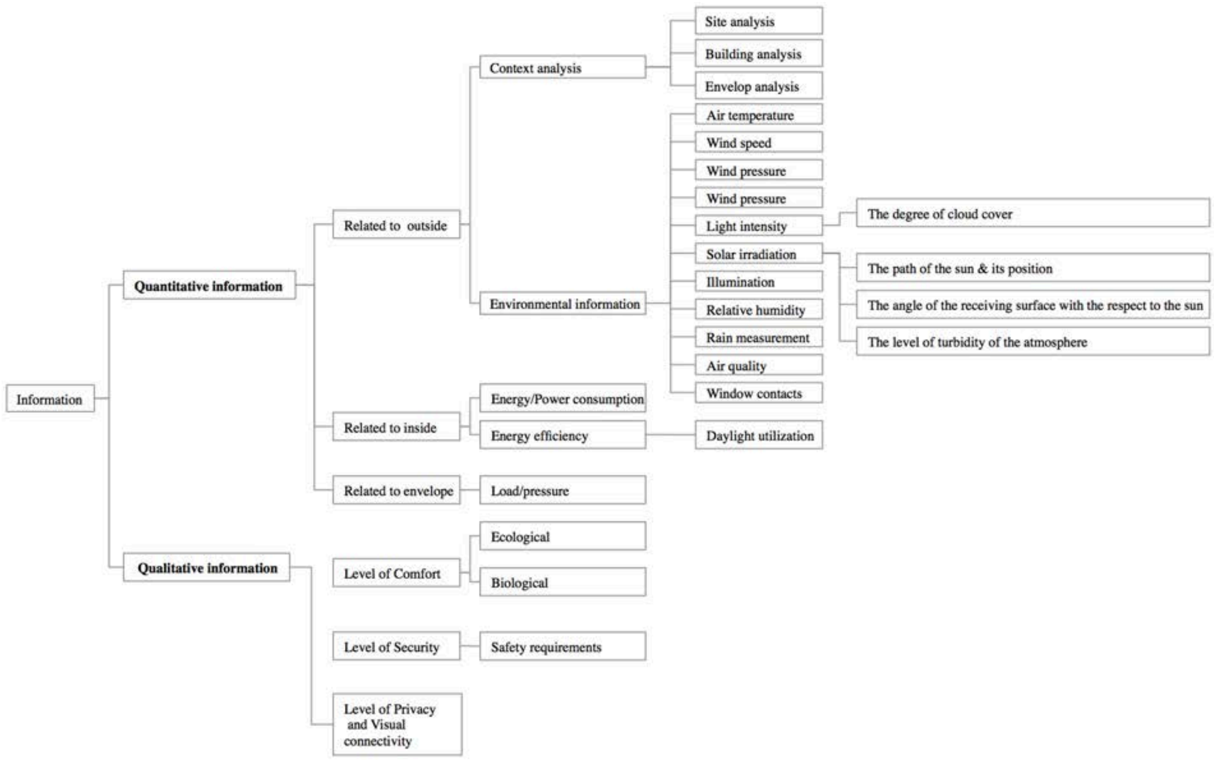

Figure 193. Information required for the TSS design process.

Detailed TSS Phase Map

Since this research was focused more on the motion design phase, a detailed process map was created to clearly define the sequence in which the multiple activities within that phase needed to be performed.

This detailed phase map represents the use of swim lanes, divided into five categories of information:

1. Reference information (input): The required sources of information for each activity in the process.
2. Reference skills (input): The required level of skill for each activity in the process.
3. Reference knowledge (input): The required knowledge for each activity in the process.
4. Process: The sequence of activities performed within a given process phase.
5. Exchange solution or sub-solution (output): The deliverables obtained from the specific activities that form the input sources of future phases. Some of the sub-

solutions will act as future inputs. This acknowledges that formulating solution conjectures often also help to clarify the overall problem. At lower levels, there are similar interactions between identifying sub-problems and generating sub-solutions. This attempts to demonstrate that the relationship is not one way, traveling from input (problem) to output (solution), but rather that a problem's definition is often dependent upon the generation of solution concepts.

In order to create detailed maps, the process phase was divided into a set of sequential steps. The process map included detailed maps for each of these four steps:

1- Early design;

2- Conceptual design;

3- Design development; and

4- Design for fabrication.

The main focus of all of the detailed maps was to frame the skills, knowledge, and information exchange in play during the design phase of the TSS motion design process. In the detailed map, the author included what she learned through the AURA self-immersive case study and two transformable design studios. The focus of the map is on early design, conceptual design phases and part of design development. Because of limitation of the research and opportunities, the detailed maps mostly developed till making Performing Mock-up. There are three detailed map presenting early design, conceptual design phases and design development.

The result is illustrated maps embedded with the knowledge gained during the research process (Figure 194, Figure 195, Figure 196)

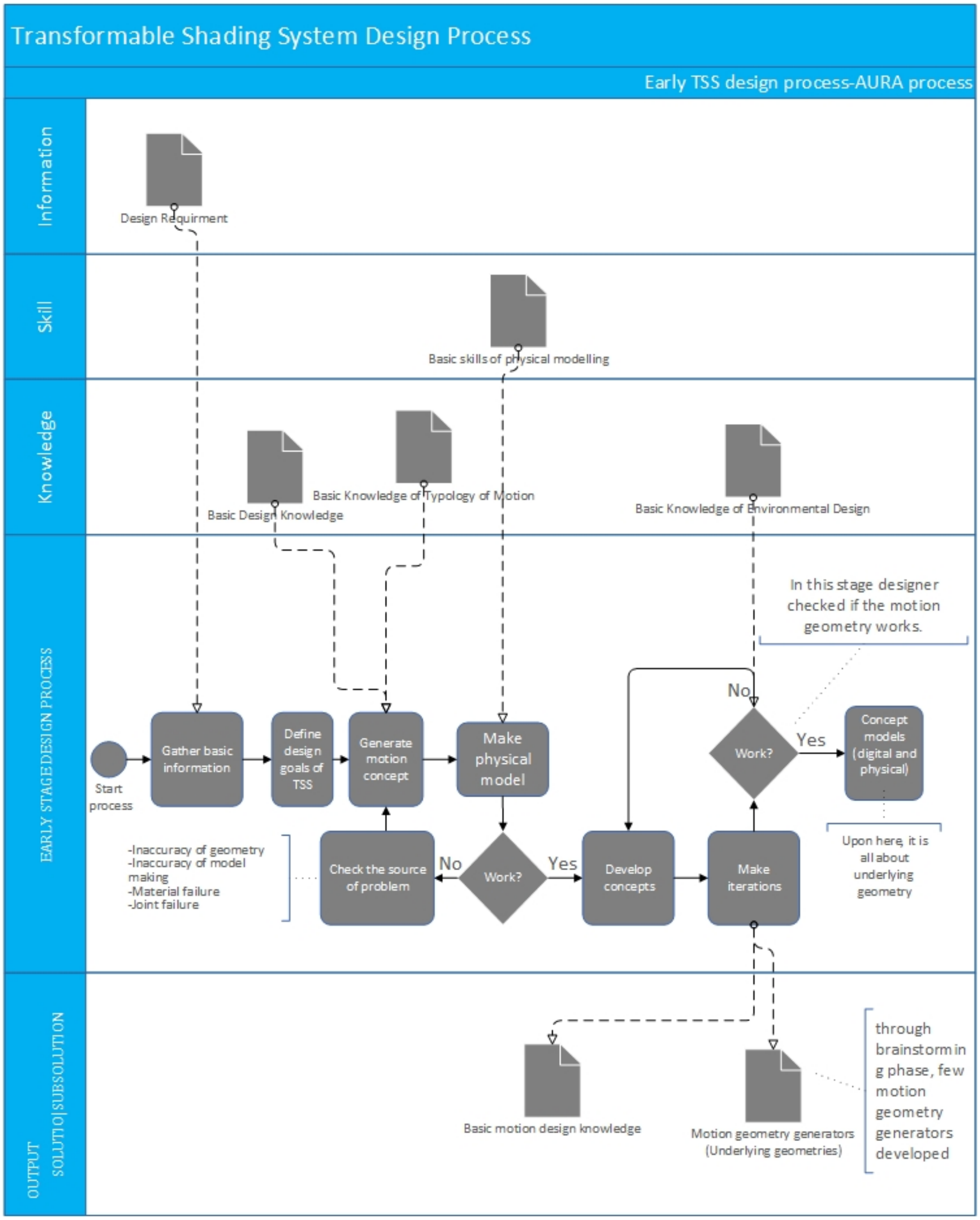

Figure 194. Detailed early stage of the TSS design process.

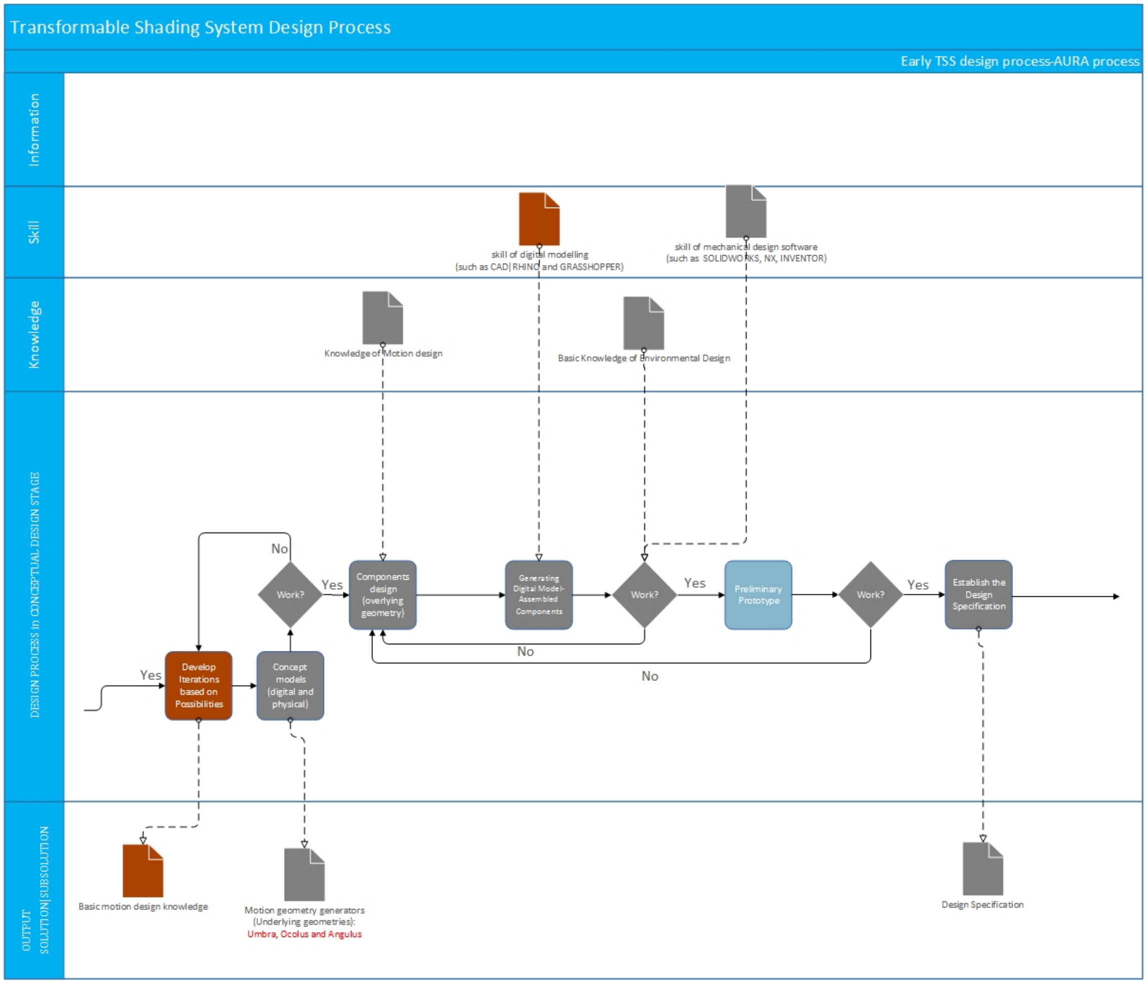

Figure 195. Detailed conceptual design stage of the TSS design process.

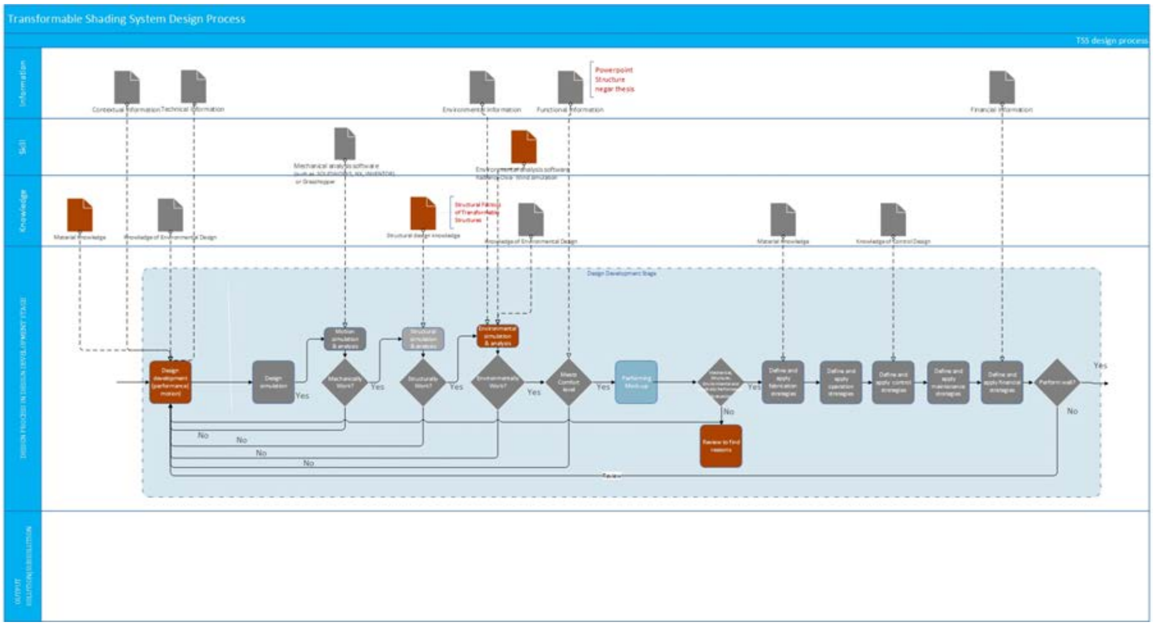

Figure 196. Detailed design development stage of the TSS design process.

6.5 Contribution of the Transformable Design Studios in Developing TSS Process Map

The AURA’ s design process developed the structure of the preliminary TSS process map. In the preliminary map, the author was more concerned about the process and actions, and the input and out put of each stage was not clearly defined (Figure 191). However, the two transformable studios, were considered as a continuous learning platform about the TSS design process and validating and refining the preliminary process map that came out of AURA design process and literature reviews. The studios assisted to refine the preliminary process map with the following aspects:

1- Reframing the preliminary design process map in a cross-functional flowchart

After the two studios, the author was able to reformat the preliminary map from basic flowchart format (Figure 191) to cross-functional flowchart (BPMN standard). In this phase, she was able to distinctly realize the inputs, actions and outputs of the design process.

2- Organizing the required KSI for ever stage of design process

During AURA design process, the author was observing and recording the process to understand the required knowledge, skill and information as the main inputs in TSS design process, however the order of these inputs and the contents of each inputs were not clear until she examined it in the studios.

For example, the author mentioned the necessity of basic motion design knowledge during the early design stage. But, it was not completely clear that what is this knowledge and how to be taught to the students. By developing series of lectures and workshop, it became clear for the author when, what and how these knowledge, skill and information should be transferred.

3- Expand the preliminary design process

Since the author was the only researcher, observer and map developer of AURA design process, there are aspects that have been not included due to the clarity of them for the author (decision that made intuitively without planning) or other limitations during AURA design process. During the two studios, since 22 other designers that were new to topics of transformability explored the topics and went through the preliminary design process map, they reveal the voids and gaps in the process, and then the author had to include those components to the map.

4- Explore in-depth each steps and components of preliminary process map.

This result to clarify for the author which topics and aspects should be included in each steps and what knowledge and skills are necessary for students to know in that particular design stage. For example, in preliminary process map, there are components that have been included but not thoroughly investigated. Author had to investigate them deeply before presenting them to the students (Figure 198, Figure 199, Figure 200, Figure 201, Figure 202).

In the detailed process map, there are components defined by maroon color that indicated the lesson learned from the two studios. Those are the direct effects of lesson learned through the studios.

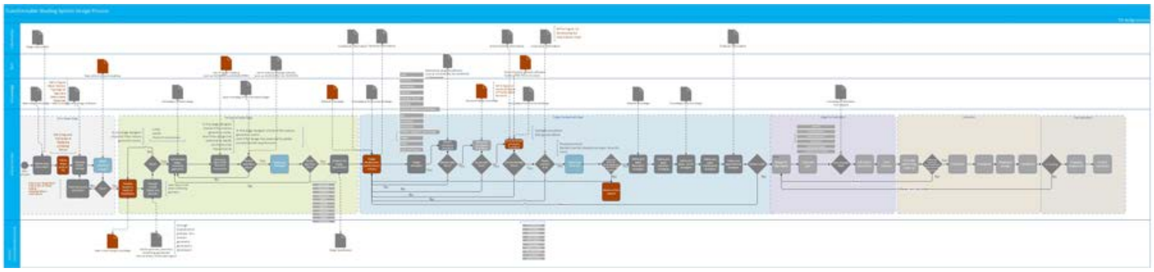

Figure 197: Detailed process map of TSS developed after AURA design process and two design studios- Please refer to Appendix C

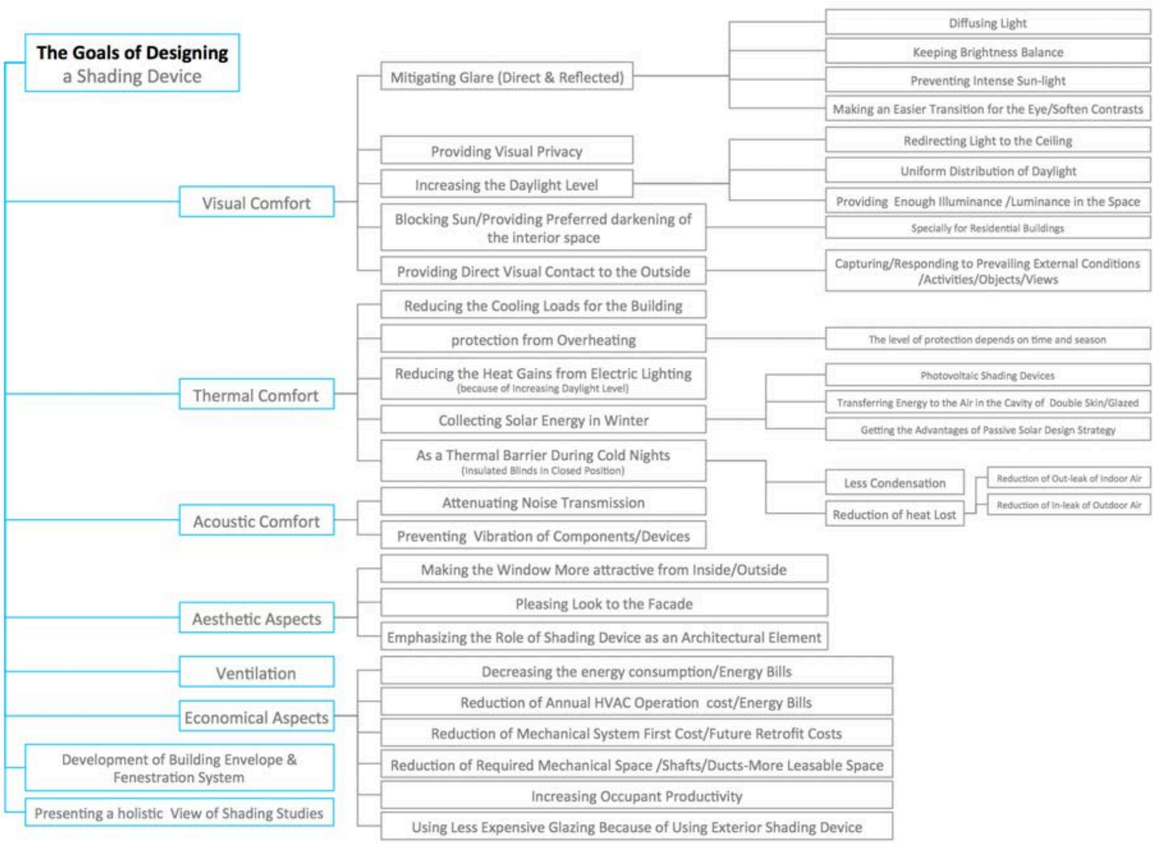

Figure 198. Developing the goals of designing a shading device

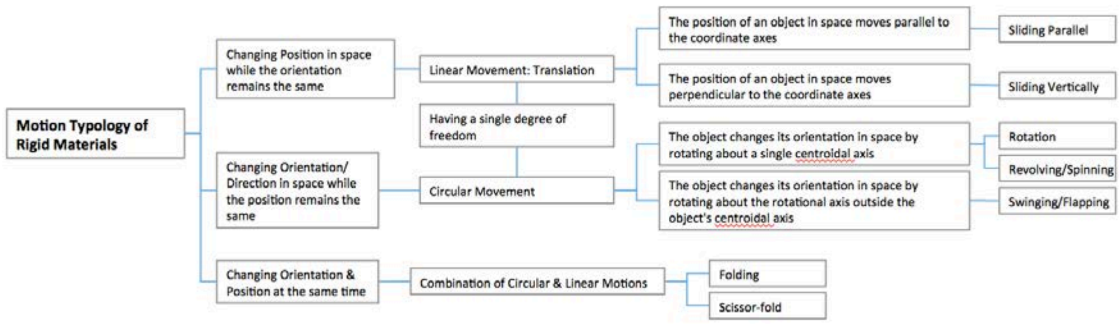

Figure 199. Motion typology of rigid materials [95]

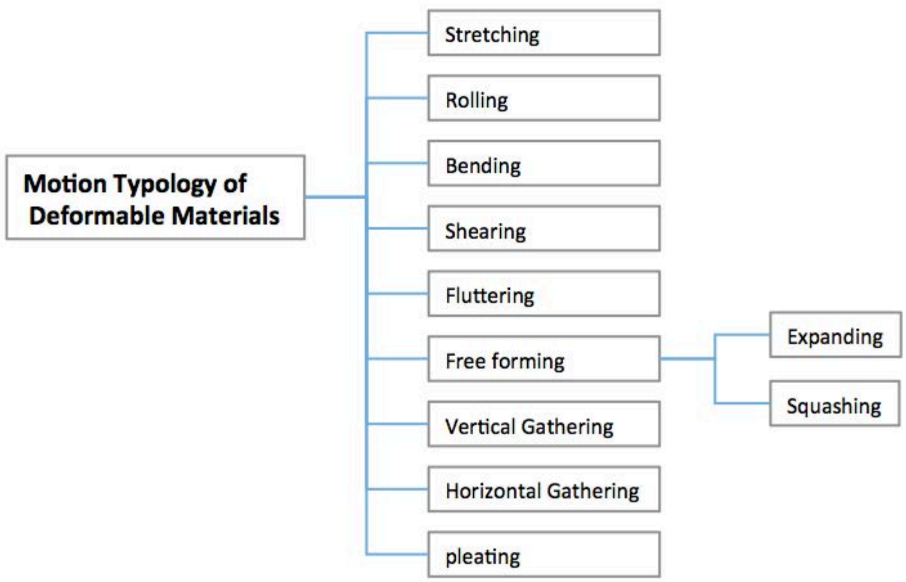

Figure 200. Motion typology of deformable materials[96]

[95] Move-Architecture in Motion - Dynamic Components and Elements-Michael Schumacher Oliver Schaeffer Michael-Marcus Vogt-Birkhauser-2010 P- 36, 44, 45

[96] Move-Architecture in Motion - Dynamic Components and Elements-Michael Schumacher Oliver Schaeffer Michael-Marcus Vogt-Birkhauser-2010 P- 47

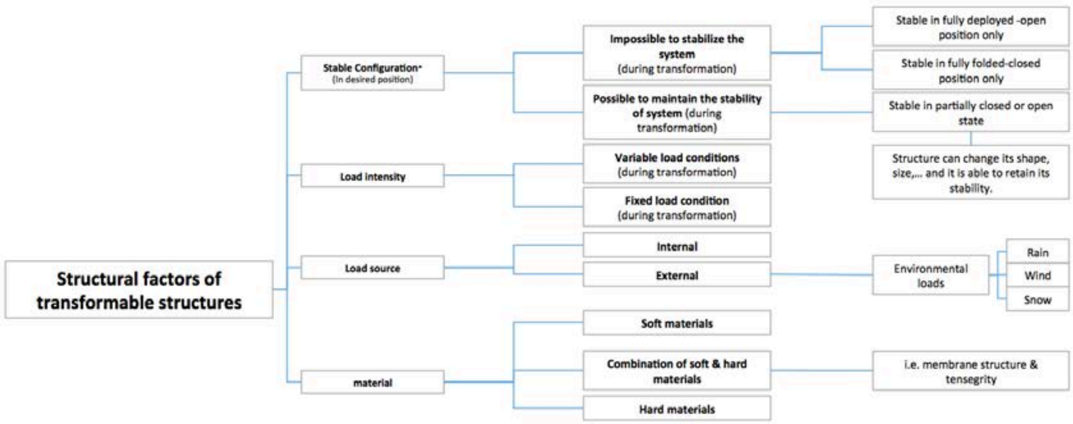

Figure 201: Developing structural factors of transformable structures[97]

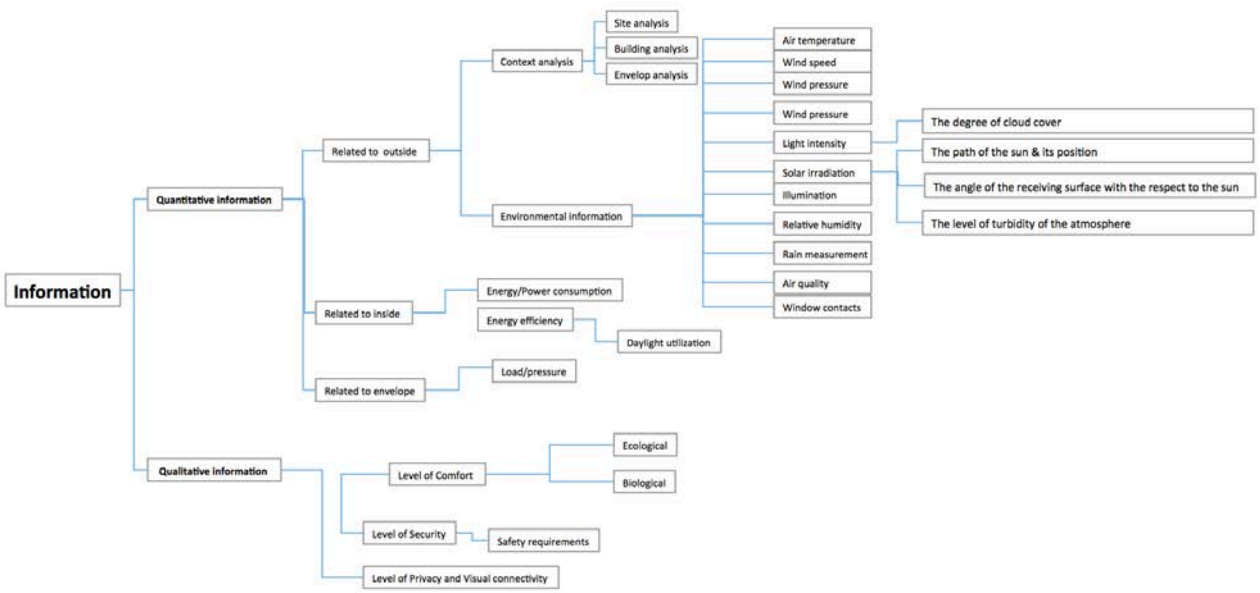

Figure 202: Required information for designing a TSS

[97] Asefi, M. 2010.Transformable and Kinetic Architectural Structures, VDM Verlag Dr. Muller, Saarbrucken, P.15 , 226, 286

6.6 Improvement of TSS Design Process

George Shultz[98] drew a distinction between “problems you can solve” and “problems you can only work at (Hamel and Breen 2007) .” These two kinds of problems have names: the ones that can be solved are “tame,” and the ones that can only be worked on are “wicked.” With this definition, the design process is the challenge of taming wicked problem. Although the process map could facilitate dealing with wicked problems, the process will never be completely captured and structured. Therefore, the TSS design process map is cyclic. Each cycle of solution formulation can reveal a new understanding of the problem. This means that the more one practices in this domain, the better one will understand the problem. The TSS design process model would continuously evolve and deepen.

In TSS design process, despite similarities between a current problem and a previous one, there may always be additional distinguishing properties that are of overriding importance. The TSS process map in not a solution-making map. It is intended to help the designer perceive a situation in a certain way, and adopt certain concepts to describe the situation, possible patterns of reasoning, and eventual problem solving associated with that way of seeing; this leads to the opportunity to act effectively, within that situation.

In this research the author used mapping processes to represent, analyze, and evaluate wicked problems, and then to choose actions that ameliorate them. The design process model would frame[99] (not structure) wicked problems. The TSS design process model is designed to facilitate a standpoint from which a wicked problem can be tackled.

Because of the nature of a wicked problem, there is no opportunity to well structure all of the steps toward and process of accomplishing a solution. However, in the TSS process map, the author tried to frame the possible steps toward possible solutions. The design

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[98] Former Secretary of State

[99] “'Framing” is the term commonly used for the creation of a novel standpoint from which a problematic situation can be tackled (Dorst 2011).

process map may never be saturated because of the nature of the design and each time that designers use the TSS map, it would be more developed and detailed.

6.7 Transformable Design in a Broader Context

The design process of AURA is a process of creating a series of kinetic shading devices. Thus, throughout the act of designing and making, a number of different ways of addressing the key principles of motion geometry are investigated. By combining and harmonizing two simple movements (as vocabulary), a number of mechanisms are produced. In addition, several design concepts are generated based on geometry of motion (as syntax). The main intention of conducting the design process of AURA is to discover how a particular set of combinations can be generated from a particular set of rules. The design process of AURA demonstrates that motion language is a set of guidelines for designers to understand the nature of motion studies and it does not reduce the complexity of motion to a set number of rules or formulas. The most important thing that comes out of the design process of AURA is to be able to look behind the given constraints and problems. In this view, the language of motion is generative rather than limiting.

The lack of design knowledge relevant to transformable architecture, in relation to both architectural education and practice, is a major challenge. The key questions, then, are: What is the role of architectural education and the architecture profession in addressing motion design challenges? What are the subjects that architectural education and architecture practice should articulate? What should be the characteristics of motion-related courses taught in schools of architecture? How should these courses be offered?

By contextualizing these two design studios and questioning the importance of motion studies in architectural education, the author endeavored to explore static and dynamic forms in both their technical and spatial aspects, as armatures for architectural thinking.

The results of transLAB and tranSTUDIO was a set of examinations, disseminations, developments, and evaluations aimed squarely at tackling transformable architecture via multiple correlated design activities. By encouraging a modest level of integrated understanding of motion design principles, the studios attempted to spark students' passion for design and rekindle their imagination. The author aspires students will look back on their time in the studios as a meaningful learning experience. Many aspects of motion pedagogy are yet untouched, but the studios provided a valuable platform offering access to inquiry-based topical investigations into the study of motion architecture. The goal was not to offer a studio that could cover all characteristics of transformable shading devices in one semester, but rather to construct a line of architectural thinking that could be investigated systematically for years to come. The main objective of these fast-paced studios was not to explain the entirety of the motion design process, but rather to review its potential. The hope is that the studios led the students to observe, conjecture, and debate the role of transformability in architecture, which will contribute to their future career advancement and perhaps even motivate them to embark on an entirely new career. To consider a wider scope of opportunities and concerns for transformable architecture, both transformable design studios not only focused on the "how" of making transformable devices but also simultaneously emphasized "why" they should be so.

By looking deeply into how the distance between static and kinetic design approaches can be bridged, architecture schools should herald a gradual transition from static- to dynamic-based pedagogies. If architectural education incorporates the pedagogy of motion, students will be able to design architecture that actively responds to its surrounding environment. In this way, buildings of the future will not only transform their sizes but also change their properties through continuous adaptation.

This dissertation searched for thoughtful ways to urge architectural education and practice to expand the use of transformable architecture. To infuse motion into architecture, this research emphasized the following:

- Transformable architecture exposes us to a new paradigm of thinking about design and architecture. In terms of the dynamics that motion can bring to materials, products, and environments, the relationship between motion studies and conventional architecture necessitates a shift to a new territory of involvement. To transfer motion studies away from existing passive circumstances and move it to a more engaged and critically aware investigation, architects should acquire appropriate motion design principles and intelligently apply them to their design projects.

- In the field of sustainable architecture, transformability is an important way of actively responding to ambient conditions while also meeting the needs of occupants and addressing issues of building performance. Within contemporary architecture, there is a growing interest in motion; buildings and their parts are gradually shifting from static to dynamic. Predominantly, motion-related private enterprises outside academic institutions beget unprecedented levels of transformation in the spatial foundation of architecture.
- In recent years, there is a growing need for students and academics to research and design adaptive architecture, building components, and architecture that changes the quality of space and the connection humans have with their environment. There is no pervasive historiography on motion studies to narrate the lack of a quest for motion design education. With a historiographical reflection on motion-related courses, it would be easier to articulate the impact of existing motion-related courses on the education of future architects.
- Much of the scholarly activity and conceptual, technological, and professional developments in transformable architecture are still in their infancy. Although there are a few fundamental discourses about what constitutes transformable architecture, reviewing the literature on the related subjects does not provide conceptual clarity regarding what it means for architecture to be transformable and what constitutes transformable architecture. Transformable architecture embraces a number of closely associated camps such as adaptive, responsive, and performative architecture and, in general, sustainable architecture.
- In the last several decades, few of the design proposals for the active class of buildings have been built, and those that have are operated in poor accordance with their underlying intent; this may be due to the complexity in designing such systems where often knowledge of fabrication, assembly, systems integration and actuation in addition to performance are required. However, the main reason is

architects' lack of familiarity with the whole process of design. In general, design motion principles are unknown to most architects. In spite of various emerging technologies, this lack of sufficient large-scale and well-designed transformable projects with minimum construction malfunctions can be attributed to an absence of the information, resources, or expertise needed to design and implement motion.

- The technical and operational failures of transformable projects are the most important challenges in the field of motion design. By casting a light on the poetic dimensions of motion, this dissertation emphasized on the relevance of performance and the fabrication process. The architects of these failing projects can mainly be divided into two main groups. In the first group, architects are totally ignorant of the function of the mechanical devices they are about to work on. In many cases, a lack of fabrication skill and knowledge, as well as poor technological sensibilities, are the biggest causes. With less explicit connections between knowledge and performance, the second group of architects have relatively good technical knowledge but fail to apply their knowledge to specific kinetic situations. In some cases, architects abstractly imagine their proposed mechanisms and details outside of the technical specifications and scope of the project that requires their implementation. Generally speaking, in a transformable project a designer's ability to ascertain the relative magnitude of a design challenge and offer solutions to those challenges is directly tied to her technical and operational skill and knowledge, both before and during the design process.
- The technological advances associated with designing physical transformability bring a whole new range of design challenges to propound the imagining, designing, and visualizing of the physical processes of transformation. While transformable architecture in larger building applications may involve a great degree of automation, it can often be confused with automated architecture. Mere mechanisms such as levers, gears, cams, and bearings, and mere use of mechanical parts, mechatronic components (such as actuators, motors, pumps,

and fans), smart materials, and sensors are not adequate for a system to beconsidered transformable.

- Transformable architecture depends upon motion not only for its physical re-configurations but also for its unexplored non-physical manifestation. To magnify the expression of physical and non-physical motion in architecture, motion aesthetics can be revisited through the use of technological innovations, and in particular via emerging technologies such as sensors, actuators and microcontrollers.
- This dissertation is part of a larger subset of a search for understanding how motion studies can identify their relevant design parameters and clarify the structure of their design process. To conclude the study in the correct way, it is important to distil the essence of the language of motion through a design process. In this sense, motion language is meant to define the principles of motion formation. Motion language is a way to gather different aspects of a motion design process and reconfigure them in relation to one another. This dissertation persuades designers and educators to take a greater interest in motion language and to embrace this language to empower the process of design.
- Motion language is a link between research and design and a synthesis of practice and theory. Therefore, the language of motion is improved by availing itself of theoretical analysis and empirical synthesis. A wide acceptance of motion language is dependent on the level of involvement of researchers, educators, and designers throughout the design process of any motion composition.
- By exposing the principles and variables of a motion composition and making them easy to perceive, motion language describes what the boundaries of transformability are and how they can be addressed. This language incorporates the study of motion at two levels. On the first level, it involves an analysis of the possible changes from one form to another within the movement, and addresses the relationships that generate the motion form. On the second level, it facilitates an understanding of how to use these rules to design a motion composition. In addition to expanding designers' repertoire of reasoning frameworks about

transformable architecture, the language of motion can help designers explore how to unpack some of the inherent complexities involved in their transformable designs. By employing the language of motion, the author believes that the vocabulary and syntax of motion can help designers of transformable architecture and provide them with a feedback mechanism regarding how to resolve some of the limitations associated with the design and use of different mechanism.

- As a main syntax, geometry of motion reveals the geometric constraints of motion. Regardless of the function, size, and weight of movable elements, the individual habits of the users or the frequency with which these elements are used, motion geometry describes the geometric disposition of movable elements. This geometry harbors the precise geometric elaboration of a sequence of movements that occur over time in order to enlighten one's change of position from a stationary condition to a new circumstance.
- Any element that moves as a whole at a large scale or sequential movements occurring at a detailed level follows a hierarchical structure informed geometrically by motion geometry. This geometry includes an underlying structure that acts as a superordinate constituent (the parent) and an overlaid pattern serving as a subordinate constituent (the child). The overlaid pattern of a movement is not automatically a byproduct of its underlying geometry. In the design process, an ongoing dialogue takes place between the attributes of the underlying geometry and overlaid patterns of a motion composition. The correlation between these two depends upon either the functional and economic requirements or formal expression. By using the principles of motion geometry, the variety of different possible movements is almost endless. A complex motion at a macro level can be afforded through the additive combination of basic motions at a micro level.
- Although research and development work in the field of motion study is still in its infancy, the careful scrutiny of the existing projects and the built and un-built examples reveals the great advantages that architecture can gain from motion.

- The relationship of motion study to architectural education is manifold and can be regarded from many different perspectives. By grounding motion fundamentals in a pedagogical territory far removed from the existing static lexicons, motion pedagogy challenges the very nature of what architectural education really is.
- Within motion pedagogy, there is a unique opportunity to equip architectural educators to move from training architecture students (work related to meeting the demands of the immediate job market) to educating individuals in architecture (serving the best interests of the students ´ long-term professional lives).
- As interaction with the design process become much more integrated with the cross-disciplinary knowledge necessary to design a transformable design, the boundaries between the different disciplines become less distinct. To this end, it is essential that designers of transformable designs express their design concepts with clarity and precision to team members from different disciplines.
- In the design process of AURA, the architectural attributes of the mechanism, or the ability to change in shape and pattern, are the main concerns. In AURA, the main body of the author's design research fosters exploration around one central question: how can motion be suggested, depicted, or physically incorporated in the building envelope?

6.8 Future of this Research

Motion pedagogy is not static in nature. It is preferred more by those who see the education of architects as a vivid resonance of social, cultural, technological, spatial, and pedagogical forces. Further on, improving education in transformable architecture should inspire not only from the top down (educators and administrators generating environmental wellbeing) but also from the ground up (young students demanding schools provide them with the capacity to design transformation). Through developing the pedagogy of motion, the author intention is to foment an engagement with and dialogue between instructors and students on conceptual, material, and professional levels. The goal is to create collaborative networks between all agents involved in the education of transformable architecture by furthering transformable design pedagogy and discussing the role of architecture institutions throughout the U.S.

Due to the various advances in technology and new circumstances and priorities that demonstrate possible future ways of living, the practice of architecture is sure to change. In recent years, a number of rapid inventions, often from outside the architectural profession, have begun to appear and, thus, expand the performance limits of transformable architecture and overcome a number of technological challenges. On the forefront of architecture, the advent of new materials and fabrication means and methods increases the potential for moving components to appear in stationary buildings.

In recent years, on the verge of moving from static physical spaces to spaces capable of flexing, moving, and reconfiguring themselves, transformable architecture has evolved to include emerging fabrication techniques, innovative materials and interactive interfaces, and multiple simulation software platforms. As electromechanical control technologies and accompanying actuator and sensor technologies become progressively more advanced, architecture needs to adapt to incorporate these nascent developments. Through increasing the use of integrated micro- computers and data interfaces, a new breed of designers and architects are emerging.

The biggest evolutionary jump for architectural education and practice is attributable to the influence of today's digital landscape and computer-oriented culture. Many architects live and breathe digital tools, leading to the integration of the computer into architecture. Accordingly, transformable architecture is undergoing substantial changes, due to the advances in mechatronic devices that have been made over the past two decades; it is now in a position to move from mechanical to more digital approaches. Thus, simple mechanistic approaches are not sufficient to reveal the potential of transformable architecture. In contemporary architecture, there is evidence of attempts to make architecture mechanically and/or electronically transformable. Recent transformable projects are no longer confined to the use of mechanical devices propelled by mechanical or electrical power, and instead include circuits, sensors, actuators, micro-controllers, and smart materials that facilitate the desired motion to be implemented in, on, and across buildings. By combining motion with sensing and actuation, transformable architecture gives rise to new possibilities and, ultimately, expectations. Recognition that analogue (mechanical) and digital approaches are inseparable poles of transformable design creates a tremendous opportunity for designers and design educators. To open up a vast array of avenues to fortify motion, the equilibrium between these approaches can lead to the ascendance of transformability in architecture.

With a focus on the impact, translation, and integration of emerging technologies such as cloud computing, artificial intelligence, and robotics in architecture and design, future transformable studios will attempt to serve as a threshold for significant changes in our relationship to the environment, and to each other.

References

2015. *Hyposurface* [cited 2 february 2015].

(DOE), The U.S. Department of Energy. 2012. Windows Technology R&D Stakeholder Engagement Workshop.

Alkhayyat, Jamil Majed Jamil. 2013. *Design strategy for adaptive kinetic patterns: creating a generative design for dynamic solar shading systems*, Architecture, University of Salford.

Asefi, M. 2010. *Transformable and kinetic architectural structures*. Breinigsville: VDM Verlag.

Belardi, P. 2014. *Why Architects Still Draw*: The MIT Press.

Bergdoll, Barry, Peter Christensen, Ron Broadhurst, and Art Museum of Modern. 2008. *Home Delivery: fabricating the modern dwelling*. New York: Museum of Modern Art.

Birch, William. 1986. "Towards a Model for ProblemBased Learning." *Studies in Higher Education* (1):73-82.

Brager, Gail S., Gwelen Paliaga, and Richard De Dear. 2004. "Operable Windows, Personal Control, and Occupant Comfort." *ASHRAE Transactions* no. 110:17-35.

Carraher, E. . 2015. Integrating Technologies in Beginning Design Studio. Paper read at National Conference on the Beginning Design Student (NCBDS)-31, at Houston.

Chilton, John. 2013. "Lightweight envelopes: ethylene tetra-fluoro-ethylene foil in architecture." *Proceedings of the Institution of Civil Engineers* no. 166 (6):343.

Craig, David J. 2006. The Future Tents

Kinetic Sculptor Chuck Hoberman

Expands the Boundaries of Design The Magazine of Columbia University.

Cross, Nigel. 2000. *Engineering design methods : strategies for product design*. Chichester; New York: Wiley.

Cross, Nigel, and Norbert Roozenburg. 1992. "Modelling the Design Process in Engineering and in Architecture." *Journal of Engineering Design* no. 3 (4):325-337. doi: 10.1080/09544829208914765.

Dewey, John. 1997. *How We Think*: Dover Publications.

Downton, P. 2003. *Design Research*: RMIT Publishing.

Dubberly, Hugh. 2013. *How do you design?* 2005 [cited 10/12/2013 2013]. Available from http://www.dubberly.com/articles/how-do-you-design.html.

Dubberly, Hugh. 2013. *A Model of The Creative Process* 2009 [cited 10/12/2013 2013]. Available from http://www.dubberly.com/concept-maps/creative-process.html.

Ebert, David S. 2003. *Texturing and Modeling: A Procedural Approach*. US: Morgan Kaufmann Publishers Inc.

El-Zanfaly, Dina. 2011. Active Shapes. Introducing guidelines for designing kinetic architectural structures. Paper read at SIGraDi.

Ferguson, Eugene S. 1992. *Engineering and the mind's eye*. Cambridge, Mass: MIT Press.

Fortmeyer, Russell, and Charles D. Linn. 2014. *Kinetic architecture : designs for active envelopes*. Mulgrave, Vic.: Images Publishing Group.

Fox, Michael. 2002. "Beyond Kinetic." In *Transportable Environments 2*, edited by Joseph Lim and Wong Yunn Chii Robert Kronenburg. London: Spon press.

Fox, Michael, and Miles Kemp. 2009. *Interactive architecture*. New York: Princeton Architectural Press.

Frampton, K. 2001. *Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture*: The MIT Press.

Givoni, Baruch. 1994. *Passive and low energy cooling of buildings*. New York: Van Nostrand Reinhold.

Gore, N. 2004. "Craft and Innovation: Serious Play and the Direct Experience of the Real.". *Journal of Architectural Education* no. 58.

Gray, David E. 2004. *Doing research in the real world*. Thousand Oaks, Calif; London: SAGE.

Green, K. . 2006. Architecture Plus: The Collaborative Animated Work Environment Design Research Project. Paper read at Association of Collegiate Schools of Architecture.

Grisham, Thomas. 2009. "The Delphi technique: a method for testing complex and multifaceted topics." *International Journal of Managing Projects in Business* no. 2 (1):112-130. doi: http://dx.doi.org/10.1108/17538370910930545.

Groat, Linda N., and David Wang. 2002. *Architectural Research Methods*. New York: J. Wiley.

Groat, Linda N., and David Wang. 2013. "Architectural Research Methods." In. Hoboken: Wiley. http://VT.eblib.com/patron/FullRecord.aspx?p=1166322.

Hansanuwat, Ryan. 2010. *Kinetic facades as environmental control systems: Using kinetic facades to increase energy efficiency and building performance in office buildings*. Vol. 48.

Heidegger, Martin. 1968. *What is called thinking?* New York: Harper & Row.

Heidegger, Martin Heim Michael. 1984. *The metaphysical foundations of logic*. Bloomington: Indiana University Press.

Hensel, Michael. 2013. *Performance-oriented architecture: rethinking architectural design and the built environment*. Chichester, West Sussex: Wiley, A John Wiley and Sons, Ltd, Publication.

Herzog, Thomas, Roland Krippner, and Werner Lang. 2004. *Facade construction manual*. 1st ed. Basel ; Boston: Birkhauser-Publishers for Architecture.

Hoberman. 2015. *HelioTrace* 2010a [cited February 10 2015]. Available from http://www.hoberman.com/portfolio/heliotrace.php?projectname=HelioTrace.

Hoberman. 2015. *Tesseallate* 2010b [cited Februray 10 2015]. Available from http://www.adaptivebuildings.com/tessellate-surface.html.

Hunt. 1978. *Kinematic Geometry of Mechanisms*: Clarendon Press.

International Energy Agency, I. E. A. Solar Heating. 2000. *Daylight in Buildings: A Source Book on Daylighting Systems and Components. A Report of IEA SHC Task 21, ECBCS Annex 29*: International Energy Agency, IEA, Solar Heating and Cooling Programme, SHC, Energy Conservation in buildings and Community Systems Programme, ECBCS.

Kalantar, and Borhani. 2015. Beginnings in Transformable Design Pedagogy. Paper read at The National Conference on the Beginning Design Students (NCBDS), , at University of Houston.

Kalantar, and Borhani. 2016a. Starting with Transformation. Paper read at The National Conference on the Beginning Design Students (NCBDS), at University of Cal Poly.

Kalantar, and Borhani. 2016b. "Studio in Transformation: Transformation in Studio." *Journal of Architectural Education (JAE) 70:1* no. 70.

Kalantar, N, and A Borhani. 2013. Establishing the language of motion formation for the AURA kinetic shading system. In *International Conference on Adaptation and Movement in Architecture (ICAMA)*. Toronto, Canada.

Krauss, Rosalind E. 1981. *Passages in modern sculpture*. Cambridge, Mass: MIT Press.

Leatherbarrow, David. 2009. *Architecture oriented otherwise*. New York: Princeton Architectural Press.

Leung, Wai-Ching. 2001. "How to design a questionnaire." *British Medical Journal*.

Leupen, Bernard, René Heijne, and Jasper van Zwol. 2005. *Time-based architecture*. Rotterdam: 010 Publishers.

Lynn, Greg. 1999. *Animated Form*. New York Princeton Architectural Press.

Massey, Jonathan. 2006. "Buckminster Fuller's cybernetic pastoral: the United States Pavilion at Expo 67." *The Journal of Architecture* no. 11 (4):463-483. doi: 10.1080/13602360601037883.

Mazzoleni, Ilaria, and Shauna Price. 2013. *Architecture follows nature: biomimetic principles for innovative design*. Boca Raton: CRC Press.

McQuaid, Matilda, Serralves Museu, Arts Royal Academy of, Frankfurt Schirn Kunsthalle, and Art Museum of Modern. 2002. *Envisioning architecture: drawings from the Museum of Modern Art*. New York; London: Museum of Modern Art.

Mendel, Joanne. 2012. "A taxonomy of models used in the design process." *interactions* no. 19 (1):81-85. doi: 10.1145/2065327.2065343.

Menges, A. , and S. Ahlquist. 2011. *Computational Design Thinking*: John Wiley & Sons.

Merleau-Ponty, M. 2008. *The World of Perception*: Routledge.

Mitchell, W. . 2001. *Roll Over Euclid: How Frank Gehry Designs and Builds*. New York: Guggenheim Museum Publications.

Moloney. 2009. *Morphology of pattern for kinetic facades*, Architecture, Building and Planning, The University of Melbourne.

Moloney, Christopher. 2007. "A Framework for the Design of Kinetic Facades." In.: Springer.

Moloney, J. 2006. Between Art and Architecture: The Interactive Skin, 2006.

Moloney, Jules. 2011. *Designing kinetics for architectural facades : state change*. Abingdon, Oxon; New York: Routledge.

Mostafavi, Mohsen, and David Leatherbarrow. 1993. *On weathering: the life of buildings in time*. Cambridge, Mass: MIT Press.

Moussavi, Farshid Kubo Michael. 2006. *The function of ornament*. Barcelona; Cambridge, Mass.: Actar ; Harvard University, Graduate School of Design.

Myszka, David H. 2012. *Machines and mechanisms : applied kinematic analysis. 4th ed*: Upper Saddle River, N.J. : Pearson Prentice Hall, [2012]

4th ed.

Nesbitt, Kate. 1996. *Theorizing a new agenda for architecture : an anthology of architectural theory, 1965-1995*. New York: Princeton Architectural Press.

Newman, Peter Dr, Timothy Beatley, and Heather Boyer. 2009. *Resilient cities: responding to peak oil and climate change*. Washington, DC: Island Press.

Norton, Robert L. 2012. *Design of machinery : an introduction to the synthesis and analysis of mechanisms and machines. 5th ed*, *McGraw-Hill series in mechanical engineering*: New York : McGraw-Hill, 2012.

5th ed.

Pallasmaa, J. 2005. *The Eyes of the Skin: Architecture and the Senses*: John Wiley & Sons.

Parkes, Amanda Jane. 2009. *Phrases of the kinetic: Dynamic physicality as a dimension of the design process*, MIT.

Parkes, Amanda, Ivan Poupyrev, and Hiroshi Ishii. 2008. Designing kinetic interactions for organic user interfaces. NEW YORK: ACM.

Perez-Gomez, A. 2008. *Built upon Love: Architectural Longing after Ethics and Aesthetics*: The MIT Press.

Peters, B. , and T. Peters. 2013. *Inside Smart geometry: Expanding the architectural possibilities of computational design*. Vol. 1. West Sussex, United Kingdom: John Wiley & Sons Ltd. .

Rabin, Emily. 2015. *Harnessing Daylight for Energy Savings* 2006 [cited 2/14/2015 2015]. Available from http://www.greenbiz.com/news/2006/04/17/harnessing-daylight-energy-savings.

Rajagopal, Avinash. 2013. *Computer Control* [Online magazine] 2013 [cited September 2013].

Rea, Mark Stanley, and Illuminating Engineering Society of North America. 2000. *The IESNA lighting handbook : reference & application*. 9th ed. 1 vols. New York, NY: Illuminating Engineering Society of North America.

Rickey, George W. 1963. "The Morphology of Movement: A Study of Kinetic Art." *Art Journal* no. 22 (4):220-231.

Sanders, Liz. 2008. "ON MODELING: An evolving map of design practice and design research." *interactions* no. 15 (6):13-17. doi: 10.1145/1409040.1409043.

Scheer, D. 2014. *The Death of Drawing: Architecture in the Age of Simulation*: Routledge.

Schielke, Thomas. 2015. *Light Matters: Glass Beyond Transparency with James Carpenter* [cited April, 12 2015].

Schön, Donald A. 1983. *The reflective practitioner: how professionals think in action*. New York: Basic Books.

Schumacher, Michael, Oliver Schaeffer, and Michael-Marcus Vogt. 2010. *Move : architecture in motion--dynamic components and elements*. Basel ; Boston: Birkhäuser.

Sharaidin, Kamil. 2014. *Kinetic Facades: Towards design for Environmental Performance*, RMIT University.

Spradley, James P. 1980. *Participant observation*. New York: Holt, Rinehart and Winston.

Stein, Benjamin. 2006. *Mechanical and electrical equipment for buildings*. Hoboken, N.J: Wiley.

Terzidis, Kostas. 2003. *Expressive form: a conceptual approach to computational design*. New York; London: Spon Press.

Trachtenberg, M. . 2010. *Building in time: From Giotto to Alberti and modern oblivion*. New Haven-London: Yale University Press.

Tuan, Y. 2001. *Space and Place: The Perspective of Experience* Univ. Of Minnesota Press.

Tucker, Richard, and Neda Abbasi. 2012. Conceptualizing teamwork and group-work in architecture and related design disciplines. In *Architectural Science Association*. Queensland.

Tzonis, Alexander. 2004. *Santiago Calatrava: the complete works*. New York: Rizzoli.

U.S. Department of Energy, Office of Energy Efficeiency & Renewable Energy. 2014. RESEARCH AND DEVELOPMENT ROADMAP: WINDOWS AND BUILDING ENVELOPE

. Office of Energy Efficeiency & Renewable Energy.

Vinogradov, Oleg. 2000. *Fundamentals of Kinematics and Dynamics of Machines and Mechanisms*. Boca Raton: CRC Press.

Wigginton, Michael, and Jude Harris. 2002. *Intelligent skins*. Oxford: Architectural Press.

Yin, Robert K. 1994. *Case study research: design and methods*. Vol. 5.; 5. Thousand Oaks, CA: Sage.

Zarzycki, Andrzej. 2013. "Integrating Physical and Digital Assemblies." *International Journal of Architectural Computing* no. 2 (2).

Zuk, William, and Roger H. Clark. 1970. *Kinetic architecture*. New York,: Van Nostrand Reinhold.

Appendices

Appendix A: IRB Approvals, Surveys Questions and Related Documents (Virginia Tech and Texas A&M)

Appendix B: AURA Designs, Complete Sets

Appendix C: TSS Design Process Models, Complete Full Size Map

Appendix A

Office of Research Compliance
Institutational Review Board
North End Center, Suite 4120, Virginia Tech
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-4606 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE: January 14, 2014

TO: James R Jones, Negar Kalantar Mehrjardi

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires April 25, 2018)

PROTOCOL TITLE: Kinetic Shading Systems

IRB NUMBER: **13-1147**

Effective January 14, 2014, the Virginia Tech Institution Review Board (IRB) Chair, David M Moore, approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As: **Exempt, under 45 CFR 46.110 category(ies) 2**
Protocol Approval Date: **January 14, 2014**
Protocol Expiration Date: **N/A**
Continuing Review Due Date*: **N/A**
*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

DATE: May 27, 2015

MEMORANDUM

TO: Negar Kalantar Mehrjardi
TAMU - Texas A&M University - Not Specified

FROM: Dr. James Fluckey
Chair
TAMU IRB

SUBJECT: Exempt Approval

Study Number:	IRB2015-0023
Title:	the design process of transformable (kinetic) building envelope
Approval Date:	04/08/2015
Continuing Review Due:	03/01/2020
Expiration Date:	04/01/2020

Comments: n Wednesday, May 6, 2015, the TAM Institutional Review Board voted to change studies determined to be exempt to expire in 5 years, rather than 3 years. nce an exempt study reaches the end of the 5-year expiration, an exempt continuation form will need to be submitted to continue the study for another 5 years.

This research project has been approved. As principal investigator, you assume the following responsibilities:

1. **Continuing Review:** The protocol must be renewed by the expiration date in order to continue with the research project. A Continuing Review application along with required documents must be submitted by the continuing review deadline. Failure to do so may result in processing delays, study termination, and/or loss of funding.
2. **Completion Report:** Upon completion of the research project (including data analysis and final written papers), a Completion Report must be submitted to the IRB.
3. **Unanticipated Problems and Adverse Events:** Unanticipated problems and adverse events must be reported to the IRB immediately.
4. **Reports of Potential Non-compliance:** Potential non-compliance, including deviations from protocol and violations, must be reported to the IRB office immediately.
5. **Amendments:** Changes to the protocol must be requested by submitting an Amendment to the IRB for review. The Amendment must be approved by the IRB before being implemented.
6. **Consent Forms:** When using a consent form or information sheet, you must use the IRB stamped approved version. Please log into iRIS to download your stamped approved version of the consenting instruments. If you are unable to locate the stamped version in iRIS, please contact the office.
7. **Audit:** Your protocol may be subject to audit by the Human Subjects Post Approval Monitor. During the life of the study please review and document study progress using the PI self-assessment found on the RCB website as a method of preparation for the potential audit. Investigators are responsible for maintaining complete and accurate study records and making them available for inspection. Investigators are encouraged to request a pre-initiation site visit with the Post Approval Monitor. These visits are designed to help ensure that all necessary documents are approved and in order prior to initiating the study and to help investigators maintain compliance.
8. **Recruitment**: All approved recruitment materials will be stamped electronically by the HSPP staff and available for download from iRIS. These IRB-stamped approved documents from iRIS must be used for

recruitment. For materials that are distributed to potential participants electronically and for which you can only feasibly use the approved text rather than the stamped document, the study's IRB Protocol number, approval date, and expiration dates must be included in the following format: TAMU IRB#20XX-XXXX Approved: XX/XX/XXXX Expiration Date: XX/XX/XXXX.

1. **FERPA and PPRA:** Investigators conducting research with students must have appropriate approvals from the FERPA administrator at the institution where the research will be conducted in accordance with the Family Education Rights and Privacy Act (FERPA). The Protection of Pupil Rights Amendment (PPRA) protects the rights of parents in students ensuring that written parental consent is required for participation in surveys, analysis, or evaluation that ask questions falling into categories of protected information.
2. **Food:** Any use of food in the conduct of human subjects research must follow Texas A&M University Standard Administrative Procedure 24.01.01.M4.02.
3. **Payments:** Any use of payments to human subjects must follow Texas A&M University Standard Administrative Procedure 21.01.99.M0.03.

This electronic document provides notification of the review results by the Institutional Review Board.

Questions:

1. For designing an energy-efficient building that respond to its surrounding environment while meeting the needs of the occupants, which part of this building should be transformable?

2. From what you know, what does transformable (kinetic) building envelope mean? In how many ways can a building envelope transform?

3. Do you know of any projects with transformable (kinetic) envelops, if so please name the projects or architects of the projects?

4. Have you ever designed any transformable objects or buildings? Please describe it.

5. How familiar are you with the principles, factors and decisions that govern transformable design process- Very familiar, somewhat familiar, somewhat unfamiliar or very unfamiliar?

6. Can you describe the major issues during the design process of transformable (kinetic) building envelopes? Please mention the steps and influential parameters that can affect the design process of a transformable (kinetic) envelope.

7. What are the key decision-making issues for design of kinetic envelope systems when considering the relationship of the system to the total building?

8. What are the key decision-making issues for the design of kinetic envelope systems when considering the relationship between the system and the building occupant?

9. Which disciplines or experts other than architects should be involved in the design process?

10. Which software could be used for designing kinetic parts, visualizing their movement sequences and evaluating the physical processes of transformation?

11. If buildings components shift from static to dynamic, what will be the key design knowledge to support this new domain? What are the main design challenges?

12. From your point of view, are there any differences in the fabrication and installation process of conventional static systems and kinetic systems? How can the technical aspects of kinetic systems influence the performance goals or operability of the system?

13. During your last four years of studying architecture at Virginia Tech, have you had any courses that address the design process or design methodology of transformable architecture? If so, what were they?

14. How do you see the development and use of kinetic envelopes extending architectural theory?

tranSTUDIO -Texas A&M - Spring 2015

Questions:

1. For designing an energy-efficient building that respond to its surrounding environment while meeting the needs of the occupants, which part of this building should be transformable?

2. From what you know, what does transformable (kinetic) building envelope mean? In how many ways can a building envelope transform?

3. Do you know of any projects with transformable (kinetic) envelops, if so please name the projects or architects of the projects?

4. Have you ever designed any transformable objects or buildings? Please describe it.

5. How familiar are you with the principles, factors and decisions that govern transformable design process- Very familiar, somewhat familiar, somewhat unfamiliar or very unfamiliar?

6. Can you describe the major issues during the design process of transformable (kinetic) building envelopes? Please mention the steps and influential parameters that can affect the design process of a transformable (kinetic) envelope.

7. What are the key decision-making issues for design of kinetic envelope systems when considering the relationship of the system to the total building?

8. What are the key decision-making issues for the design of kinetic envelope systems when considering the relationship between the system and the building occupant?

9. Which disciplines or experts other than architects should be involved in the design process?

10. Which software could be used for designing kinetic parts, visualizing their movement sequences and evaluating the physical processes of transformation?

11. If buildings components shift from static to dynamic, what will be the key design knowledge to support this new domain? What are the main design challenges?

12. From your point of view, are there any differences in the fabrication and installation process of conventional static systems and kinetic systems? How can the technical aspects of kinetic systems influence the performance goals or operability of the system?

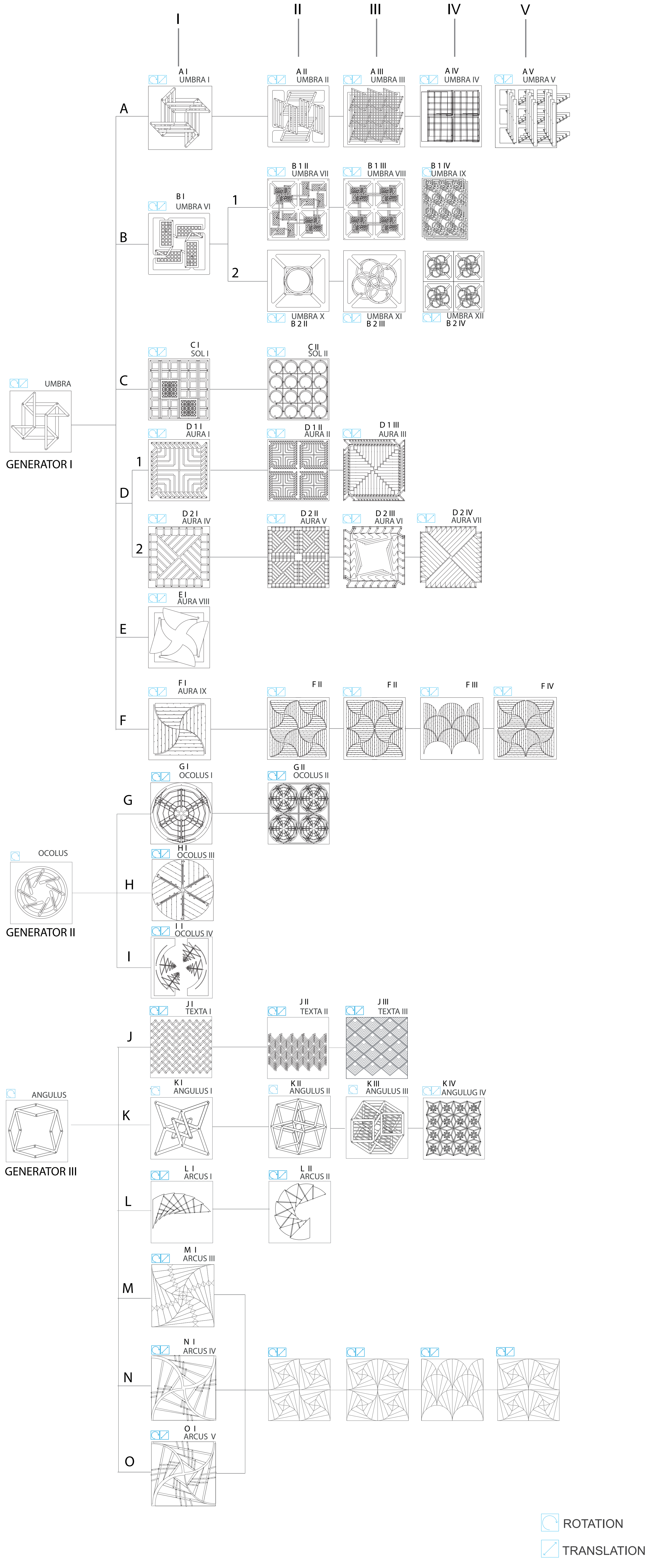
13. During your last four years of studying architecture at Texas A&M, have you had any courses that address the design process or design methodology of transformable architecture? If so, what were they?

14. How do you see the development and use of kinetic envelopes extending architectural theory?

15. In your opinion, tranSTUDIO should be offered in which year of undergraduate program? Why?

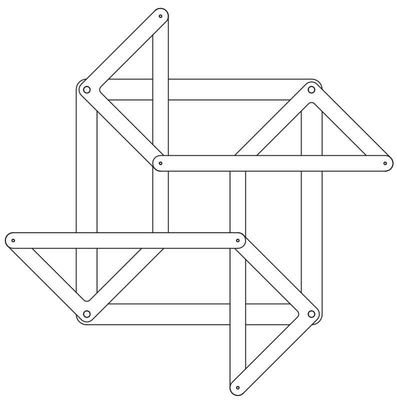
16. What are the major things that you have learnt from this studio?

Appendix B


I
II
III
IV
V
A
A I UMBRA I
A II UMBRA II
A III UMBRA III
A IV UMBRA IV
A V UMBRA V
B
B I UMBRA VI
1
2
B 1 II UMBRA VII
B 1 III UMBRA VIII
B 1 IV UMBRA IX
UMBRA X B 2 II
UMBRA XI B 2 III
UMBRA XII B 2 IV
C
C I SOL I
C II SOL II
UMBRA
GENERATOR I
D
D 1 I AURA I
D 1 II AURA II
D 1 III AURA III
D 2 I AURA IV
D 2 II AURA V
D 2 III AURA VI
D 2 IV AURA VII
E
E I AURA VIII
F
F I AURA IX
F II
F II
F III
F IV
G
G I OCOLUS I
G II OCOLUS II
OCOLUS
GENERATOR II
H
H I OCOLUS III
I
I I OCOLUS IV
J
J I TEXTA I
J II TEXTA II
J III TEXTA III
ANGULUS
GENERATOR III
K
K I ANGULUS I
K II ANGULUS II
K III ANGULUS III
K IV ANGULUG IV
L
L I ARCUS I
L II ARCUS II
M
M I ARCUS III
N
N I ARCUS IV
O
O I ARCUS V
ROTATION
TRANSLATION

GENERATOR I: UMBRA

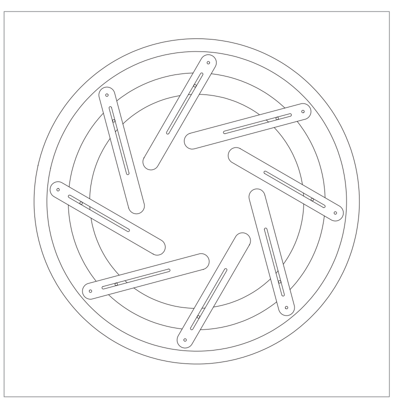
Type of Motion: Rotation + Translation



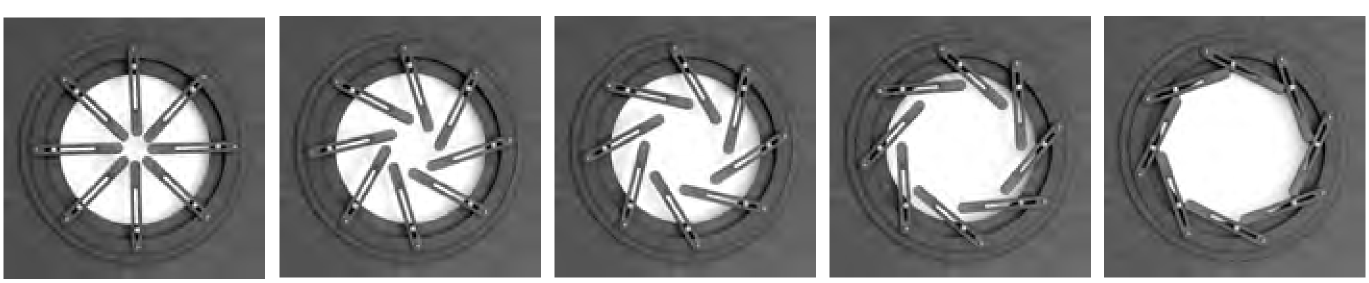
Number of Links: 8 (4 L shape links + 4 straight bars)
Number of Joints: 12
Type of Joints: Revolute
Number of Points of Connection: 4
Boundary of Design: Fix however the links cross over the boundry
Parking Position of Movable Parts: straight bars stack over the refrence frame. The L shape links extend over the reference frame during the sequence of movement.

GENERATOR II: OCULUS

Type of Motion: Rotation

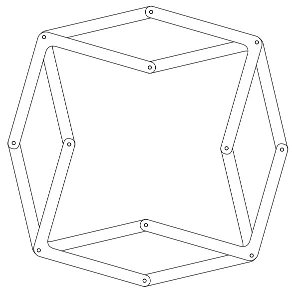


Number of Links: 8 (8 straight bars)
Number of Joints: 16
Type of Joints: Revolute, the straight links change their orientation in space by rotating about the rotational axis outside the links' centroidal axis
Number of Points of Connection: 8
Boundary of Design: Fix
Parking Position of Movable Parts: straight bars stack over the circular refrence frame.



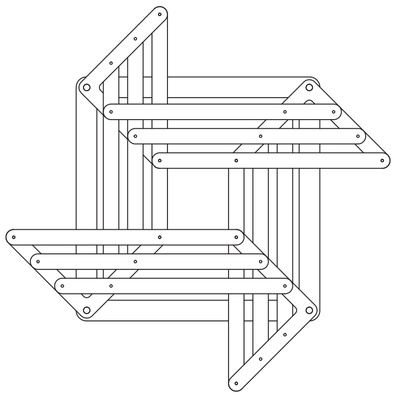
GENERATOR III: ANGULUS

Type of Motion: Rotation

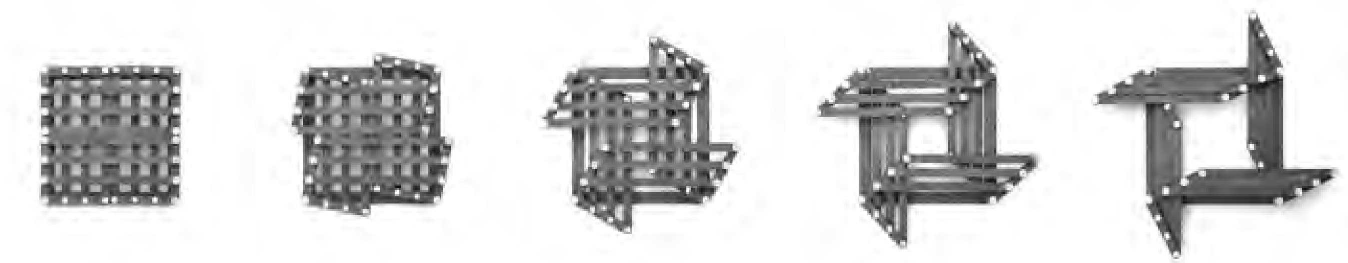


Number of Links: 8 (8 L shape links)
Number of Joints: 12
Type of Joints: Revolute
Number of Points of Connection: Changable
Boundary of Design: Fix however the links cross over the boundry
Parking Position of Movable Parts: each two L shape links stack over eachother.

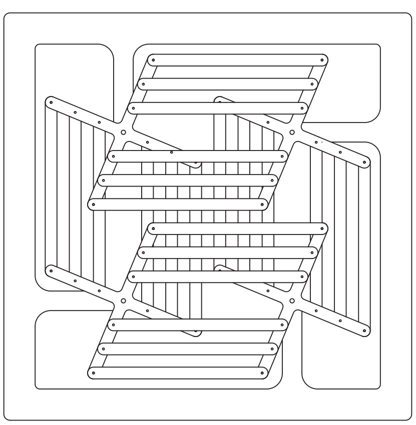
A I	Design Name: UMBRA I	Type of Motion: Rotation + Translation



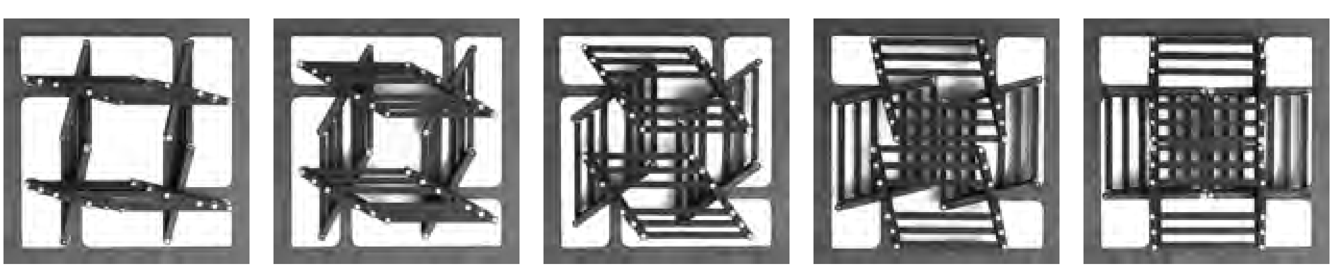
Number of Links: 16 (4 L shape links + 12 straight bars)
Number of Joints: 28
Type of Joints: Revolute
Number of Points of Connection: 4
Boundary of Design: Fix
Parking Position of Movable Parts: straight bars stack next to each other over the refrence frame. The L shape links extend over the reference frame during the sequence of movement.



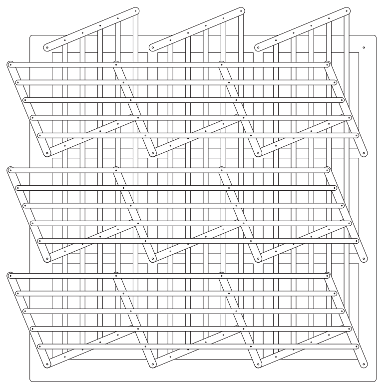
A II	Design Name: UMBRA II	Type of Motion: Rotation + Translation



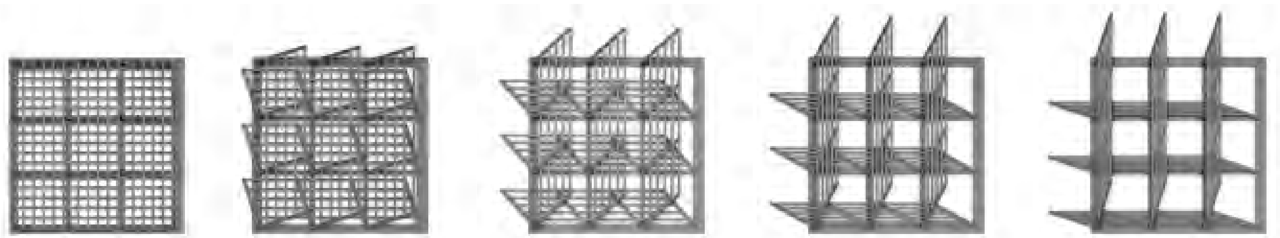
Number of Links: 28 (4 cross shape links + 24 straight bars)
Number of Joints: 52
Type of Joints: Revolute
Number of Points of Connection: 4
Boundary of Design: Fix
Parking Position of Movable Parts: straight bars stack next



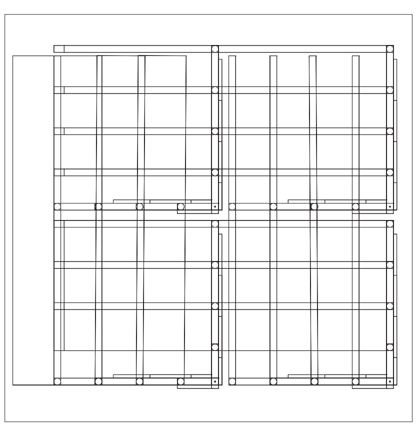
A III	Design Name: UMBRA III	Type of Motion: Rotation + Translation



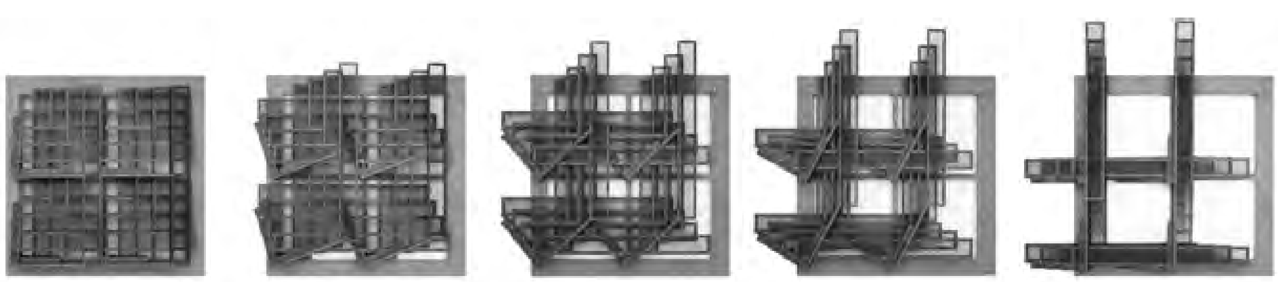
Number of Links: 45 (9 L shape links + 6 short straight bars + 30 long straight bars)
Number of Joints: 120+15=135
Type of Joints: Revolute
Number of Points of Connection: 15
Boundary of Design: Fix
Parking Position of Movable Parts: straight bars stack next to each other inside the reference frame. The links extend over the reference frame during the sequence of movement.



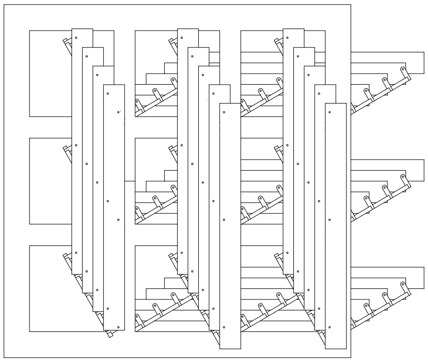
A IV	Design Name: UMBRA IV	Type of Motion: Rotation + Translation



Number of Links: 16 (4 L shape + 16 straight links)
Number of Joints: 32+4=36
Type of Joints: Revolute
Number of Points of Connection: 4
Boundary of Design: Fix
Parking Position of Movable Parts: straight linksstack over each other over the refrence frame. The links extend over the reference frame during the sequence of movement.

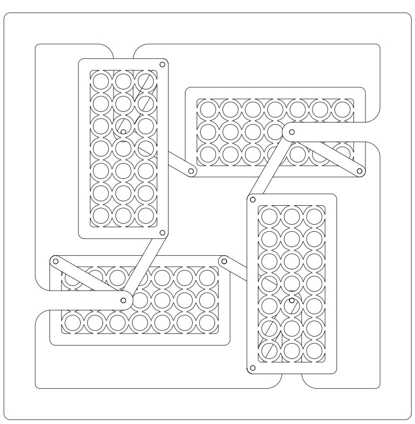


A V | Design Name: UMBRA V | Type of Motion: Rotation + Translation

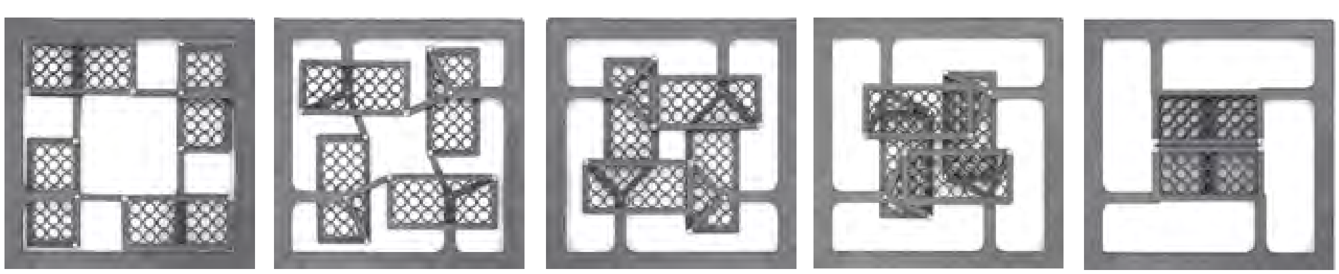


Number of Links: 16 (9 L shape + 30 straight links)
Number of Joints: 90
Type of Joints: Revolute
Number of Points of Connection: 9
Boundary of Design: Fix
Parking Position of Movable Parts: straight linksstack over each other over the refrence frame. The links extend over the reference frame during the sequence of movement.

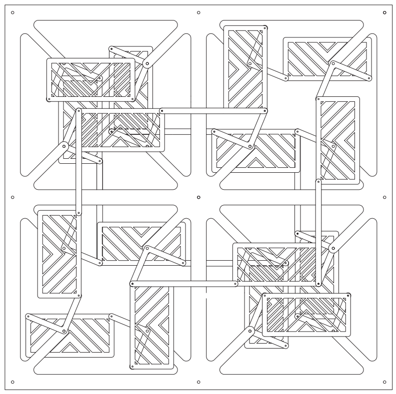
B I | Design Name: UMBRA VI | Type of Motion: Rotation + Translation



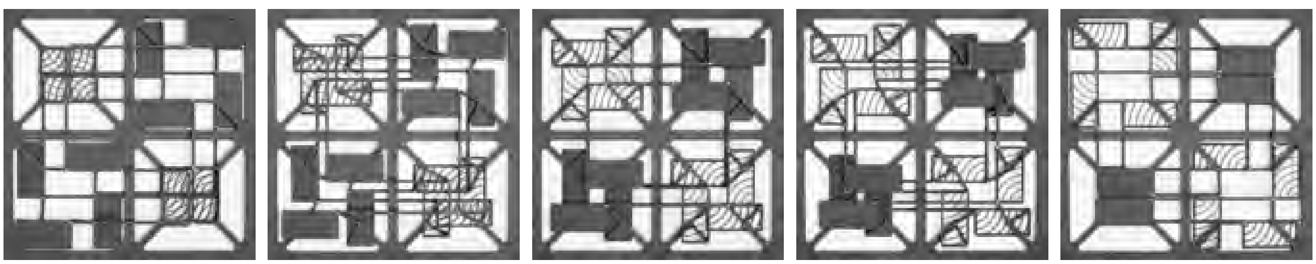
Number of Links: 8 (4 L shape + 4 rectangle overlaying links)
Number of Joints: 8+4=12
Type of Joints: Revolute
Number of Points of Connection: 4
Boundary of Design: Fix
Parking Position of Movable Parts: each 4 rectangle links goes to one corner of reference frame.



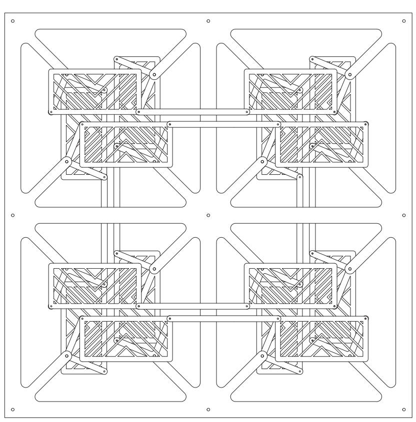
B1 II | Design Name: UMBRA VII | Type of Motion: Rotation + Translation



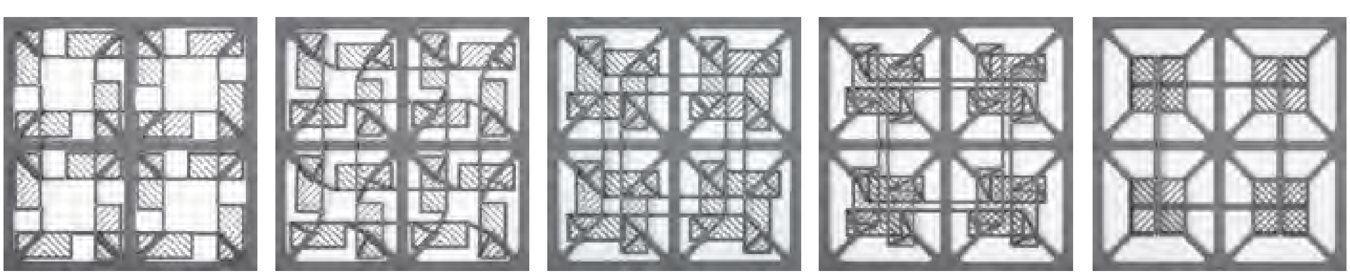
Number of Links: 44 (16 L shape + 12 straight bars+16 rectangle overlaying links)
Number of Joints: 8+4=12
Type of Joints: Revolute
Number of Points of Connection: 16
Boundary of Design: Fix
Parking Position of Movable Parts: the refrence frame divided to four smaller frames. when two diagonal frames open, the two others close. The rectangle links go to the corner of frames while openning.

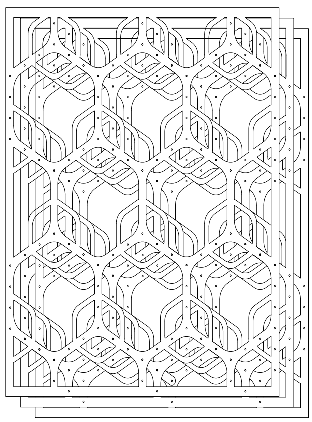


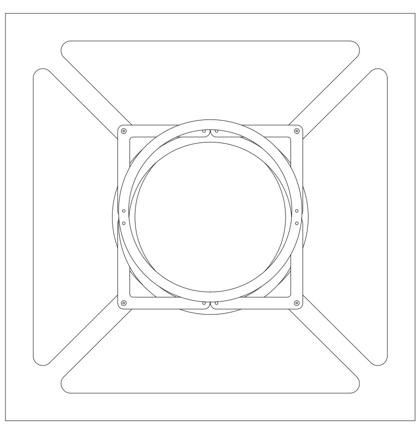
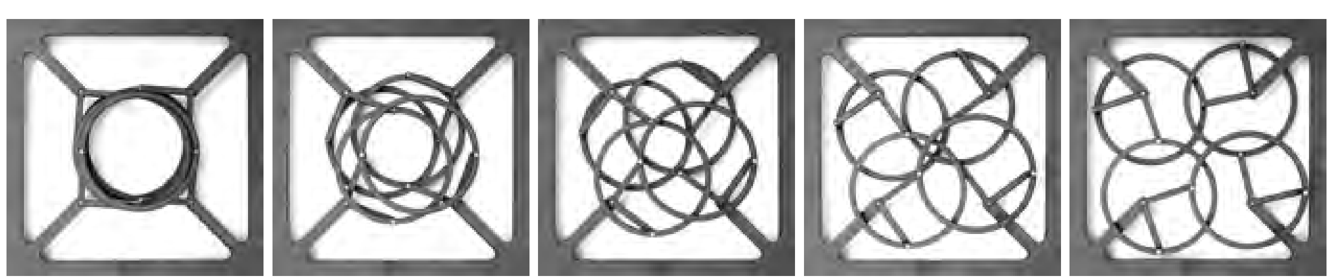
B1 III | Design Name: UMBRA VIII | Type of Motion: Rotation + Translation



Number of Links: 44 (16 L shape + 12 straight bars+16 rectangle overlaying links)
Number of Joints: 8+4=12
Type of Joints: Revolute
Number of Points of Connection: 16
Boundary of Design: Fix
Parking Position of Movable Parts: the refrence frame divided to four smaller frames.The rectangle links go to the sides of small frames.

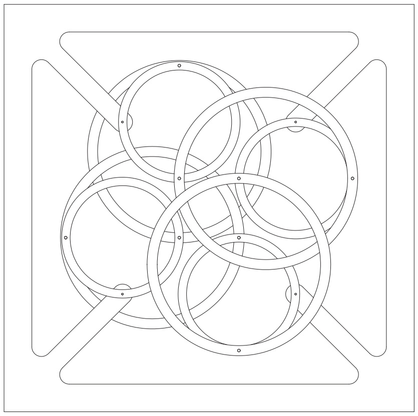


B1 IV	Design Name: UMBRA IX	Type of Motion: Rotation
		Number of Links: 12 (8 short straight bars+4 surfaces) Number of Joints: 12 Type of Joints: Revolute Number of Points of Connection: 4 Boundary of Design: Fix Parking Position of Movable Parts: The first surface works as the refrence frame and the three surfaces rotate over each other and they extend over the first layer.
		

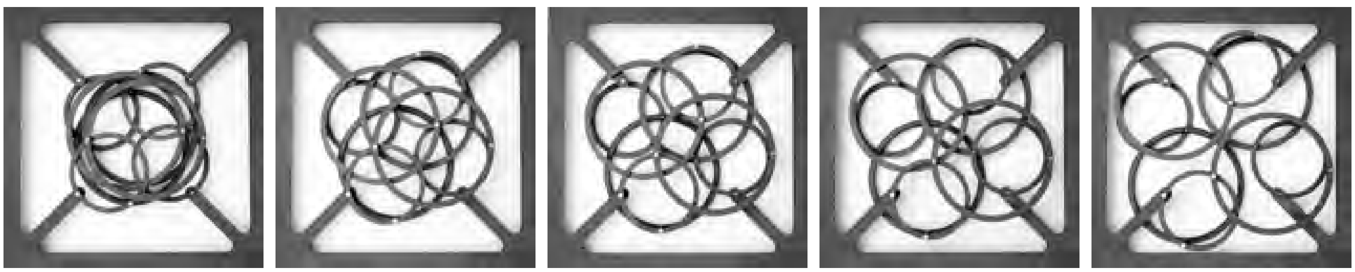
B2 II	Design Name: UMBRA X	Type of Motion: Rotation + Translation
		Number of Links: 8(4 L shape + 4 circular links) Number of Joints: 8+4=12 Type of Joints: Revolute Number of Points of Connection: 4 Boundary of Design: Fix Parking Position of Movable Parts: Each circle goes to one corner of the refrence frame
		

B2 III Design Name: UMBRA XI

Type of Motion: Rotation + Translation

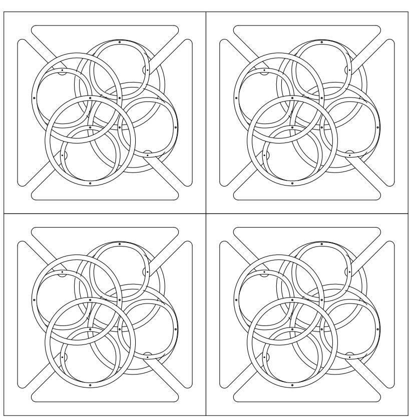


Number of Links: 8 (8 circular links)
Number of Joints: 8+4=12
Type of Joints: Revolute
Number of Points of Connection: 4
Boundary of Design: Fix
Parking Position of Movable Parts: Each circle goes to one corner of the refrence frame

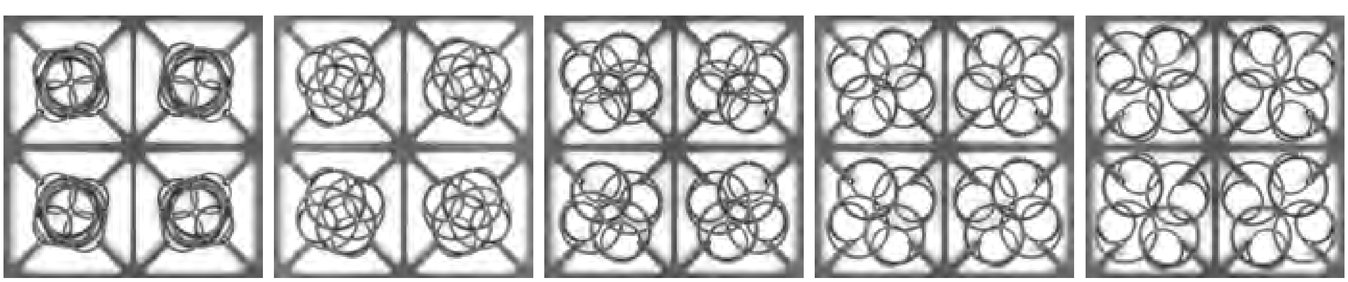


B2 IV Design Name: UMBRA XII

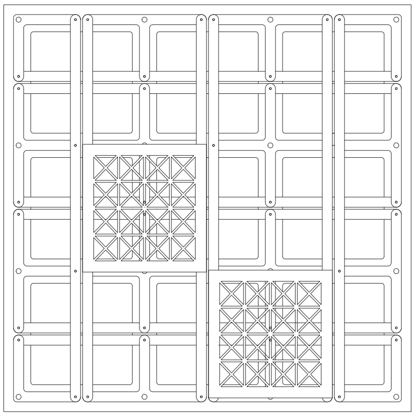
Type of Motion: Rotation + Translation



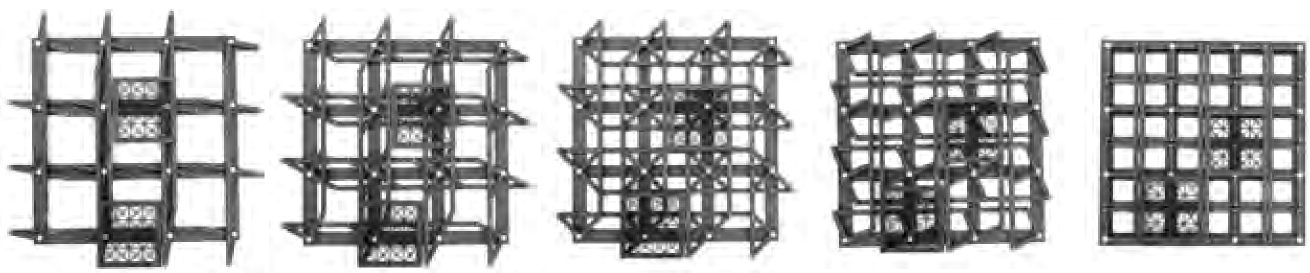
Number of Links: 32 (each small frame consists of 8 circular links)
Number of Joints: 12X4=48
Type of Joints: Revolute
Number of Points of Connection: 16
Boundary of Design: Fix
Parking Position of Movable Parts: The refrence frame divided to four smaller frames. The circles go to the corner of small frames



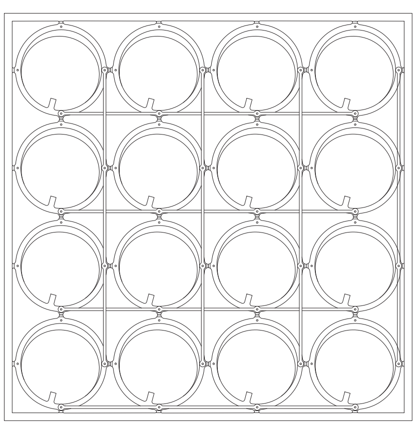
CI	Design Name: SOL I	Type of Motion: Rotation + Translation



Number of Links: 28 (4 cross shape links + 8 T shape links + 4 L shape links + 12 straight bars)+ 2 square shapes of overlaying surface
Number of Joints: 12+32+20=64
Type of Joints: Revolute
Number of Points of Connection: 28
Boundary of Design: Fix
Parking Position of Movable Parts: the reference frame divided to nine small frames by four structural dividers. The straight bars stack next to frame structural dividers.

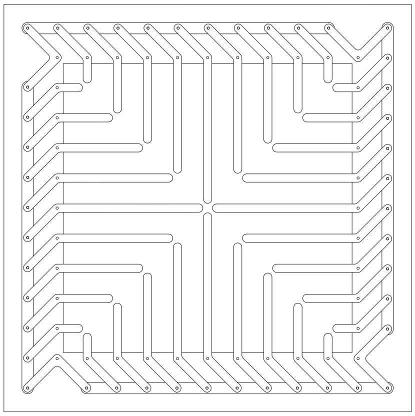


C II	Design Name: SOL II	Type of Motion: Rotation + Translation



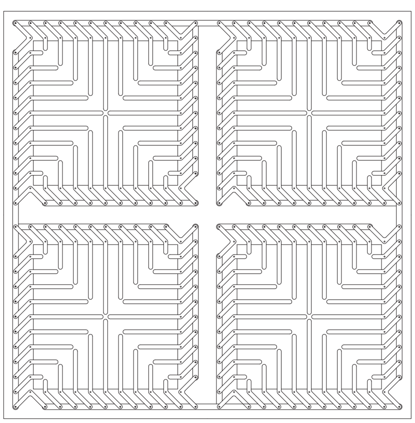
Number of Links: 24(16 circular links + 8 straight bars) + 16 circular shapes of overlaying surfaces
Number of Joints: 12+32+20=64
Type of Joints: Revolute
Number of Points of Connection: 32
Boundary of Design: Fix
Parking Position of Movable Parts: the reference frame divided to 16 small circular frames. The circular overlaying surfaces change only their orientations and they do not change their positions.

D 1I | Design Name: AURA I | Type of Motion: Rotation + Translation

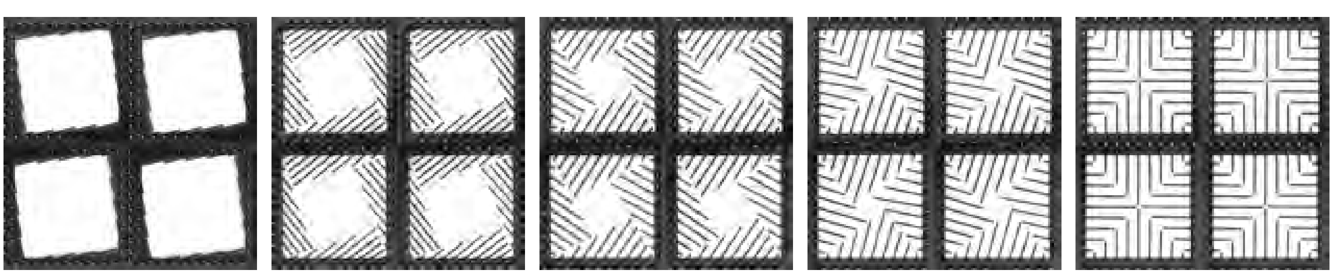


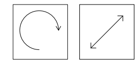
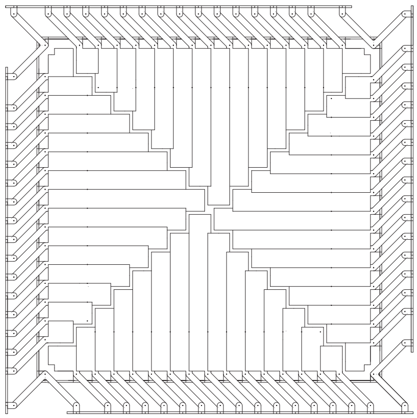
Number of Links: 44 (40 angulated links + 4 straight bars)
Number of Joints: 80
Type of Joints: Revolute
Number of Points of Connection: 40
Boundary of Design: Fix
Parking Position of Movable Parts: the links stack next to each other inside the reference frame.

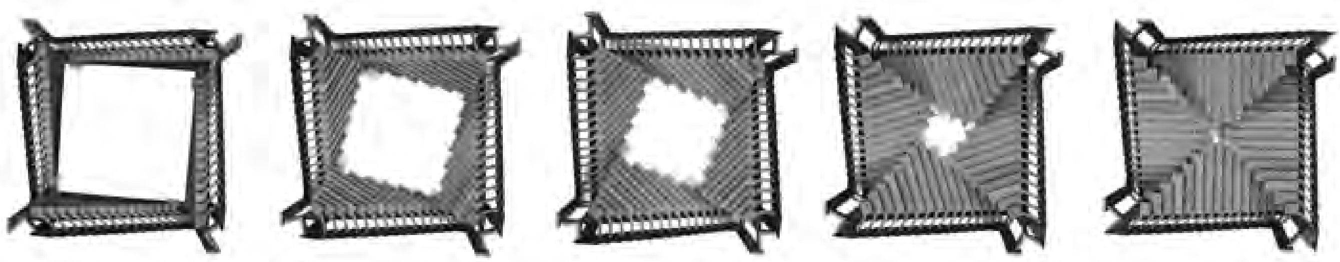
D 1II | Design Name: AURA II | Type of Motion: Rotation + Translation



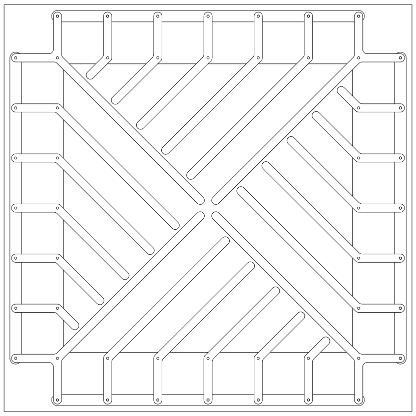
Number of Links: 164 (4X40 angulated links + 4 straight bars)
Number of Joints: 320
Type of Joints: Revolute
Number of Points of Connection: 160
Boundary of Design: Fix
Parking Position of Movable Parts: the links stack next to each other inside the reference frame.



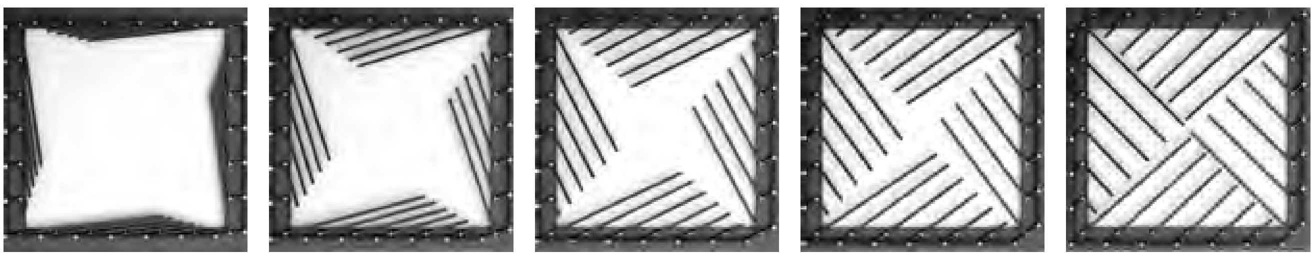
D 1III	Design Name: AURA III	Type of Motion: Rotation + Translation 
		Number of Links: 68 (60 angulated links + 4 L shape links + 4 straight bars) Number of Joints: 120+12=132 Type of Joints: Revolute Number of Points of Connection: 64 Boundary of Design: Fix Parking Position of Movable Parts: the angulated links stack over each other inside the reference frame.



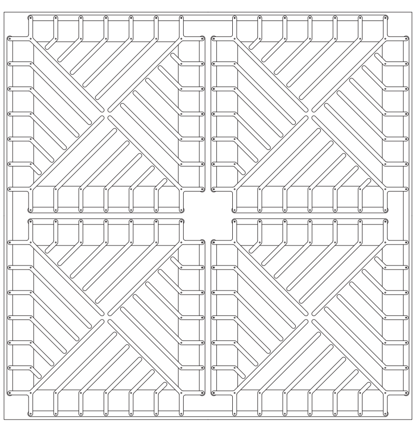
D 2I | Design Name: AURA IV | Type of Motion: Rotation + Translation



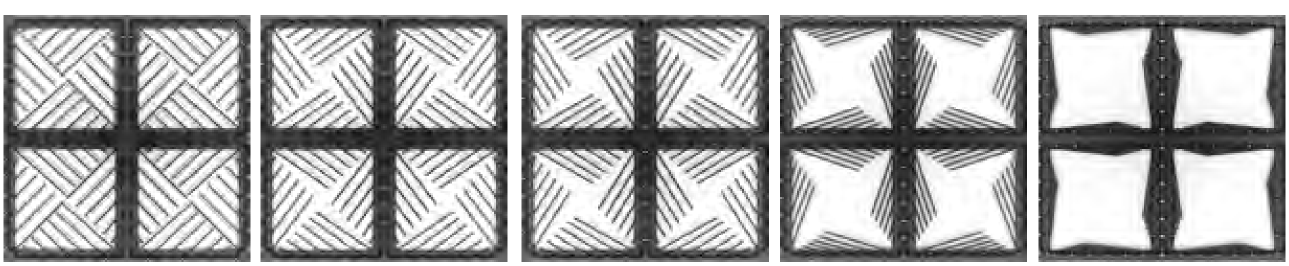
Number of Links: 28 (20 angulated links + 4 Y shape links + 4 straight bars)
Number of Joints: 40+12=52
Type of Joints: Revolute
Number of Points of Connection: 24
Boundary of Design: Fix
Parking Position of Movable Parts: the links stack next to each other inside the reference frame.



D 2 II | Design Name: AURA V | Type of Motion: Rotation + Translation

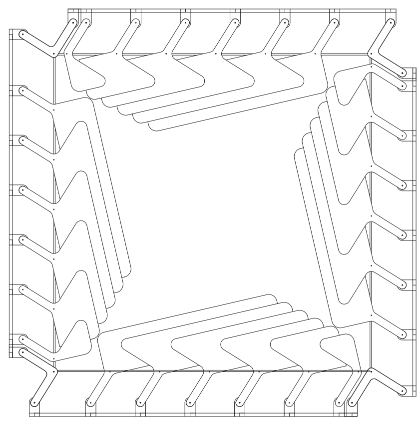


Number of Links: 100 (4X20 angulated links + 4X4 Y shape links+ 4 straight bars)
Number of Joints: 204
Type of Joints: Revolute
Number of Points of Connection: 96
Boundary of Design: Fix
Parking Position of Movable Parts: the links stack next to each other inside the reference frame.

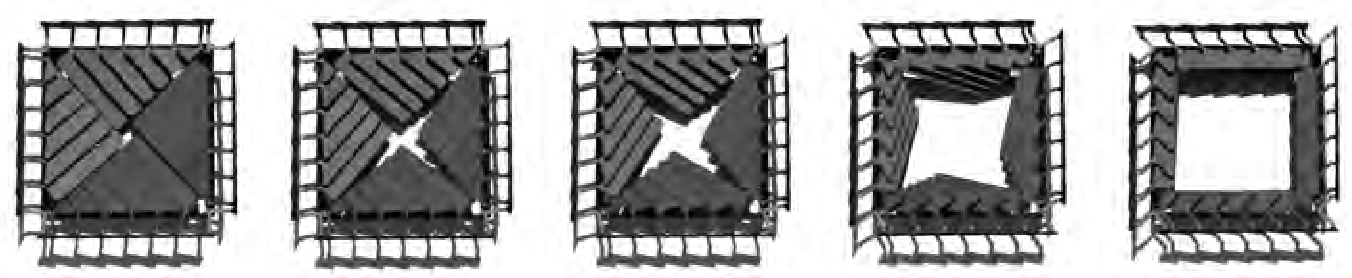


D 2III Design Name: AURA VI

Type of Motion: Rotation + Translation

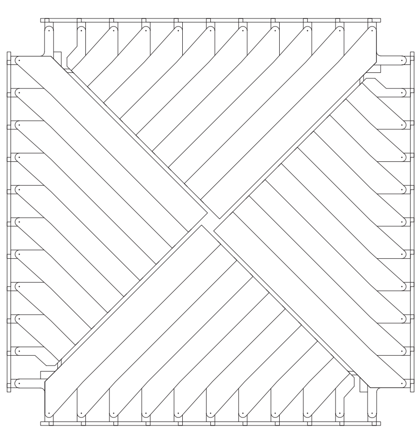


Number of Links: 32 (24 angulated links + 4 L shape links + 4 straight bars)
Number of Joints: 48+12=60
Type of Joints: Revolute
Number of Points of Connection: 28
Boundary of Design: Fix
Parking Position of Movable Parts: the angulated links stack over each other inside the reference frame.

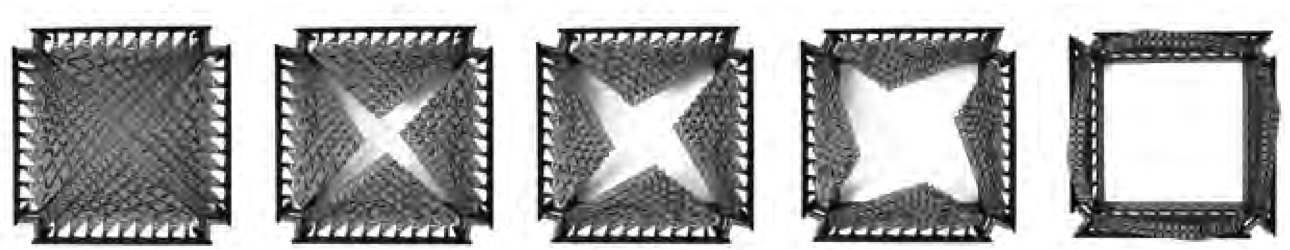


D 2 IV Design Name: AURA VII

Type of Motion: Rotation + Translation



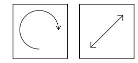
Number of Links: 88 (40 angulated links + 4 L shape links + 40 short straight connection bars + 4 long straight bars)
Number of Joints: 132+12=144
Type of Joints: Revolute
Number of Points of Connection: 40
Boundary of Design: Fix
Parking Position of Movable Parts: the angulated links stack over each other inside the reference frame.

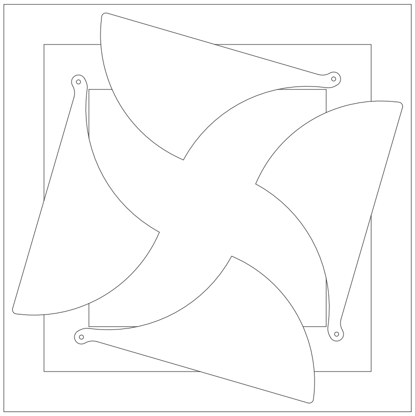


E I

Design Name: AURA VIII

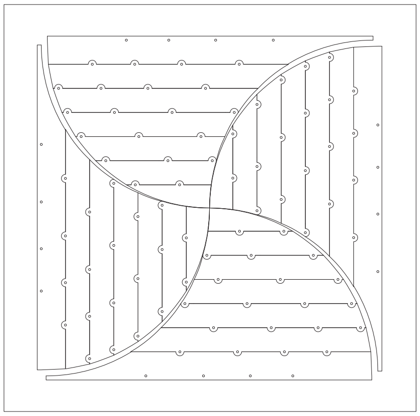
Type of Motion: Rotation + Translation



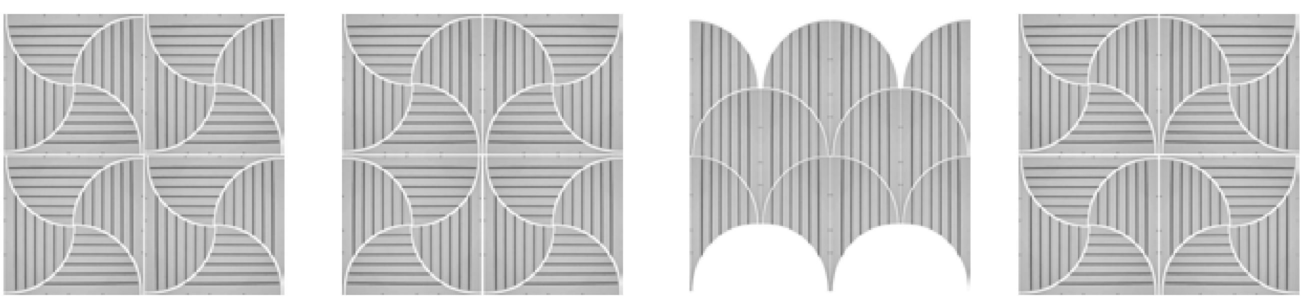


Number of Links: 8 (4 wings + 4 straight bars)
Number of Joints: 10
Type of Joints: Revolute
Number of Points of Connection: 4
Boundary of Design: Fix
Parking Position of Movable Parts: the wings extend over the reference frame.

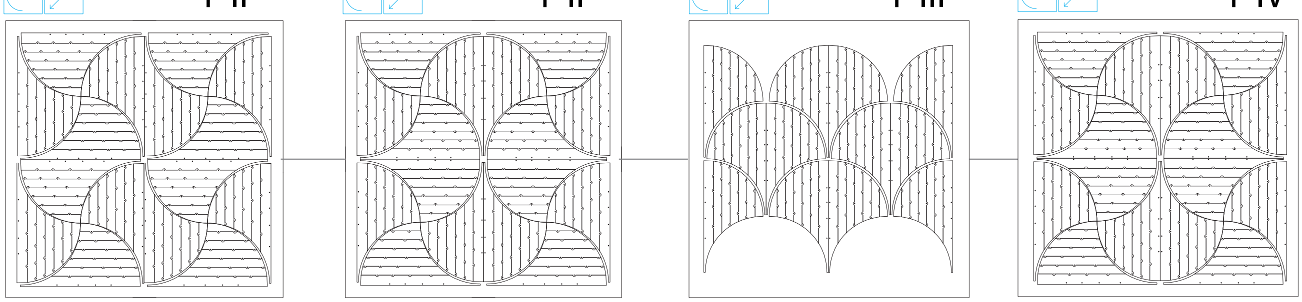
F I	Design Name: AURA IX	Type of Motion: Rotation + Translation

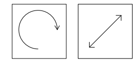


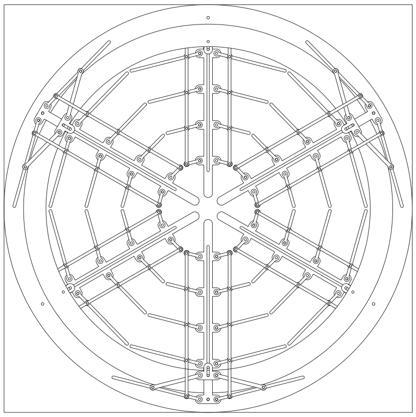
Number of Links: 24(24 fins + 24 straight bars)
Number of Joints: 24X4=96
Type of Joints: Revolute
Number of Points of Connection: 16
Boundary of Design: Fix
Parking Position of Movable Parts: the fins stack under each other under the reference frame.



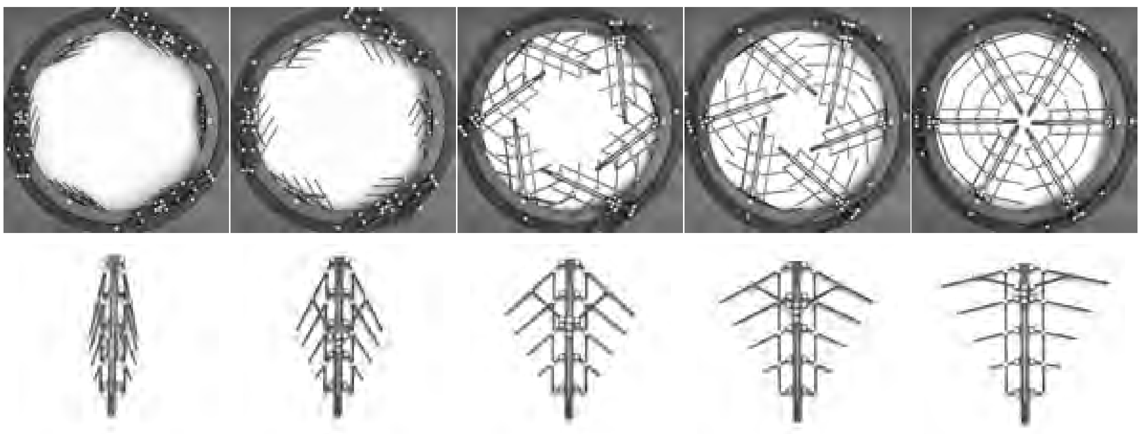
F II F II F III F IV

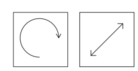


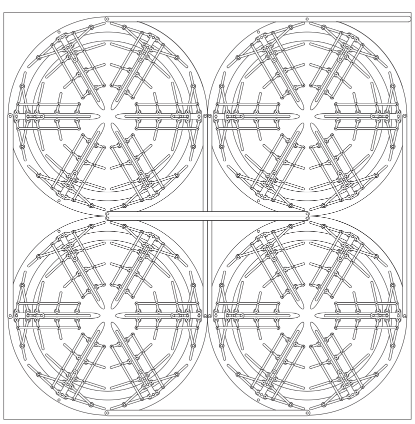
G I	Design Name: OCOLUS I	Type of Motion: Rotation + Translation 



Number of Links: 86 (14X6 straight bars shaping 6 wings + 2 circular rings over the reference frame)
Number of Joints: 24X6=64
Type of Joints: Revolute, Pin in slot
Number of Points of Connection: 6
Boundary of Design: Fix
Parking Position of Movable Parts: all members of each wing stack together and each wing goes close the boundary of the reference frame.



G II	Design Name: OCOLUS II	Type of Motion: Rotation + Translation 

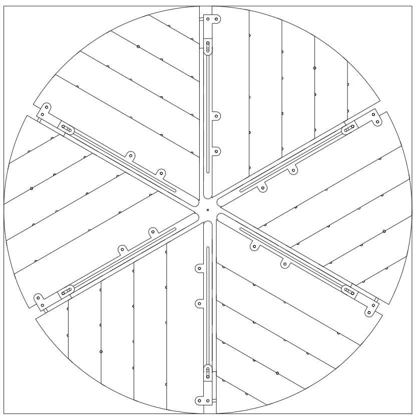


Number of Links: 352 (84X4 straight bars shaping 24 wings + 8 circular rings over the reference frame + 8 long straight bars)
Number of Joints: 64X4+12=268
Type of Joints: Revolute, Pin in slot
Number of Points of Connection: 24
Boundary of Design: Fix
Parking Position of Movable Parts: all members of each wing stack together and each wing goes close the boundary of the reference frames.

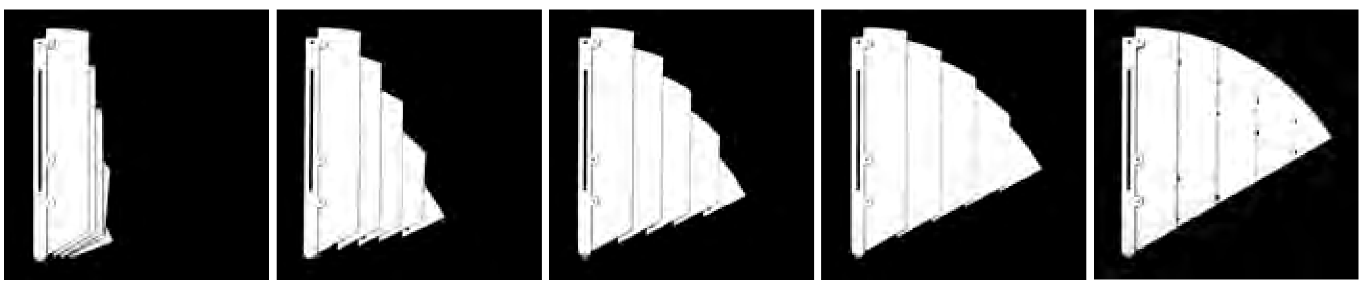
H I

Design Name: OCOLUS III

Type of Motion: Rotation + Translation



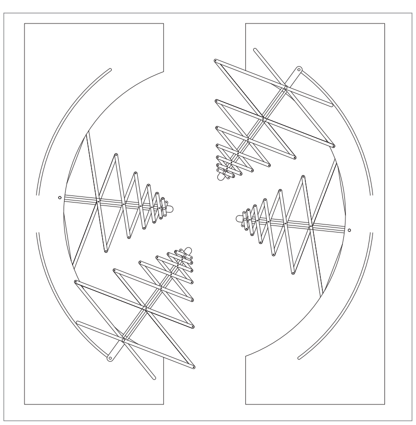
Number of Links: 24(30 fins + 60 straight connection bars +6 straight bars)
Number of Joints: 12+32+20=64
Type of Joints: Revolute, Pin in slot
Number of Points of Connection: 6
Boundary of Design: Fix
Parking Position of Movable Parts: the fins of each wing stack under each other.



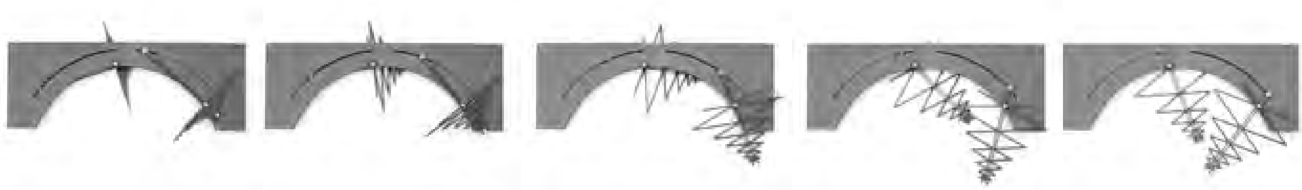
I I

Design Name: OCOLUS IV

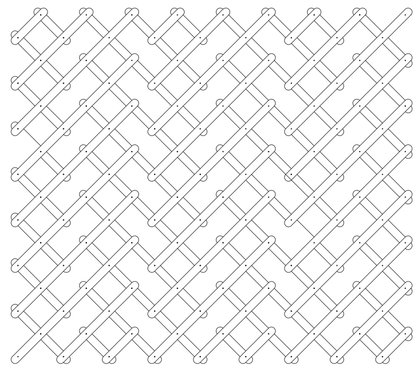
Type of Motion: Rotation + Translation



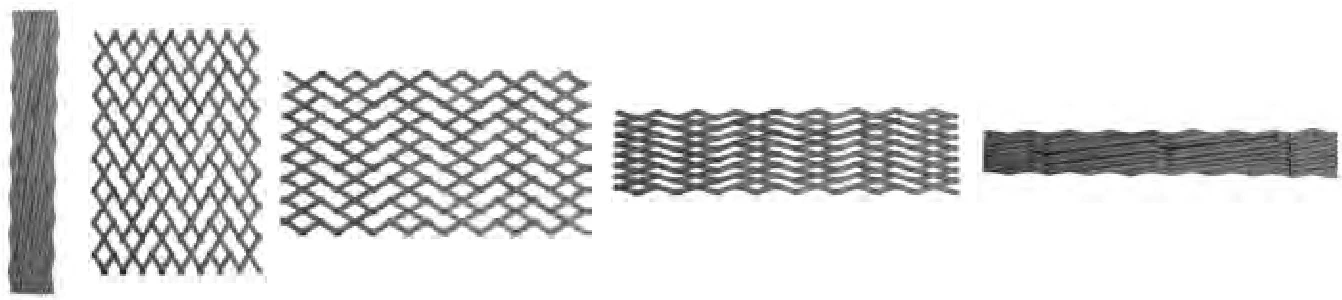
Number of Links: 26
Number of Joints: 40
Type of Joints: Revolute, Pin in slot
Number of Points of Connection: 4
Boundary of Design: Fix
Parking Position of Movable Parts: the fins of each wing stack next to each other close to the boundary of the reference frame.



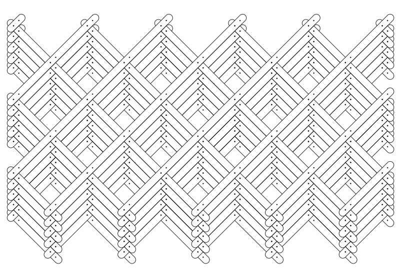
J I	Design Name: TEXTA I	Type of Motion: Rotation + Translation



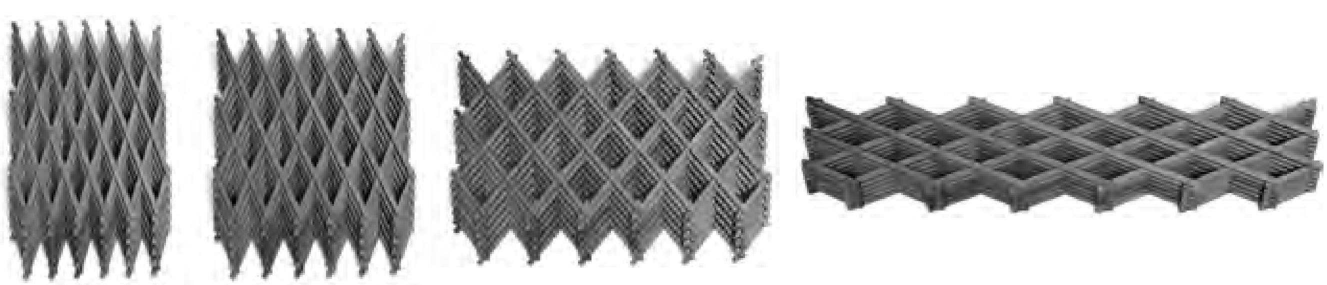
Number of Links: 72 straight bars
Number of Joints: 160
Type of Joints: Revolute
Number of Points of Connection: -
Boundary of Design: Changable
Parking Position of Movable Parts: the bars conected as scissors structure and they stack next to each other.



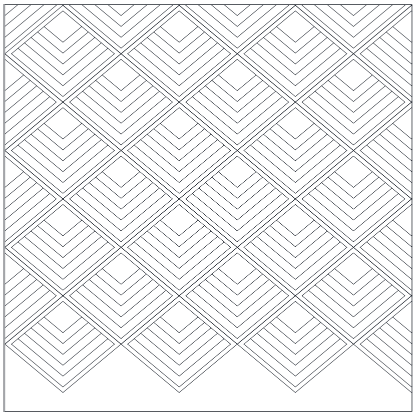
J II	Design Name: TEXTA II	Type of Motion: Rotation + Translation



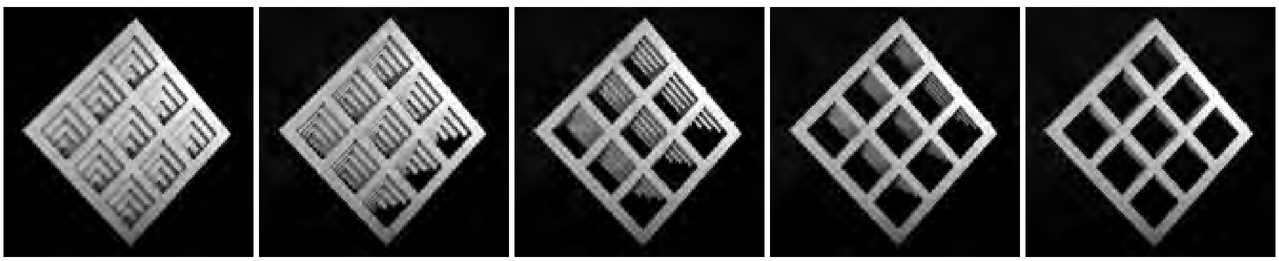
Number of Links: 80 straight bars
Number of Joints: 121
Type of Joints: Revolute
Number of Points of Connection: -
Boundary of Design: Changable
Parking Position of Movable Parts: the bars conected as scissors structure and they stack next to each other.



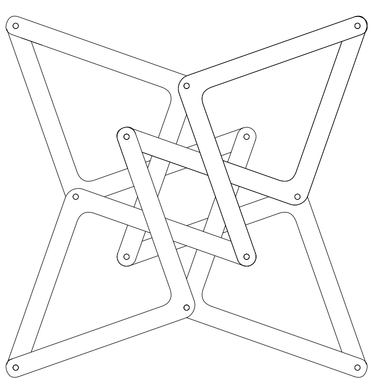
J III	Design Name: TEXTA III	Type of Motion: Rotation + Translation



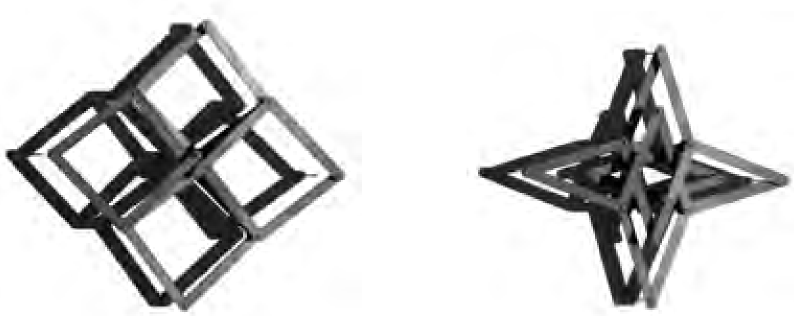
Number of Links: 5 surfaces + 6 connection links
Number of Joints: 30
Type of Joints: Revolute
Number of Points of Connection: 5
Boundary of Design: Fix
Parking Position of Movable Parts: The surfaces stack under each other under the reference frame.



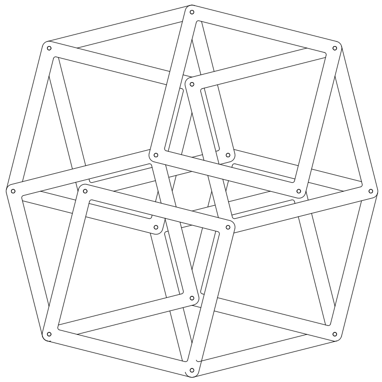
K I	Design Name: ANGULUS I	Type of Motion: Rotation



Number of Links: 8 L shape links
Number of Joints: 12
Type of Joints: Revolute
Number of Points of Connection: -
Boundary of Design: Changable
Parking Position of Movable Parts: the links pivot over each other.

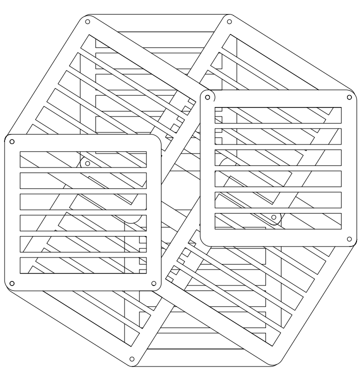


K II	Design Name: ANGULUS II	Type of Motion: Rotation



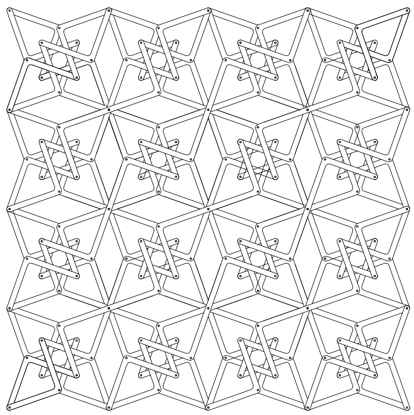
Number of Links: 8 square shape links
Number of Joints: 16
Type of Joints: Revolute
Number of Points of Connection: -
Boundary of Design: Changable
Parking Position of Movable Parts: the links pivot over each other.

K III	Design Name: ANGULUS III	Type of Motion: Rotation

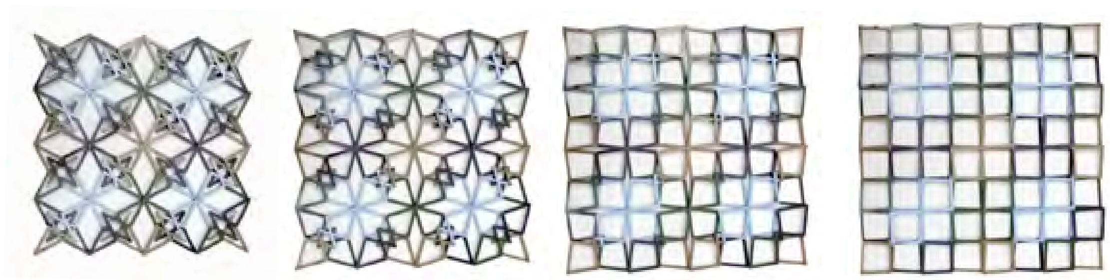


Number of Links: 8 square shaped links
Number of Joints: 12
Type of Joints: Revolute
Number of Points of Connection: -
Boundary of Design: Changable
Parking Position of Movable Parts: the links pivot over each other.

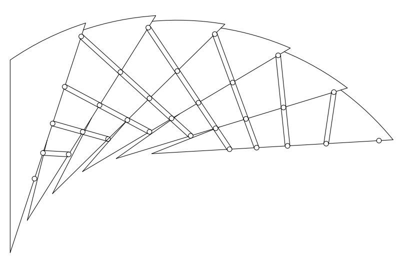
K II	Design Name: ANGULUS II	Type of Motion: Rotation



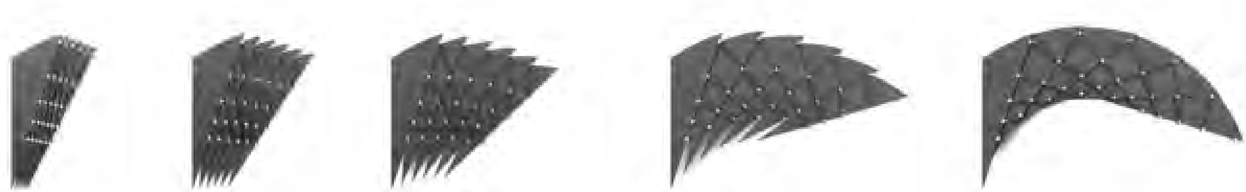
Number of Links: 84
Number of Joints: 64+25=89
Type of Joints: Revolute
Number of Points of Connection: -
Boundary of Design: Changable
Parking Position of Movable Parts: the links pivot over each other.



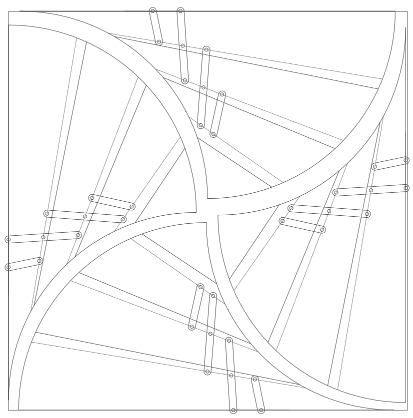
L I	Design Name: ARCUS I	Type of Motion: Rotation + Translation



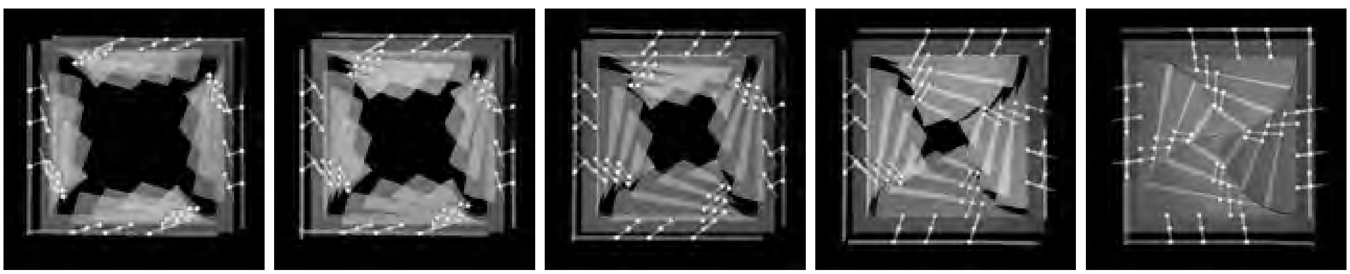
Number of Links: 14 (6 fins + 8 bars)
Number of Joints: 27
Type of Joints: Revolute
Number of Points of Connection: -
Boundary of Design: not applicable
Parking Position of Movable Parts: the fins stack under each other



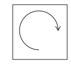
N I	Design Name: ARCUS IV	Type of Motion: Rotation + Translation

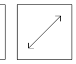


Number of Links: 50 (16 fins +34 bars)
Number of Joints: 72
Type of Joints: Revolute
Number of Points of Connection: 12
Boundary of Design: Fix
Parking Position of Movable Parts: the fins stack over each other next to the sides of the reference frame.

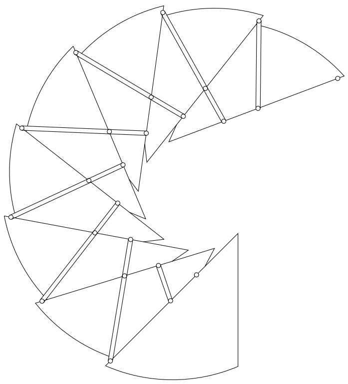


L II | Design Name: ARCUS II | Type of Motion: Rotation + Translation

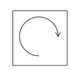


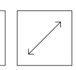


Number of Links: 14 (6 fins + 8 bars)
Number of Joints: 27
Type of Joints: Revolute
Number of Points of Connection: -
Boundary of Design: not applicable
Parking Position of Movable Parts: the fins stack under each other

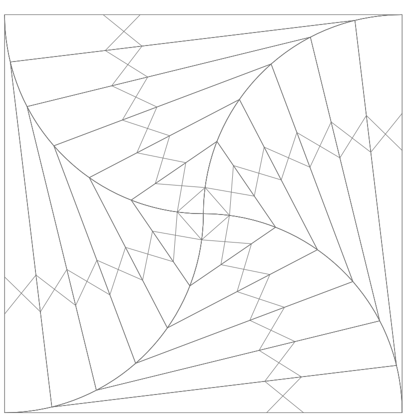


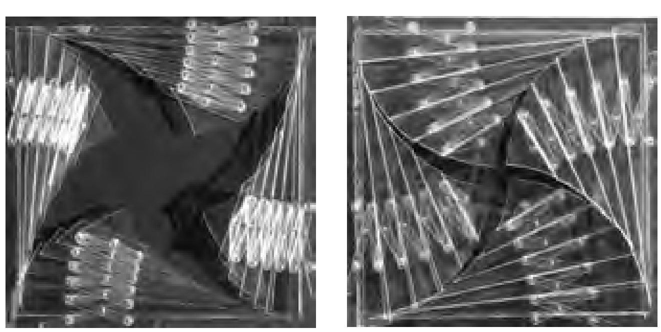
M I | Design Name: ARCUS III | Type of Motion: Rotation + Translation



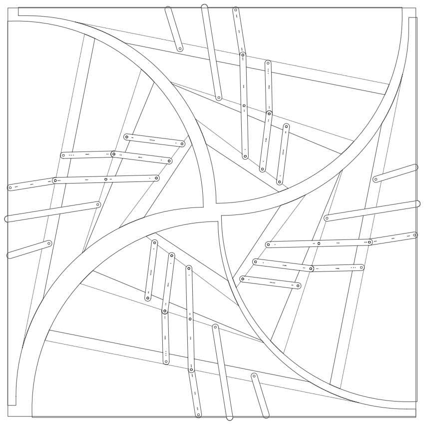


Number of Links: 14 (36 fins + 48 bars)
Number of Joints: 72
Type of Joints: Revolute
Number of Points of Connection: 8
Boundary of Design: FIx
Parking Position of Movable Parts: the fins stack over each other next to the sides of the reference frame.

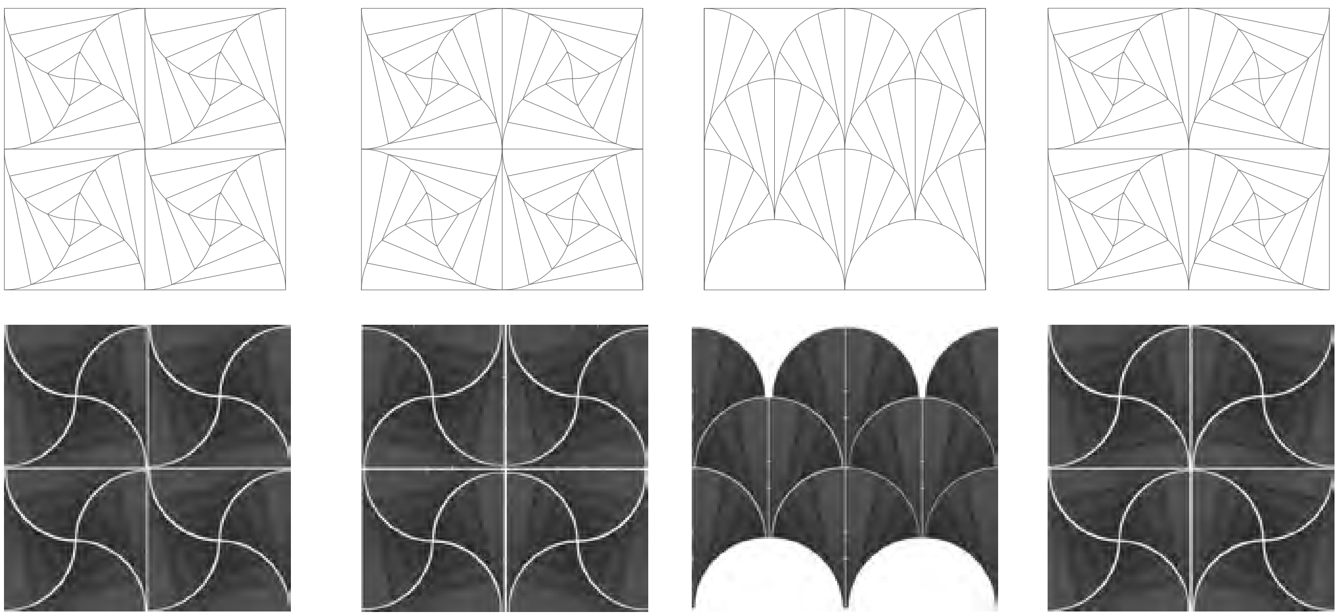




O I	Design Name: ARCUS V	Type of Motion: Rotation + Translation

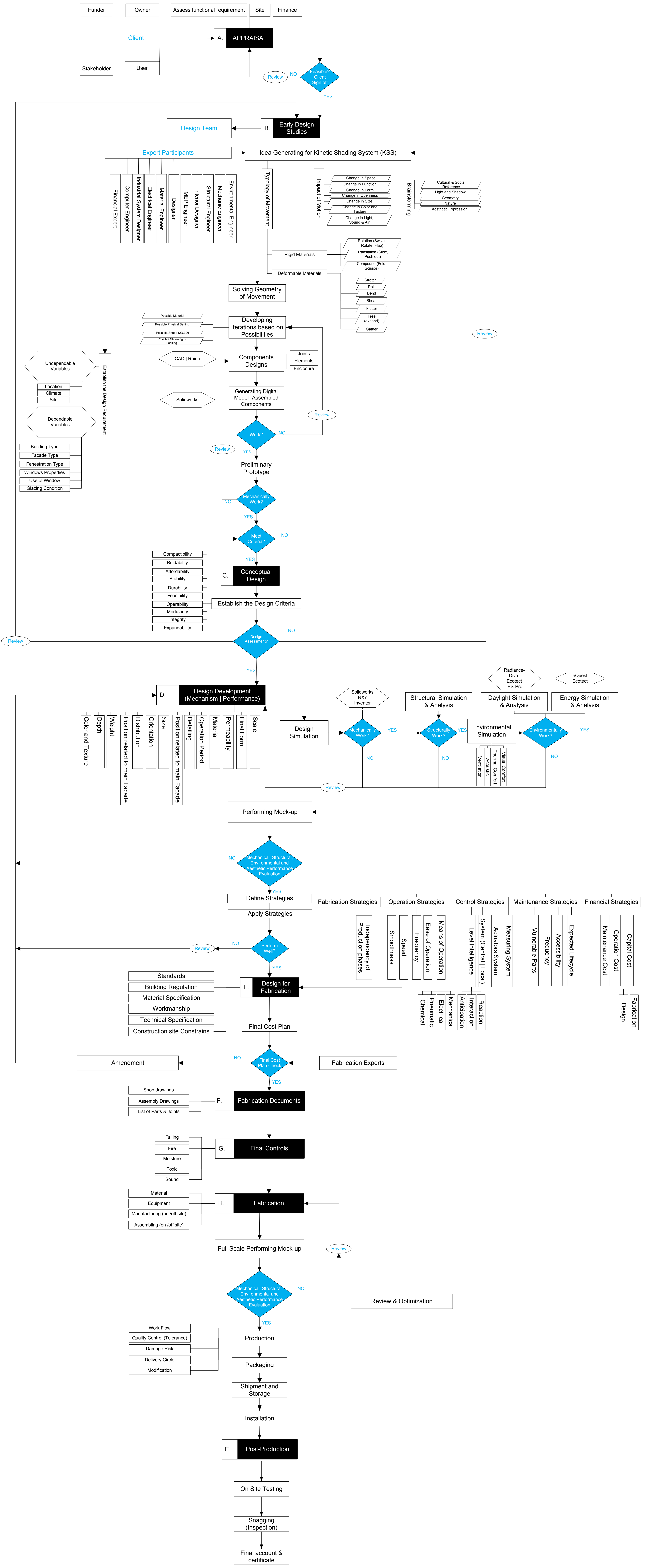


Number of Links: 14 (16 fins + 28 bars)
Number of Joints: 52
Type of Joints: Revolute
Number of Points of Connection: 12
Boundary of Design: Fix
Parking Position of Movable Parts: the fins stack over each other next to the sides of the reference frame.



Appendix C

A Design Process Framework for Understanding the Relationship between a Proposed Kinetic Shading System and Issues of Implementation



Transformable Shading System Design Process
TSS design process
Information
Skill
Knowledge
DESIGN PROCESS
OUTPUT SOLUTION|SUBSOLUTION
Design Requirement
Contextual Information
Technical Information
Environmental Information
Functional Information
Ref to Figure 12: Developing the Information Chart
Financial Information
Basic skills of physical modelling
skill of digital modelling (such as CAD|RHINO and GRASSHOPPER)
skill of mechanical design software (such as SOLIDWORKS, NX, INVENTOR)
Mechanical analysis software (such as SOLIDWORKS, NX, INVENTOR) or Grasshopper
Environmental analysis software Radiance-Diva- Wind simulation
Basic Design Knowledge
Ref to Figure 9&10: Motion Typology of Rigid and Deformable Materials
Basic Knowledge of Typology of Motion
Knowledge of Motion design
Basic Knowledge of Environmental Design
Material Knowledge
Knowledge of Environmental Design
Structural design knowledge
Ref to Figure 11: Structural Factors of Transformable Structures
Knowledge of Environmental Design
Material Knowledge
Knowledge of Control Design
Knowledge of fabrication From experts
Early Design Stage
Start process
Gather basic information
Define design goals of TSS
Generate motion concept
Make physical model
Ref to Figure 8: The Goals of Designing a Shading Device
-Inaccuracy of geometry
-Inaccuracy of model making
-Material failure
-Joint failure
Check the source of problem
No
Work?
Yes
Conceptual Design Stage
In this stage designer checked if the motion geometry works.
-Links
-Joints
-Point of connection
Work?
No
Yes
Develop Iterations based on Possibilities
Concept models (digital and physical)
Upon here, it is all about underlying geometry
Components design (overlying geometry)
Generating Digital Model-Assembled Components
In this stage designer checks if the motion geometry works. And if the design has potential to satisfy environmental requirements
Motion Geometry Work?
Yes
Preliminary Prototype
In this stage designer checks if the motion geometry works. And if the design has potential to satisfy environmental requirements
Motion geometry Work?
Yes
No
No
Establish the Design Specification
Performance
Compatibility
Buidability
Affordability
Stability
Durability
Feasibility
Operability
Modularity
Integrity
Expandability
Design Development Stage
Scale
Final Form
Permeability
Material
Operation Period
Detailing
Position related to main Facade
Size
Orientation
Distribution
Position related to main Facade
Weight
Depth
Color and Texture
Design development (performance|motion)
Design simulation
Yes
Motion simulation & analysis
Mechanically Work?
Yes
Structural simulation & analysis
Structurally Work?
Yes
Environmental simulation & analysis
-Daylight simulation
-Energy simulation
Environmentally Work?
Yes
Meets Comfort level
Physical comfort
Mental Comfort (Aestetic,privacy, Security, View)
Yes
Performing Mock-up
Mechanical, Structural, Environmental and Aesthetic Performance Evaluation
Yes
No
Review to find reasons
Define and apply fabrication strategies
Define and apply operation strategies
Define and apply control strategies
Define and apply maintenance strategies
Define and apply financial strategies
Perform well?
No
No
No
No
No
Review
Air temperature
Wind speed
Wind presure
Light intensity
Solar irradiation
Illumination
Relative humidity
Rain measurment
Air quality
Window contacts
Design for Fabrication
Standards
Building Regulation
Material Specification
Workmanship
Technical Specification
Construction site Constrains
Yes
Design for fabrication
Final cost plan
Final cost plan check
Fabrication documents
Final controls
Fabrication
Full scale performing moke-up
Mechanical, Structural, Environmental and Aesthetic Performance Evaluation
Yes
No
Production
Packaging
Shipping & storage
Installation
Review
Post-Fabrication
On site testing
No
Snapping (Inspection)
Product certificate
Review and Costumization
Basic motion design knowledge
Motion geometry generators (Underlying geometries): Such as Umbra, Ocolus and Angulus
through brainstorming phase, few motion geometry generators developed
Design Specification