Topologies and Design Methods for Folding Kinetic Structures: Expanding the Architectural Paradigm

by

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Abstract

Built environments are the most prominent and important part of our material culture. Although they are vital for accommodating the exponentially growing and increasingly urbanized population under the challenging conditions of severe climatic changes and destabilized global societies, researchers note that the methods of both their design and construction need to be significantly improved. The construction industry is the largest source of waste and remains inefficient, while the architectural profession is being challenged by digital technologies, conflicting paradigms, and adverse market realities. What then are the obstacles in improving buildings? Is it the lack of viable ideas? Or, is it the social reluctance to accept novel ideas? How can architects be the socially relevant force contributing viable concepts? This thesis builds upon the current theories asserting the importance of human behavior and intentionality for understanding built environments, thus considering the complexity of both the technical and cultural circumstances. It establishes that although architecture is usually considered as a solid and invariable static form, it never has been a static shell merely delimiting discrete spaces. Through all times, buildings comprised both fixed structures and adjustable devices, which were the interactive interfaces between the static structures and the transiency of human action. This study focuses on rigidly foldable kinetic structures as they exemplify the potential advantages and challenges of novel architecture; and they are a logical expansion of the traditional adjustable architectural elements. For decades, theorists expected kinetic architecture to address the shortcomings of the traditional buildings. However, solving folding kinetic geometries is difficult and is hindered by the unintuitive nature of the current digital tools. Furthermore, kinetic environments challenge the traditional expectations of occupants. In response, the present thesis investigates the evolving, influenced by digital technologies, paradigms of public spaces, and human reasoning-driven design tools, while incorporating such human-centric considerations as social dynamics, history, and culture into the engineering and architectural design methods for built environments. It is concluded that architecture, its design and construction are primarily a social endeavor. Therefore understanding the cognitive barriers of design tools
and negotiating the social expectations are essential when advancing new technologies for architecture.
Preface

Parts of this dissertation have appeared in previously published work, as summarized below.

- Parts of Chapter 4 are based on the material accepted for publication in:

- Parts of Chapter 5 are based on the material published in:
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# Nomenclature

## Acronyms

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<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>ACIS</td>
<td>Geometric modeling kernel developed by Spatial Corporation</td>
</tr>
<tr>
<td>AEC</td>
<td>Architectural-Engineering-Construction</td>
</tr>
<tr>
<td>BIM</td>
<td>Building Information Modeling</td>
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<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CAE</td>
<td>Computer Aided Engineering</td>
</tr>
<tr>
<td>CAM</td>
<td>Computer Aided Manufacturing</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
</tr>
<tr>
<td>FIS</td>
<td>Fuzzy Inference System</td>
</tr>
<tr>
<td>GCM</td>
<td>Global Climate Model</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation, and Air Conditioning</td>
</tr>
<tr>
<td>IAI</td>
<td>International Alliance for Interoperability</td>
</tr>
<tr>
<td>ICT</td>
<td>Information Communication Technologies</td>
</tr>
<tr>
<td>IFC</td>
<td>Industry Foundation Classes</td>
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<tr>
<td>IGES</td>
<td>Initial Graphics Exchange Specification</td>
</tr>
<tr>
<td>IM</td>
<td>Information Management</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro-Electro-Mechanical Systems</td>
</tr>
<tr>
<td>MIT</td>
<td>The Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time Between Failures</td>
</tr>
<tr>
<td>SAT</td>
<td>Standard ACIS Text</td>
</tr>
<tr>
<td>STEP</td>
<td>Standard for the Exchange of Product model data</td>
</tr>
<tr>
<td>PD</td>
<td>Proportional-Derivative</td>
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Syntax

‘ ’ Single quotation marks are used for emphasis
“ ” Double quotation marks are used for inline citations
## Glossary

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<td>Actinotherapy</td>
<td>Medical treatment by exposure to ultraviolet light.</td>
</tr>
<tr>
<td>Age of Enlightenment</td>
<td>A cultural movement, in the 17th and 18th centuries, aiming at reforming society using reason, challenging ideas grounded in tradition and faith, and advancing knowledge through the scientific method.</td>
</tr>
<tr>
<td>Age of Reason</td>
<td>Another term for the Age of Enlightenment.</td>
</tr>
<tr>
<td>Anthropogenic</td>
<td>Caused or produced by humans.</td>
</tr>
<tr>
<td>Anthropomorphism</td>
<td>Attribution of human form or other characteristics to anything other than a human being.</td>
</tr>
<tr>
<td>Antikythera mechanism</td>
<td>An ancient mechanical calculator for astronomical positions. Dated at 1st century BC, it was recovered from the Antikythera wreck in 1900–1901.</td>
</tr>
<tr>
<td>Building Information Modeling</td>
<td>A comprehensive and integrated set of digital tools for designing and maintaining buildings.</td>
</tr>
<tr>
<td>Classical antiquity</td>
<td>A period of cultural history centered on the Mediterranean Sea, comprising the interlocking civilizations of ancient Greece and ancient Rome.</td>
</tr>
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<td>Damocles</td>
<td>A character of a classical Greek anecdote referred to as ‘the Sword of Damocles,’ an expression for enjoying something while under a precariously dangling sword.</td>
</tr>
<tr>
<td>Edo period</td>
<td>A period in 17th to 19th century Japan characterized by strong economy, isolationist politics, and flourishing arts.</td>
</tr>
<tr>
<td>Heliotherapy</td>
<td>Medical treatment by exposure to light.</td>
</tr>
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<td>Impressionism</td>
<td>An art movement that originated in 1850-1860, thus coinciding with the commercialization of photography. Impressionists eschewed photorealistic depictions. Instead, they pursued the perception of light through synthesizing patterns of primary colors.</td>
</tr>
<tr>
<td>Kinematics</td>
<td>Geometrical analysis of motion.</td>
</tr>
<tr>
<td>Material culture</td>
<td>A product of anthropogenic activity.</td>
</tr>
<tr>
<td>Meridional</td>
<td>Along a meridian: in the north–south direction.</td>
</tr>
<tr>
<td>Parametric modeling</td>
<td>A fusion of geometrical and formulaic modeling.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>Psychotropic</td>
<td>Affecting mental activity, behavior, or perception: mood-altering.</td>
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<tr>
<td>Pueblo</td>
<td>Apartment-like structures built of stone, adobe mud, and other local material by Native Americans in the Southwestern US.</td>
</tr>
<tr>
<td>Reflexive archaeology</td>
<td>A trend in archaeology to acknowledge the subjectivity of the used methods and own presumptions, and to include such considerations in the record.</td>
</tr>
<tr>
<td>Tantalus</td>
<td>A Greek mythological figure, most famous for his eternal punishment: being in the immediate reach of the desired object and yet failing to grasp it.</td>
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Acknowledgements

First, I wish to thank the members of my supervisory committee for their advice, stewardship, encouragement, and for contributing the richness of their own experience to this interdisciplinary study.

In particular, my sincere gratitude and appreciation are extended to my Research Supervisor, Prof. Clarence W. de Silva, for his proactive attitude toward innovative ideas, his support and guidance, and helpful advice. I thank him for taking an active interest in my research, for his patience in reading and editing my latest publications, and for providing financial support for attending conferences.

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A big thank you to our department chair, Prof. Hillel Goelman for his patient guidance, for his emotional and financial support, and for the many opportunities to participate in the most exciting activities in our unique department, and;

I would also like to thank for detailed information and image permissions Theo Jansen, Christopher John Butler of the Armagh Observatory, Dan Grayber, Richard Wilson, Ion Sørvin of Studio N55, Michael Jantzen, Bertrand Roussel of Musée d'Archéologie de Nice, Fabio Tobler of Stadt Zürich, Lars Aronsson of Project Runeberg, Tiziano Casartelli of Fondo Angelo Invernizzi, Klaus Schmidt of German Archaeological Institute, Reinhard Junker and Marion Bernhardt of Studium Integrale Journal, Janne Jönsson of Landskrona Museum, and Nina Petersson of the Tycho Brahe Museum.
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On a personal note, I am thankful to my family, Ramunas and Ram Michael, who are unwavering in their trust, presence, and love.
Dedication

To my son Ram Michael
CHAPTER 1 Introduction

1.1 Motivation

Rigidly foldable enclosing structures embody the concept of transforming on demand from one stable form into another, thus presenting an exciting potential for expanding the traditional paradigms of built environments, shelters, and space management. The idea, physically defined entirely within the engineering domain of solving the kinematics of foldable geometries, was the seed of this study. Initially, such sterile demarcation created “a solution looking for a problem” (Schiffer, 2011), an orphaned state sustained solely in the theoretical domain of technological possibility. Like an artificially induced and unstable void, this demarcation created a pressure of questions, doubts, and possibilities that were building up outside the engineering domain: whether the idea was useful; whether it was viable and marketable; whether the entire effort was worthwhile. This thesis has embraced this instant of intellectual solace as an opportunity to explore processes, circumstances, and emotions involved in developing new technologies, and as a time for an introspection of the entire design and research effort. Such multi-dimensional narrative about an engineering concept immersed in the subjective realm of a designer’s cognition, social expectations, and cultural context has become the proper focus of the thesis. The gradually expanding horizon of this context revealed a rich interlinked and unbounded interdisciplinary landscape, in which “the human, material, and practices all undergo dynamic changes” (Ihde, 2008).

1.2 Engineering versus Architecture – The Evolving Paradigms

The concept of foldable structures links the two main themes of this thesis: engineering and architecture. While this most immediate interdependency continues to be the subject of vigorous academic discourse (Kroes et al., 2008), the millennia-old relationship between
the two professions has spanned the extremes of being both symbiotic and adversarial. Although they share the same goal of “production of our material environment,” they are currently affected by the long-standing “division of intellectual labour between the arts and sciences” (Jones, 2004) as well as by “the contractual situations or tender processes” (Knippers, 2013), and currently they are viewed as “quite different practices” (Kroes et al.). In particular, Davis (2008) noted a troubling estrangement of architectural work from “the activity of building” and the consequent decline of the “quality of the built environment.” Davis stressed that improvement could be achieved only through a comprehensive reform of the industry based on “breaking down the barriers between design and construction.” Knippers also indicated “significant potential for innovation” if the limitations of the “classical linear sequence of design” could be surmounted.

The purely theoretical framework of this investigation has enabled bypassing of the practical contractual divisions between the professions, and assuming, as needed, any of the differing perspectives. While thus transitioning between the architectural search for new paradigms for public spaces and the engineering challenge of constructing viable folding geometries, it became apparent that an abstract idea and a tool-technology form an inseparable, mutually influencing system unified by the common goal of developing a socially relevant solution.

1.3 A Human-Centered Perspective

The interdisciplinary context of this project has emphasized the challenge of assuming a suitable viewpoint, an intellectual perspective intended, according to Hautamäki, as a “way to conceptualise the world” (as cited in Liz, 2014). Liz argued that points of view form an integral part of academic inquiry, thus asserting the relativistic nature of knowledge as being continuously recast through different points of reference:

The sort of efficacies achieved when a point of view is adopted, in particular through our personal points of view, suggest that both the bearers of the points of view and the things that are under the perspective of the points of view can change in ways that cannot be forecast in advance.
Consequently, “points of view have to be aggregated to our scientific image of the world” (ibid.). Such notion was conducive for the introspective aspect of this thesis. Furthermore, it facilitated organizing the referential framework of disparate disciplines using a human-centered perspective. The point of view of the present investigation reflects the state of current knowledge, the “here and now” (Knights, 1994), as cast through a review of the referenced research.

Acknowledging the importance of social perspectives has provided the present investigation with a broad range of directions for reaching across disciplinary divides and for researching the historical evidence. Under any circumstances, developing a new idea-technology is a daunting, resource and time-consuming task yet further aggravated by its uncertain outcomes. Including the broader social context is instrumental in addressing the general concerns designers face throughout their work. What then are the factors that drive the development of new technologies? Why do some technologies succeed while others fail? Such questions are vital for both designers and decision-makers. Although many scholars agree that technologies are merely manifestations of social processes, the common view objectifies technologies as autonomous phenomena that are isolated from their social contexts (Dobres and Hoffman, 1994). According to Dobres and Hoffman, however, such an “artificial separation” plays the unsavory role of surrendering people to imposed technological changes while at the same time clearing decision-makers from responsibility for the results of these changes. Consequently, theorists and policy-makers tend to dismiss society’s ability to influence the technological progress, while instead promoting the advantages and impact of new technologies (ibid). Thomas (2004) commented that such “exclusions” are characteristic of modern societies experiencing the “erosion of established sources of social stability.” Pustovrh (2013) observed that indeed the weakened societies of the era of globalization are susceptible to “value and interest fragmentation.” He cautioned that “novel technologies imposed without societal deliberation or consent” are detrimental to “economic development and innovation.”

The present thesis builds upon the notions that technology is a “dynamic cultural phenomenon” (Dobres and Hoffman) and that its outcome, which is all material culture, is inseparable from its social context (Gamble, 2007). From this perspective, the “processes of innovation are certainly politically and socially charged” (Dobres and Hoffman), and the
outcomes of design processes “always have public consequences” (Pustovrh). Furthermore, “stable social environments” (Adolf et al., 2013), “societal co-operation and cohesion” (Pustovrh), “conscious and strategic decision making” and social support such as sponsorships, grants, and patronage (Dobres and Hoffman) are identified as the key enablers for the successful development and implementation of new technologies. An integral view of society, its culture, and its artifacts considers technology as “an arena for dynamic social interaction” (Dobres and Hoffman), thus positioning material culture as what Jones described as “a ‘boundary object’ having physical presence in both the past and the present.” Furthermore, Jones asserted the contributing role of archaeology, “as the study of material culture, whether in the past or present,” in understanding the “critical relationship between people and things,” the relationship, in which

Culture has become inextricably bound up with complex technological systems and environments. (Lister et al., 2009)

1.4 Kinetic Architecture

This thesis asserts that built environments are not, and never were, merely static shells demarcating habitable spaces, and that configurable and transient elements were always essential functional interfaces between rigid structures and the dynamics of human behaviors. The history of such elements is a narrative about the nature of human interaction with physical environment, about the primordial human behaviors, about the patterns of technological precedence, about the progress of built environments, and about evolving theories of architecture and material culture. Within this narrative, new kinetic technologies discussed by theorists and envisioned to combat obsolescence (Zuk and Clark, 1970), to optimize material use (Menges and Reichert (2012), and to reduce the environmental impact (BRE, 2006), are a contemporary response to the perpetual dynamics of the human condition and its material setting. For the designers of the future kinetic environments, the historical narrative establishes a comprehensive reference on human intentionality and technologies-archetypes, and most importantly, it “gives sense to the present” (Johnson, 1994).
1.5 Design Tools

In a remarkable case of symmetry, this contextual complexity is also reflected inside the design domain, since each aspect of the supposedly purely technical process of designing kinetic structures in fact is also cognitively-driven and culturally-influenced. The emergence of digital technologies has ended the millennia-long neutrality of design tools. The simplicity and universal availability of traditional hand drawing tools did not impose specific workflows or design methods. Digital tools, however, have exclusive design processes permanently embedded in them, since they are the expressions of the programmers’ choices and assumptions. These arbitrary programming choices are in turn imposed on designers through software structure and interfaces. Liebing (2011) noted that the programmers’ notion about what is intuitive is profoundly different from that of the designers’. According to Shelden and Witt (2011), such a cognitive gap is serious enough to "represent a crisis in the implementation" of digital technologies. Furthermore, digital tools embody marketing strategies and corporate goals. Proprietary formats, licenses, and upgrade policies have created digital ghettos of functional exclusions and imposed brand loyalties. Such market fragmentation is further aggravated by the inherent volatility of the software business: terms like ‘new releases,’ ‘updates,’ ‘patches,’ and ‘service packs’ are the linguistic evidence of software’s short lifecycles and rapid obsolescence. Ironically, instead of advancing their actual design skills, designers now must dedicate considerable effort just to learn new software. The development of digital tools is governed as much by available technologies as by economic and political choices, while the outcomes are uncertain and unpredictable. Consequently, digital tools have exposed architects to an unprecedented phenomenon of “continually evolving design environments” (Davis and Peters, 2013).

The history of digital tools reveals a complex landscape of competing ideas, corporate take-overs, and marketing strategies, where product features have been driven as much by arbitrary marketing assumptions as by user expectations. Although design tools have been evolving into totally integrated cross-disciplinary design environments like Building Information Modeling (BIM), their underlying structure remained analytic, parametrically driven, and for decades unchanged, thus “severely” limiting their usefulness
for design work (Bettig and Hoffmann, 2011). Cardoso Llach (2013) noted that the industry was primarily driven by a desire to “automate traditional drafting procedures.”

Yet at the same time, digital tools can empower designers. Peters (2013) pointed out an emerging trend whereby architects “create software” rather than merely using it. While building upon “advances in scripting interfaces” (Davis and Peters) and the now universally available Application Programming Interfaces (API), the “creation of the design environment is itself becoming the domain of the designer” (ibid.). In fact, since off-the-shelf parametrics are “useful only to a very limited extent,” developing customized tools tailored to the specifics of each project is becoming increasingly important (Knippers). Furthermore, algorithmic parameter-based form generation is no longer the “most expedient use” of computing (Berkel, 2013). Instead, the “post-parametric” tools must aim at evaluating “designed spaces from an occupant’s perspective” (Derix and Izaki, 2013). According to van Berkel, computational tools must overcome “the inability to individually translate or quantify” such behavioral and perceptive criteria. He outlined a concept of informational networks spanning “social, economic, political and material” contexts. Such “Knowledge Platforms” could form dynamic links “between practice and research” (ibid.), thus enabling “cogeneration” of architecture and functional programs “from a human-centric perspective” (Derix and Izaki). Similarly, Shelden (2013) theorized a new architectural paradigm as an “interwoven fabric of spatial and epistemic structures” where technologies of construction and communication intersect with “digital knowledge.” Consequently, the yet-to-be-conceived computational design tools, the “cloud-based information stores connected to people, places and artefacts through portals, devices and other digital–physical transponders,” (ibid.) would be able to instance a desired optimal solution from such virtual domain of unlimited possibilities. By aiming at customization, cross-platform interoperability, transcending the traditional design strategies, and inclusion of broader non-quantitative criteria, the present research effort complements the proprietary and brand-driven side of digital tools. Ultimately, the digital era has imposed significant new challenges on designers, as besides tackling design problems, they must also consider software and its customization, and most importantly, they must engage in the collaborative process of negotiating future architectural paradigms.
Knippers observed that even for designing more elaborate static shapes, “off-the-shelf programs are not available or not satisfactory.” Consequently, the core problem of this thesis – the design of rigidly foldable structures – adds yet another challenge, how to solve the motion of complex geometries. Formulaic descriptions of the kinematics of freeform foldable geometries, even if available, are too cumbersome to be practical in designing such structures. This problem is further aggravated by the intrinsically analytic nature of parametric digital tools, which are formula- and explicit data-driven. Designers are therefore subjugated to an analytic, bottom-up approach, which confines them to abstract and unintuitive representations in “an excruciatingly descriptive process” (Dritsas and Yeo, 2013), a situation which impedes a tangible engagement with the initial idea. Taking up the analytic parametric approach entails an arduous and blind scripting procedure, in which “foldability” and the final shape cannot initially be estimated. Furthermore, such parametric dependencies tend to be inscrutable (Scheurer and Stehling, 2011), thus making any adjustments unpredictable. As we are intimately familiar with our physical world and, without involving too much theory, we can anticipate the behavior of common structures and mechanisms. Architects and engineers further extend this intuitive comprehension through educated abstractions. Unfortunately “the lack of intuitive content” in parametric models (Picon, 2011) prevents designers from utilizing the vast potential of their trained cognition when editing digital models.

### 1.6 Human Reasoning and Parametric Modeling

The present thesis proposes novel means for engaging intuitive and experiential human knowledge with the analytic domain of typical parametric modelers. Such a synergetic link between human reasoning and the computational capacity of digital tools would allow designers to focus on the design intent instead of being sidetracked into its algorithmic deconstruction. This intent-driven approach aims to address “the impoverishing effects of computation on the design process” (Lostritto and Vardouli, 2012). The method for solving the fundamental issue of encoding a natural human intent in the digital domain came from the engineering discipline itself. Soft computing and in particular fuzzy logic excel in reasoning with human knowledge (Karray and de Silva, 2004). Furthermore, recent
advances in intuitionistic fuzzy logic have provided tools for capturing such subtle traits of the human mind as hesitation and contradiction (Montiel and Castillo, 2007). The cognitive formation of an initial concept involves multilayered and often vague analogies, which are continuously reinterpreted and refined in designer’s mind (Lostritto and Vardouli). Since such model is highly unstructured from an analytic perspective, the crisp and explicit interfaces of typical digital workflows discard most of the rich but vague references. This makes the initial design input a severely truncated and distorted approximation of the original idea. Such simplistic coding of a design intent provides little margin for meaningful design elaboration and adjustments once inside the digital workflow unless a designer reconfigures the inputs using an incidental recollection of the initial idea. The method for capturing accurately the loosely structured human expression of an initial concept, as proposed in the present thesis, can provide a more gradual transition between a designer’s cognition and the analytic domain of a parametric model. Furthermore, this method can be used for reasoning with the kinematics of a folding shape, whereby intuitive human conjectures provide inputs for inferring adjustments to its geometry.

1.7 Contributions and Structure of the Thesis

This thesis is an exploration of the design process of flexible built environments. An engineering problem, which is the seed of this design process, establishes a dynamic link between a broad external context of socio-cultural drivers of new ideas-technologies, and a network of internal design processes involving design paradigms, design technologies, and human cognition. The detailed survey of both external and internal contexts, as carried out in the present thesis, has revealed gaps in the current state of knowledge, thus identifying the areas of interest and contributions of the present investigation: an understanding of the evolving paradigms of built environments, the history of kinetic architectural elements, concepts of rigidly foldable structures, the cognition-driven designing of folding geometries, and the history of digital design tools.

The structure of the thesis reflects the interdisciplinary character of the project and it follows the specific areas of interest as listed above. Detailed literature survey, theoretical framework, and methodologies are provided within the chapters as appropriate.
Chapter 2 examines the concept of kinetic architecture as a co-evolution of a theoretical idea, intellectual whimsy, and avant-garde experimentation. The potential advantages, design and implementation challenges, and most recent advances in kinetic architecture are discussed.

Chapter 3 presents an original historical analysis of kinetic architectural elements in the context of relevant architectural theories, evolving theories of technology and material culture, and a modern understanding of built environments.

Chapter 4 focuses on the concept of rigidly foldable structures and their potential advantages. Novel concepts, design methods, and challenges of modeling kinematics are discussed.

Chapter 5 discusses digital design tools. Analyzed is the history of digital design tools, their current state, and future trends. The novel concept of interfacing human reasoning with parametric modelers, as proposed in the thesis, is described.

Chapter 6 presents results of computational simulations using the design tools and concepts proposed and developed in the thesis, related to practical applications of folding structures.

Chapter 7 discusses the main contributions of the thesis and outlines future directions for research.
CHAPTER 2 Kinetic Architecture: The Vision

Yesterday’s dreams are today’s intentions; they will define tomorrow’s reality. This chapter seeks clues and directions on built environments of the future in our material culture, in art, and in social theories. Understanding the universal drivers of human behavior is used here to frame the cognitive perspective. The present discussion of kinetic art and conceptual projects explores the changing perception and cognition of mechanically-driven motion and human-machine relationship. The impact of digital technologies on architectural profession is examined to seek answers regarding future design paradigms, design methods, and the current challenges.

2.1 Cognitive Perspective

Inanimate physical objects can be characterized by their defiance of time; they are immutable and permanent, at least on the scale of human life. As such, they are the indifferent time travelers bearing the scars of the past, they are the enduring witnesses to history. Human interaction with the physical realm yields artifacts, a domain of intentionally altered or crafted objects which institute our “material culture” (Miller, 2007). Built environments are the most prominent feature of a material culture. According to Knights (1994), this Heideggerian “dimension of dwelling” creates momentary vantage points of “the ‘here and now’, built for the reconnaissance of the ‘everywhere and always.’” Knights’ concept of the “everywhere and always” ascertains the continuity between the past and the future. From a cognitive perspective, material culture becomes a temporal cusp where ambiguous interpretations of the past intersect with uncertain possibilities of the future, thus continually reconstructing a relative clarity of the present.

Besides being the most conspicuous manifestation of human culture, architecture also fulfills a profound symbolic role:
Architecture is a specially powerful mode of external symbolic storage, for the built environment actually constitutes our way of living, makes concrete our social institutions, frames our perceptions and forms the arena within which social and other relations are played out. (Watkins, 2004)

Gamble used Merleau-Ponty’s conjecture that “the body is our general medium for having a world” for recapping the relationship between humans and their built environments:

The house is a material metaphor that all agree upon. . . . The house is a body for the body. (2007)

Built environments are the records of social practices, they are “theatres of memory” conveying our culture (Watkins) through tangible spatial practices of our bodies (Gamble).

Yet, according to researchers, architects tend to ignore both history and behavioral context in their work. Their historical consideration is limited merely to the latest trends:

Architects obviously believe in the importance of architecture, but are mostly concerned with contemporary or recent Western architecture in their writings. (Watkins)

As for social action, it is left out almost entirely:

The notion that people’s experience of space derives from their bodies was something that most practising architects had just not considered let alone been taught. Consequently, architectural drawings are ‘peopled’ by a de-sensitised, schematically drawn modular-man, while in a further striking parallel with archaeology, architecture journalism is full of pictures of buildings with no one in them. (Gamble)

The key goal of this thesis is to theorize architecture that is increasingly kinetic and interactive, while considering how such architecture might alter the dynamic system of society and its material culture. Yet, one needs to realize that first and foremost, a built environment (one that is synthesized rather than naturally created) must meet the specific purpose and needs while incorporating reasonable considerations of comfort and mental satisfaction, within such constraints as cost, available space and time. To understand the nature of interaction in a human-material culture, we need to ask about the primordial drivers of human behavior. Podborský and Kovárník (2006) identified the “spontaneous wish to protect oneself against the dangers of the surrounding world” as one of such drivers. These dangers can be “real or imagined” (ibid.), thus reaffirming the tentative
distinction between the actual and the perceived (Renfrew, 1998). Seeking protection from
dangers is driven by fear. Fear, according to Panksepp and Biven (2012), was “handed
down as evolutionary memories,” emotional and behavioral responses that facilitated our
survival, like for instance fear of the dark (Smail, 2008). Fear is also essential in memory
formation (Coolodge and Wynn, 2009), thus establishing the important self-enforcing
mechanism of fear-and-response. Another important driver, and, according to Dunbar
(1996), the primary purpose of human mind, is social interaction. Socializing is
accomplished through communication between individuals (ibid.). Communicating to
establish social hierarchies, to assert one’s position, to gain a group support, or to influence
a group, is a timeless concept and it consumes a “very substantial amount of time”
(Dunbar, 2004). Smail noted that communication fulfills also an important psychotropic
need. We socialize, chat, and gossip because we enjoy it (ibid.). The universal desire to
engage in activities that improve our mood (ibid.) is yet another key driver of our
behaviors. Thus, we need to acknowledge the prominent role of entertainment:

Enthrallment is among the most enduring responses to the
physical universe. (Stafford, 2001)

In conclusion, the baseline for human behavior remained unchanged throughout the known
history of humankind: we seek shelter, security, social acceptance, and we engage in
activities improving our mood.

What kept changing, however, were the methods and the efficiency of
accomplishing our primordial objectives. According to Dunbar (1995), the growing
demands of maintaining social structures drove the evolutionary development of our brain
and the emergence of language as a more efficient method of social interaction than
grooming. More important for the present thesis, however, is the idea that the “human
mind and human culture have co-evolved (Watkins). While moving away from hunting-
gathering towards sedentary settlements, humans faced “novel social situations” (ibid.).
Built environments became the “structuring devices” of the increasingly complex social
groups and their interactions/interrelations:

By means of architecture, they constituted not only frameworks
for the social life of the community and its constituent families
or households but also “theatres of memory” in which the
history of the community, its inhabitants and former inhabitants, and much else was recorded, retained and transmitted. (ibid.)

Contemporary built environments still fulfill such “structuring” role:

Class hierarchies are continuously reproduced through the structure of domestic housing. (Parker Pearson and Richards, 1994)

However, technologies of globalization are posing new challenges undermining the traditional significance of architecture. Local symbolic and historic values are threatened:

International styles destroy concepts of place and local community. (ibid.)

Modern transportation technologies such as cars and airplanes brought back a pronounced nomadic component in our lives as we spent a significant amount of time on the road or in transitional “non-places” (Augé, 2000). However, they too primarily represent environments. Furthermore, technologies of connectivity have intersected traditional physical spaces with a much larger virtual domain of geographically unbound social chatter (Renò, 2005), thus resulting in “zombification” (Codrescu, 1994) of inhabitants, who, although physically present, are socially divorced from the behavioral setting of a place. What role will kinetic architecture play in negotiating such challenges? Will it strengthen the role of urban centers? Will it provide better conditions for inhabitants? Or, will it be merely another technology of social efficiency at the service of arbitrary economic indicators? According to Gamble,

the study of past technology requires a simultaneous concern with social interaction, the practical knowledge of techniques and the environment as well as belief systems.

The present thesis proposes that Gamble’s argument is universal and applies equally to the past and the future. We are surrounded by artifacts that were a part of the past and will be integrated into the future. From this perspective of material and cultural continuity, which is the Knights’ “everywhere and always”, the concepts of the past and the future become interchangeable: can we tell the differences between vagueness of the past and uncertainty of the future, or between forgetting and not knowing yet? Therefore Gamble’s “simultaneous concern” with the social, the knowledge, the environment, and the beliefs is equally important for considering the future. Furthermore, this concern can be the guiding
reference for designers, who, simply by the nature of their work, are already beyond the present while fashioning artifacts of the future.

Although the environmental and cultural circumstances change, the principal need for shelter, the atavistic drive to socialize, and the self-serving craving to feel good remain the same. This seemingly simple notion is effective when analyzing the technologies of today. For instance, the BlackBerry smartphone, although supported by superior encryption and a secure server system, has yielded to the iPhone. The abstract or advanced technical specifications were not enough to compete with the fusion of easy casual interacting and the ‘enthrallment’ of multimedia. New technologies will be used to bridge the growing gap between the emotional, the physical, and the cultural. Presently, smartphones are instrumental in supporting socialization on the go, while texting is far more efficient, although perhaps much less effective, than grooming or talking. Conceivably, interactive environments and kinetic architecture could be the embedded means of providing physical and emotional comfort and satisfaction, under the demanding conditions of overpopulation and climatic instability, if faced with catastrophic depopulation, or when colonizing remote areas.

2.2 The Kinetic Dream

Art short-circuits our trained inhibitions and exposes us to raw concepts-ontologies. According to Podro, artistic interpretations circumvent the constraints of structured reasoning:

Such transcendence is an extension of the independence of the imagination in the following sense: that we imagine how the world might look from a more comprehensive perspective than we ourselves can ever obtain, because of the necessary limitations of knowledge. (2003).

Thomson acknowledged art as the enabler of social introspection:

In sum, great art works by selectively focusing an historical community's tacit sense of what is and what matters and reflecting it back to that community, which thereby comes implicitly to understand itself in the light of this artwork. (2011)
Although the research community is divided about the value of “fictional models” (Magnani, 2012), even their opponents admit the rising sense that the distinction between the scientific and the fictional is tentative:

A growing number of philosophers adopt the view that scientific models are much related to works of fiction; some use this observation to support the view that to understand what models are and how they function we would gain much by treating them as works of fiction. (Portides, 2014)

For the present thesis, works of art are the means of “thinking through doing” (Magnani); they are the conceptual models, very much like their scientific equivalents, that are useful to discover new knowledge just because they do not – or scarcely – resemble the target system to be studied, and are instead built to the aim of finding a new general capacity to make “the world intelligible.” (ibid.)

Ultimately, they are the opportunities for trans-disciplinary exploration of human perception, comprehension, and cultural significance of movement.

Two perspectives dominate kinetic art: one blurs the distinction between movement and life, the other liberates motion from any constraints of function or purpose. The first view considers movement as an inherent trait of life, as the means of bringing inanimate objects to life, and as the crux of mechanically-driven genesis. Its followers strive to achieve life-like effect while sparing no effort in hiding the clockwork underpinnings. The goals have been changing over time. In antiquity, the clockwork mimicry of the natural was most helpful in instilling the regard for the divine:

While the ancient theurgical system of wisdom claimed to have direct commerce with the gods, it actually depended on priests to operate craftily behind the scenes. (Stafford, 2001)

Later, during the Renaissance and the Age of Enlightenment, it became the standard of the utmost artisanship and a tool of marketing (Metzner, 1998; Stafford). However, human-like walking proved to be beyond the possibilities of clockwork technology. Only the fusion of mechanics and electronics has opened new directions for the robotic mimicry of life: autonomous walking and facial articulation. The mimicry category still remains the measure of technological status although individual credits for engineering brilliance have been surrendered to the prestige of corporate brands. Regardless of the epoch, the works of
mechanized mimicry were faithful reflections of social idiosyncrasies while its mechanisms, although meticulously hidden away, were the masterpieces of technological ingenuity and dedicated craftsmanship. Voskuhl reflected on their timeless power to unsettle our understanding of technology:

Because androids so effectively destabilize our sense of the boundary between humans and machines and, by extension, our sense of our own constitution, they and their histories evoke a broad range of concerns, most significantly, perhaps, those related to the promises and perils of the modern industrial age. (2013)

If ‘movement is the purpose’ could be a fitting motto for the first group, then ‘movement needs no purpose’ seems to be the guiding principle for the other one. Similarly to Impressionism and the ensuing ideological and functional repurposing of visual arts caused by the emergence of photography, this deliverance of kinetic art emerged after the commercialization of electricity, and after the traditional mystique of clockwork had yielded to the inscrutable prospects of electronics. Followers of the second view epitomize an intellectual fascination, sometimes perhaps an obsession, with the nature of mechanisms and their kinematics. Practitioners of this mechanical ‘expressionism’ breach functional and engineering conventions while exploiting the primordial properties of materials and quirks of mechanical interactions. The results tend to challenge our understanding of mechanical cause-and-effect considerations (the causality) (de Silva, 2009) and the traditional sense of purpose, they destabilize our trust in the learned canons of physics. The executions range from crude assemblages exuding a sense of perpetual work-in-progress to sleek, jewel-like finished pieces, thus affirming the unconstrained and exploratory approach of their creators. Regardless their aesthetics, these creations firmly eschew all covers, shields, or enclosures, thus prominently displaying their mechanical viscera. In effect, they fulfill our childish atavism that was acutely exacerbated while studying the sleek illusions of the first group: to tear it apart and see how it works.

The art of illusion is essential for both groups, and so is enthrallment, this “most enduring” reaction to what we see (Stafford). However, the principle of the effect is different: the ‘how’ is elusive in the first case because it is hidden, while in the other group the ‘how’ is incomprehensible although it is in plain view.
2.2.1 History

What exactly are the reasons that we humans have become so adept in symbolic representation? A circle for the Sun, a line for a boundary, a toy car for a roadster, a banknote for gold, a dollar sign for cash, and a medal for appreciation – these are some of the countless and well familiar metaphors of the actual. Perhaps the economy of effort plays a role – it is simpler to make a symbol, it is more convenient and safer to use it. Symbols invoke the actual in a typified and accessible way. Most importantly, symbols have the capacity to breach the impossibility. Not bound by the constraints of the physical world, they are the effector of our imagination. According to Stafford, they are, or at least they were, “a vast river of dead devices intended to make the divide between the human world and the divine disappear.” Renfrew (1998) noted the effectiveness of symbols: “the perceived reality, is as powerful as . . . the real, physical reality,” while Lister et al. acknowledged our propensity to defy the distinction between the virtual and the real:

We routinely discuss signs apart from what they are signs of, representations apart from what they represent, meanings apart from matter, and ideologies that mask realities, so that the world we inhabit now seems to be composed exclusively of linguistic, textual or interpretative acts. (2009)

Yet, in a Tantalian way, symbols leave out the sensory experience. On the one side, the cultural development of mankind would have not been possible without such “external symbolic technologies” and “evocative devices” as art and architecture (Donald, 1998a). On the other, symbols induce the longing for the tangible and the literal. As if the acquired over the millions of years language of metaphors was only an intermediate phase while pursuing the ultimate goal: the skill of genesis, the art of materializing metaphors. As if such symmetry, a complete cycle, of reflecting the real in a mirror of symbolic representation, in which only our mind limits the possibilities, and then materializing these visions back in the physical reality, is the ultimate and natural purpose of Donaldian (1998b) “symbiosis” with our own material culture. Hence the eternal dream of a symbolic depiction becoming the actual: an unanimated object gaining the temporal dimension of life, or at least an illusion of life – the effect of motion. If a symbol is the metaphor for an entity then movement is the metaphor for life. Therefore adding kinetics results in a layered symbolic representation, a recursive metaphor, a mirage of creation.
The history of the kinetic dream traces artistic exploration of the conceptual dichotomy between the real and the symbolic. Writers, poets, painters, and sculptors, the prodigies of the most evocative symbolic genres, they are the creators of metaphors that take us beyond the known or possible into the boundless realms of their imaginations. Yet at the same time, they were often tempted by the impossible and challenged the boundaries separating the virtual from the actual. They used their exceptional craftsmanship to bring their creations to life by overlaying levels of the symbolic make-pretend or employing inventive technologies-illusions, thus weaving a historical continuity for our fascination with artificial life:

We would like to build models that are so life-like that they cease to be models of life and become examples of life themselves. (Langton, 1986)

The Antikythera mechanism, dated to 1st century BC and most likely used for navigation, showcases an impressive level of Hellenic technology (Figure 2.1).

![Figure 2.1 The Antikythera mechanism, 1st century BC, The National Archaeological Museum in Athens (Photo by Marsyas; used under a CC BY-SA license; source http://en.wikipedia.org/wiki/Antikythera_mechanism)](http://en.wikipedia.org/wiki/Antikythera_mechanism)

Ironically, little is known about this fascinating artifact. On the other hand, surviving are detailed records about automatons employed in temples to amaze the public (Schmidt, 1899), although no physical evidence has been found. Nevertheless, the most inspiring account of bringing to life the inanimate, of “the exhilarating limitless of human creative power, and of the deeply erotic and even transcendent possibilities of art” (Hyman, 2011), is the tale about Pygmalion, a sculptor who had fallen in love with a statue he fashioned. Answering his prayers, the goddess Venus brought the statue to life thus involving the divine to breach the constraints of the symbolic-corporal divide. This
charming and timeless tribute to the epoch of classical beauty and to the love of a perfect form, written by a Hellenic writer Philostephanus, was echoed by many later.

The Renaissance, the human-centric era when a man was meant to be perfect and the perfect man was to be the measure of the universe, delivered a fitting take on kinetics. Leonardo da Vinci’s mechanical knight employed actuation modeled on the artist’s intimate understanding of human body’s skeletal structure and musculature. The mechanical knight is believed to have been able to sit down, move its arms, and turn its head. Such a synthesis of anatomy and engineering (Figure 2.2) embodied the Renaissance’s ideal of all-encompassing approach toward knowledge.

![Figure 2.2 Leonardo da Vinci, mechanical knight, reconstruction on display at the Leonardo: Mensch – Erfinder – Genie exhibition, Berlin 2005 (Photo by Erik Möller; used under a CC0 license; source http://en.wikipedia.org/wiki/Leonardo’s_robot).](image)

The Age of Enlightenment had objectified the sciences. The Newtonian notion that empirical facts alone were the source of all knowledge had established scientific realism ruled by the logic of observable cause and effect. Consequently, the universe was seen as a deterministic and perfectly predictable system, much like a rigid mechanism. Conspicuously, the Newtonian paradigm of human knowledge was a reflection of the principal technology of the day, precision clockwork:

> Teleological explanations of natural phenomena fell into disrepute in the sixteenth and seventeenth centuries – the dawn of the modern period. This period witnessed such a great
increase in clockwork technologies that it sought to explain the world as a clockwork phenomenon (Lister et al.)

Such unequivocal submission to the observable and the explainable also influenced the perception of life. Even the emotional side of the Age of Enlightenment, “the very ideal of sentimentality . . . was a very conscious strategy” (Cullhed, 2010). Consequently, the human body, its mind and emotions were seen as merely complex mechanisms that could be fashioned by a virtuoso watchmaker much like the apt Hoffmannian literary incarnations of Doctor Coppélius or Herr Drosselmeyer. As if taking such fancy most seriously, or perhaps just commercializing on the general fascination with the subject, the watchmaking elite of the Age of Enlightenment constructed dolls that could write, draw, or play an instrument. Although these automatons acted merely a repetitious illusion of a life-like behavior, they were the crowning technological feats of the time that also embodied the essence of the Enlightenment’s analytical approach toward both knowledge and emotions – the explicit determinism of clockwork cause-and-effect.

According to Stafford, Jacques de Vaucanson was the first to launch a new genre of automatons:

His elegantly dressed, coiffed, and rouged androids were a far cry from Leonardo da Vinci’s stiff, clanking knight illustrated in the Codex Atlanticus. (2001)

His first such creation, the flutist, had most of the mechanism concealed in a large base, which provided the added benefit of stability (de Silva, 2014). It quickly became a popular attraction and it assured a “commercial success” for Vaucanson (Stafford). In 1760, von Knauss constructed the first writing automaton. Again, the body of the doll-writer was merely a puppet as the bulky mechanism was hidden away in an elaborate base.

A decade later, Pierre Jaquet-Droz, Henri-Louis Jaquet-Droz, and Jean-Frédéric Leschot constructed arguably the most famous automatons, three life-sized dolls: the musician, the draughtsman, and the writer. The draughtsman and the writer were the first automatons to transcend the stigma of being a puppet. Thanks to compact spring-driven actuation (de Silva, 2007) they had their entire mechanics neatly integrated into their bodies. However, the much more elaborate torso articulation of the lady-musician resulted in a larger mechanism that had to be stowed in the seat below. The complex articulation conveyed cunningly the Enlightenment’s mannerism of manifesting emotional experiences...
through stylized body gestures. Regarding the purpose of such a significant project, Metzner acknowledged it as “frankly commercial.” After the publicity following showings of their automatons, Jaquet-Drozes established a global distribution network for their watches (ibid).

Figure 2.3 Left: The musician and the writer, Musée d'art et d'histoire de Neuchâtel (Photo by Rama; used under a CC BY-SA license; source http://en.wikipedia.org/wiki/Jaquet-Droz_automata); Right: A karakuri automaton, circa 1800, the British Museum (Photo by Phgcom; used under a CC BY-SA license; source http://en.wikipedia.org/wiki/Karakuri_ningy%C5%8D)

The Enlightenment’s automatons were exclusively the devices of spectacle: the minutiously detailed lifelike characters were entirely absorbed in narcissistic renderings of wound-up clockwork routines (Figure 2.3 left). In contrast, the distinctly stylized karakuri mechanical dolls, the Japanese contemporaries of Drozes’ androids, were the devices of social ritual and interaction (Figure 2.3 right):

When the host, seated opposite his guest, places a cut of tea in the doll's hands, it carries the cup of tea to the guest. The guest takes the cup from the doll, and it stops. After drinking the tea, the guest sets the cup back in the doll's hands. It turns around and returns to the host with the empty cup. (Kurokawa, 1994)

Karakuri, mechanically much simpler than the Swiss clockwork marvels, were also easier to manufacture; they were a popular treat during the Edo period (17th to 19th century).
Besides being used as the sociable tea-serving dolls, karakuri were also employed as the means of ‘enthrallment’:

In the same period, the automated-puppet plays of Takeda Ominoshōjo were popular in Osaka (..), and the master carpenter Hasegawa Kambei invented various mechanical stage devices for the Kabuki theater and introduced a new level of spectacle and excitement to the popular stage. (ibid.)

The general popularity and availability of karakuri distinguished them from the singular European masterpieces. Karakuri thus embodied, according to Kurokawa, the “symbiosis of mankind and technology.”

The Automaton Chess Player (Figure 2.4), created by von Kempelen in 1770, combined the finesse of mechanics with an elaborate illusion to conceal an actual human chess master. The hoax of the clockwork mind was a curious artifact of the Age of Reason and its assertion that all could be rationally, that is mechanically, explained. Many luminaries of the era played a game with the automaton. Reportedly, although many of them suspected a hoax, they enjoyed the experience thus proving the allure of blurring the boundary between the real and the metaphor. Although Lister et al. noted that “automata gradually fell from scientific and philosophical grace” at the beginning of the nineteenth century, they also acknowledged the timeless bond between technology and the obsessive quest for the ultimate illusion, that of artificial life.

Figure 2.4 Wolfgang von Kempelen, the Mechanical Turk, 1770 (Windisch, 1784; reproduction by John Overholt; used under a CC BY-SA license; source http://www.flickr.com/photos/catablogger/6080827214/)
Similarly to the Hellenic tale about Pygmalion, it is the literary work that provided a more insightful, imaginative, and visceral rendering of social implications of artificial life. In Hofmann’s short story ‘Der Sandmann,’ the young hero Nathaniel is caught in the midst of a nasty authorship dispute between the creators of a gorgeous lady-android Olympia, the subject of Nathaniel’s affection. Olympia gets destroyed by the feuding makers, while Nathaniel loses his sanity. The story reveals a tragic collision between the creators’ heartless obsession with intellectual rights and the social implications of their work. Furthermore, it raises the ethical issue of destroying artificial life. It is a farsighted allegory for modern conflicts between corporate doctrines, individual authorship, and the rights of the public.

2.2.2 Contemporary Artists

Modernism coincided with proliferation and commercialization of electricity. Such conspicuous chronology was not a mere chance as the theory of electricity marked a defining shift from the Newtonian physics of forces to the physics of energy and its novel concepts of thermodynamics and entropy. This new knowledge became a subject of artistic exploration while new, electricity-driven technologies were used as interpretative media (Clarke and Henderson, 2002). The creative pursuit of kinetics expanded to include an abstract dimension and to challenge intuitive notions of time, causality, and purpose. The new generation of artists eschewed anthropomorphism and mimicry. Instead, they explored the philosophical and perceptual concepts of motion.

Duchamp’s Rotary Glass Plates, constructed in 1920, comprised co-axially mounted strips of patterned glass that, when set in motion, appeared to be a solid disk streaked with concentric circles (Figure 2.5). Such mechanic image synthesis demonstrated the interplay between the physical and the virtual realms, resulting from the physiology of human vision.

An illusion machine may be a suitable term for the constructed by Moholy-Nagy in 1930 Light Prop for an Electric Stage. The apparatus, later dubbed the Light-Space Modulator, used an assembly of actuated screens and filters to project animated patterns of light and shadow onto the surrounding environment. Although the light effects were the supposed goal, the device itself became the center of attention as a showpiece of
impeccable craftsmanship and jewel-like finishing. Perhaps if not for the expressive beauty of its mechanics, the Light-Space Modulator might have faded away as merely a theatrical projector – an effect appliance. But Moholy-Nagy’s cult-like worship of the mechanics drew the attention to the act of effect synthesis. The tangible precision of the opto-mechanical machinery counterpoints the ephemeral and immaterial spectacle of reflections. Yet the unbreachable literal-immaterial dichotomy only becomes more obvious when referenced against the allure of the sleek mechanism.

Figure 2.5 Marcel Duchamp, Rotary Glass Plates, 1920, the Yale University Art Gallery, gift of Collection Société Anonyme (Photos courtesy of the Yale University Art Gallery)

In 1954 and later, Jean Tinguely constructed Méta-matics, simple drawing devices having their crude pulley-and-belt viscera exposed in plain view (Figure 2.6). By being algorithmic image generators, they were conceptual cousins of the Enlightenment’s drawing automatons. However, whereas the earlier automatons strived to achieve a mechanically perfect duplication of an encoded pattern, Tinguely’s machines exploited the unpredictability of composite oscillatory motion combined with the chatter of intentionally loose assemblies:

Tinguely discovered an almost inexhaustible source – a mechanism whose goal was not precision but anti-precision, the mechanics of chance. (Hultén, 1975)

Consequently, the Méta-matics embodied mechanical spontaneity rather than clockwork mannerism of the Age of Enlightenment.
Although intended as a satirical dare to industrialism, Tinguely’s Homage to New York demonstrated, perhaps unintentionally, principles of entropy, instability and system failure. The installation was expected to completely self-destruct in front of an audience. However, the kinetic mayhem stopped half-way. In an ironic twist of fate, a mechanical failure was the key to the sculpture’s partial survival. In the Homage to New York, Tinguely employed kinetics to stage a singular event exploring the uniqueness and irreversibility of a temporal experience. This exercise in intentional destruction signifies that it may be much easier to conceptualize an act of mechanical suicide than an act of autonomous creation. While one can readily stage clockwork entropy, genesis remains for now only a subject of metaphors.

Schöffer’s cybernetic sculpture CYSP 1, built in 1956, employed cutting-edge electronics of the day to detect ambient conditions and control accordingly the motion of its actuated appendices. Strangely, CYSP’s technological overkill has not aged well. As if our psychology of perception worked against its electronic complexity. Although we are aware of the possibilities of electronics, its processes remain intangible thus severing the perceptual integrity of cause and effect. Consequently, we simply consume the practical outcomes of electronics while short-circuiting any reflections about its amazing performance or about the quantum phenomena underlying its functioning. Schöffer’s mechatronic concepts fall short of the expressive energy of later, technically modest but
conceptually unsettling experiments like Ganson’s gear assembly rammed into a concrete block, or Jansen’s wandering wind creatures.

Arthur Ganson’s Machine with 11 Scraps of Paper morphs rigid mechanical motion into organic butterfly-like quiver (Figure 2.7), as if the artist possessed the secret of enlivening the oily metal of clockwork. It is a metaphor for two incompatible realms locked in a coupled system of effort-and-effect (causality): the immaterial flight of delicate winglets continues only for as long as the banal assemblage of gears below remains laboring busily, thus supplying the winglets with the potion of life.

![Figure 2.7 Arthur Ganson, Machine with 11 Scraps of Paper, The MIT Museum, Cambridge, MA (Photo © Madalina N. Wierzbicki)](image)

![Figure 2.8 Arthur Ganson, Machine with Concrete, The MIT Museum, Cambridge, MA (Photo © Madalina N. Wierzbicki)](image)
Ganson’s Machines with Concrete can be viewed as allegories of a cosmic scale. The machine on display at the MIT Museum in Cambridge, MA is the simplest of all: a straightforward train of spur gears has its output encased in a block of concrete (Figure 2.8). Although its electrical motor has been continuously whirling the input gear for many years, the tangible and in plain view determinism of gear ratio ascertains no discernible effects of preload for at least another few billion years. Both obvious and incomprehensible, this simple gear train challenges our intuitive understanding of rigid mechanics or the rigor of cause-and-effect. The blunt collision of clockwork motion with the austere stillness of concrete epitomizes the alienation of computational abstractions from the longing for tangible perception realm of human cognition.

![Figure 2.9 Theo Jansen, Animaris Percipiere, IJmuiden, The Netherlands, 2005 (Photo by Loek van der Klis; courtesy of Theo Jansen)](image)

Theo Jansen populated North Sea beaches with autonomous wind mechanisms. Comprising skeletal structures executed in cheap plastic tubing, plastic sheet flaps, and simple yet cunning kinematics, they are capable of harnessing and storing wind energy. Some of them can detect water and back away from it, others can cling to the ground when a storm is nearing. They are a compelling implementation of artificial instinct achieved purely through mechanical means. Uncanny in their enigmatic purposes and fascinating in the complexity of their movements-behaviors, they roam the sands only to assert their strange presence (Figure 2.9). The see-through, nothing-to-hide lightweight tubular
structures and the organic, unobtrusive source of energy make the creations look creepily autonomous and self-directed. By shunning any practical purpose or mimicry, and relying instead solely on the spontaneity of physical interaction with the elements, Jansen came closer to realizing the dream of mechanical genesis than the artisans of either the Renaissance or the Age of Enlightenment.

The purpose of Dan Grayber’s mechanisms is similar to that of Jansen’s: their sole function is to manifest their presence. However, although kinetic, they accomplish this function while remaining completely still (Figure 2.10). They are the meticulous study of an act of clinging. While remaining in precarious positions between vertical surfaces, they remind us of insects tirelessly stuck to surfaces in gravity-defying positions. These clinging devices induce a strange feeling of emotional anxiety as if they would let go the instant we stopped watching them. Dan Grayber has tapped into a strange quirk of our cognition where the perfectly explainable refuses to agree with our intuition.

![Figure 2.10 Dan Grayber, Cavity Mechanism #2 with Glass Dome, Formalities exhibition, the Johansson Projects Gallery, 2013 (Photo courtesy of Dan Grayber)](image)

Chuck Hoberman’s world of three-dimensional linkages is the realization of structures that can be expanded or collapsed on demand. What is unusual is the extent of these transformations: Hoberman’s geometries can expand by a factor of hundreds and maintain a fairly rigid shape in such expanded states thus defying our intuitive sense of the practical limitations of linkage mechanisms. They are the mechanical seeds that can grow structures
of any size and shape. In the category of mimesis, they would become the clockwork plants complementing the realm of anthropomorphic and zoomorphic automatons.

Richard Wilson’s the ‘Turning the Place Over’ project in Liverpool is graffiti in the most literal sense as it brands the elevation of a derelict building in an intrusive and provocative way (Figure 2.11). It is a kinetic graffiti: a 10 m across circular slice of the elevation was mounted on an oblique spindle, thus swinging in and out of the building while rotating slowly. Designers deal with similar abstractions while using three-dimensional (3D) modeling tools: cross-sections, partial, rotated, and exploded views are essential for visualizing parts that are normally hidden. However, seeing such an abstraction meticulously carved out of a real building and then animated is an unsettling experience, thus proving our cognitive separation between the digital fictions we know from cinematography or games and the real world, which by comparison we normally assume as reliably bland and tame. Wilson’s project is hinting at the possible perceptual and cognitive effects of kinetic architecture resulting from blurring our current distinction between the virtual and the actual.

Figure 2.11 Richard Wilson, Turning the Place Over, Liverpool, 2008 (Photo courtesy of Richard Wilson)

### 2.2.3 Architects

Architects have embraced the kinetic dream in their attempts to transform the urban fabric. Although a teasing vision of a walking city, conceived by Ron Herron and Bryan Harvey in 1964 (Herron and Harvey, 1964), was merely a cartoon-styled vignette with a few lines of text, it challenged the traditional notion of urbanism and its ecological footprint (Figure
2.12). “An enclosed environment of colossal size that is mobile enough to traverse the world” (ibid.) becomes a foraging organism seeking the resources for survival. Cities breaching the archetype of cultural and ecological locality are a striking forewarning of globalization and the dangers of a transnational governance. Would such cities be docile grazers or rather ruthless predators? Herron’s concept cautions how significantly the added element of mobility could unsettle the established balance of norms and paradigms.

![Figure 2.12 A concept of a walking city, based on drawings by Ron Herron](Graphics © Madalina N. Wierzbicki)

Four decades later, in 2008, the Danish design studio N55 combined an eloquent interpretation of the nomadic tradition with the advances in robotics and mechatronically-driven locomotion to conceive, build, and release into the streets of København the Walking House (Figure 2.13 Left), a forerunner of an entirely distinct genre of machines for living. While unmistakably neither an automobile nor a dwelling structure, the Walking House defies the classifications of city bylaws and parking regulations, thus revealing a new and unexplored dimension in the normally tightly governed and predictable urban fabric. This leisurely transiting machine can be best described as a pedestrian, the pervasive yet most enigmatic and transient presence amidst built ecologies. Once outside of an urban context, the Walking House becomes the Wanderer, the archetypal romantic hero of literary work and folk tradition. The wanderer motive is quite apt since the Walking House was conceived as a modern interpretation of the traditional Romani carriage and it was intended to address the needs of contemporary nomadic groups (Manual for WALKING HOUSE, n.d.).
The house is equipped with six legs, tetrahedral linkages with embedded linear actuators, which facilitate moving over any terrain. A high-tech control panel (Figure 2.13 Right) underscores the technological sophistication of the design. The maximum speed of one meter per minute allows drifting through landscapes at an organic pace of seasonal changes rather than at the rapid but alienating and endangering hurry of road vehicles. Most importantly, the incorporated modern technologies such as photovoltaic panels, small wind turbines, rain water collectors, solar water heaters, composting toilets, and compact greenhouse modules (ibid.) provide high level of comfort comparable to that of traditional buildings while eliminating the reliance on fixed infrastructures and minimizing the ecological impact. The Walking House is not only autonomous and sustainable, but it also offers a viable alternative to the comforts of built environments. Consequently, the designers anticipate the potentially far-reaching impact on the traditional notion of dwelling:

The WALKING HOUSE requires no permanent use of land and thereby challenges ownership of land and suggests that all land should be accessible for all persons. (ibid.)

Very much like Herron’s fictional concept, the Walking House challenges the established norms of land appropriation and localized governance. In doing so, it reminds us that material culture and social norms form a coupled system that is dynamic and evolving, thus susceptible to new ideas and new technologies.

Figure 2.13 Left: N55, Walking House, København, 2008; Right: The navigation/control panel (Photos courtesy of Ion Sørvin, N55)
The kinetic dream continues to seek new paradigms for the staples of today’s urban fabric, highrises. Often current technologies and entrepreneurial stakeholders swiftly materialize such dream while breaching the boundaries of practicality. An eleven story tall residential tower in Curitiba, equipped with independently revolving floors, was constructed over a decade ago and released for occupancy in 2004. Yet, the project fell to the adage about putting a price on a dream. Deemed as too expensive, the Suite Vollard became the first abandoned kinetic building and, disenchantingly, it succumbed to urban entropy. Early in 2012, graffiti aces celebrated branding the Curitiba’s forsaken kinetic dream. Fisher’s concept for an eighty story tall Dynamic Tower in Dubai vowed a visually stunning choreography of independently revolving floors. Although the project received considerable publicity in 2007 and 2008, it must have failed the scrutiny of its feasibility as its construction never started.

Figure 2.14 Michael Jantzen, M-House, 2000 (Photo courtesy of Michael Jantzen)

Michael Jantzen’s M-House, completed in 2000, liberated the primordial kinetic architectural component, a pivoting leaf of a door, from the subservient role of guarding an opening in a wall. The design relinquished the fixed shell of walls and, instead, employed an assemblage of bi-fold panels to enclose the entire habitable volume (Figure 2.14). Any set of panels can be opened or closed as needed. The interior is defined by kinetic possibilities rather than by the static determinism of enclosing walls. Such a kinetic virtualization of the house’s envelope created a dynamic, continuously morphing environment, in which the habitable space is a negotiable and tentative interaction between
the outside and the inside. The M-House thus defies the traditional notion of composition. Its swarm of articulated plates assumes space while eluding any interpretation of the form thus creating an effect of a kinetic camouflage – a precarious illusion of a habitable interior that can momentarily vanish in a morphing whim of a transformer-like kinetic beast. Jantzen's remarkable concept used kinetics to define the entire habitable space rather than merely to add subservient adjustable features.

2.3 Digital Architecture

A spirited discourse encircles the intersection of architecture and digital technologies. It surveys the current and supposes the impending. It polarizes participants amid spatial or temporal understanding of architecture, amid the material or the virtual, amid utilization or participation, and amid the deliberate or the fortuitous. Unequivocal fascination with the new and wary concern with the exaggerated span the archetypal emotional antipodes of curiosity and caution. Enthusiasts of the new argue that information technology is the force defining the architecture of today (Saggio, 2005) and that “the borders between the physical and nonphysical fade” (Bullivant, 2005a). They advocate new methodologies of “bi-directional relationships” and “non-standard architecture” (Oosterhuis, 2009). In extreme, they assert that the old paradigms have been crushed, that “architecture in the old sense becomes an embarrassment” (Bouman, 2005). Yet, more guarded theorists remind us that “there has always been a relationship between design and technology” (Bullivant, 2005c). Nevertheless, they caution that in this relationship architects failed to assert the leading role:

The methodologies of interactive architecture are heavily borrowed by architects, artists and designers from interactive media art, and this process continues. (Bullivant, 2007a)

Haque (2007) noted that, in general, “architects are notorious for naively borrowing concepts from other disciplines,” which is particularly concerning at a time when “the use of technology is easily confused with the practice of art” (ibid.). Lister et al. identified a “general blindness concerning the history and philosophy of technology” as the reason for such broad-ranging attitudes toward the new:
At times of significant change in media technologies such as we are now witnessing, this very ‘taboo’ leads, in turn, to sudden outbursts of techno-enthusiasm and the making of vastly overinflated claims. (Lister et al., 2009)

Once the fleeting hype of “newness” is gone, the role of technology “slips off the agenda” again (ibid.). In this context, Garcia’s (2007) inquiry whether interactive architecture can “make space more productive, sustainable, social or meaningful” is a voice of timeless relevance.

While adopting a human-centered view of architecture being “a format for social life” (Evans, 1997), this thesis embraces both approaches as essential to the forging of meaningful principles for interactive and kinetic architecture. As the discourse sketches out the boundaries of opinionated extremes, it also reveals the shared threads and contributes analogies, insights, and reflections that begin to enliven the barren land of rhetorics. Facilitating social interaction emerges often as the key function of digitally enhanced architecture (Bouman; Bullivant, 2007a, 2007b). Another common idea is that of intelligent architecture being able to assist users with their activities (Weinstock, 2005; Bullivant, 2005a, 2005b, 2007c) thus spearheading an idea of mass-delivered comfort provided on demand through pervasive programmatic butlers, servants, assistants, and guides.

Furthermore, shared is the belief in the influence of multi-media art on projects exploring interactive architecture (Bullivant, 2007a; Garcia). Referred to as “a form of graffiti” (Garcia), interactive visual wizardry is becoming merely a new medium of artistic expression – a digital wallpaper. A process of “digital transformation” is fusing the art of interactive multimedia with built environments (Wiberg, 2009) to the point where “there will not make much sense to distinguish the digital from the physical” (Wiberg, 2010a). The overly infatuation with computing technologies may be leading toward a “world without architects” (ibid.), thus echoing the earlier quoted Haque’s concern about confusing technology with arts and demoting architects to be merely practitioners of multimedia (Sengers et al., 2004). Such regression of the architectural paradigm could be avoided by creating “a bridge between architecture and interactive systems design” (Wiberg, 2010a) whereby architects would become skilled in integrating “interactive textures” into structural shells (Wiberg, 2010b). The art of composition would treat
structural and computational elements as equally important while seeking a balance between surface textures and a building’s tectonics (Wiberg and Robles, 2010). The concept of interactive computing as an architectural ‘texture’ brings along an element of transiency driven by susceptibility to stylistic trends and the obsolescence typically inherent in finishes and decorations. Can possibly an interactive multimedia installation become as timeless as an architectural façade? If not, then we should view such an installation as a maintenance-intensive scenography to be perpetually upgraded and redesigned, or as merely a fleeting whimsy of fashion. Yet a different possibility could emerge: a multimedia installation capable of projecting an illusion of architectural tectonics. In such an inversion of concepts, the scenography is more material than the structure. Therefore, the argument becomes infinitely nested: which is the true architectural setting for our memories, the transient décor-scenography, or the timeless tectonics of a structure?

2.4 Closing Remarks

Through works of art, this chapter explores our perceptions of and emotional responses to mechanisms and mechanically-driven motion. While centered on its practical utility and application, mechanically driven movement was always a subject of fascination; it was a source of ‘enthrallment.’ Similarly, kinetic architecture, besides its functional advantages, may also attract with its expressive forms and dynamic choreographies encompassing art, culture, and human emotion. Furthermore, kinetic structures may bring back the primeval sensual experience of space “in its full synaesthetic sense, and one which, since Cartesian rationalism, modernity has learnt to subdue” (Knights). Digital technologies have placed architecture at the crossroads of tectonics or illusion, of either the physical or the virtual, and of permanence or transiency. Digital technologies along with advances in engineering also empower architects and open new possibilities. Conceivably, new technologies will blur the distinction between the structural and the kinetic considerations, and the embedded computational intelligence will advance built environments to be our interactive and flexible companions rather than merely static partitioners of space, thus redefining our perception and understanding of architecture. Static walls, the fixed and dependable
assurances of stability and order, will yield to behavioral systems having their own agendas and idiosyncrasies, systems-environments that need to be reckoned and negotiated with. The initial responses to such environments may be quite similar to those elicited by the most extreme and avant-garde kinetic art: confusion, fear, anxiety, curiosity, and enthrallment.
CHAPTER 3 History of Kinetic Architectural Elements

This chapter discusses how people interacted with the environment, both natural and man-made, using various configurable implements. The overarching focus is on identifying the primordial behaviors and artifacts, which have contributed toward developing kinetic architectural concepts. Rather than compiling a typology of devices, this thesis traces archetypes, conceptual precedence, historical analogues, and the essential enabling circumstance in the context of social spacial practices, cultural, and geographic conditions. Thus by paraphrasing Gamble’s (2007) assertion that material culture lies “in the gap between the psychological and social,” the history of kinetic architecture is explored in the gap between the behavioral and the material. The present research delves as much into the factual evidence as into the theories and methodologies, thus acknowledging the relativistic and human-centric bond between the knowledge and the methods of acquiring it. Our comprehension of the past is subjective and driven by intent and presumptions. Therefore, knowing history is an iterative process, in which we continually reformulate our methods by reconsidering the evidence. This study is merely a singular cycle in the perpetual process of expanding our knowledge and exploring our own identity.

3.1 Context

Although architecture is usually considered as a solid, lasting, and invariable form, it is not, and never has been, a purely static shell merely delimiting discrete spaces. Through all times, built environments comprised both fixed static structures and devices that were adjustable, modifiable, or movable (kinetic). Kinetic architectural elements were essential for interfacing the rigid shells of buildings with the dynamics of human behaviors. Being the interactive and adaptable effectors of human needs, they were the means of purposeful changes and the living tissue of built environments. They were the expression of
behavioral practices encompassing the mundane and the symbolic. A history of such
devices is also a history of technologies, social needs, and cultural circumstances involved
in forming built environments. In a contemporary context, it refers to kinetic structures –
the promising yet largely unexplored segment of architecture and the construction industry.

Even though kinetic elements are an inseparable part of architecture and its history,
a systemic knowledge on this subject is currently lacking. The poor survivability of
lightweight material evidence is partly responsible. Kinetic fittings, often made from
valuable materials like wood or metal, tended to be recycled or looted (Wright, 2005).
What remained was subject to erosion and decay, thus leaving only circumstantial
evidence like traces of mountings, or wear marks (Leick, 1988). Consequently, we know
the buildings of classical antiquity mostly as masonry carcasses stripped of all behavioral
anecdote. Worse yet is the state of prehistoric sites as millennia of natural and
anthropogenic depository processes often intermingled the remaining evidence into an
inextricable composite, from which little can be learnt about “intricate patterns of activity
and movement” (Cutting, 2003). Study of such sites is challenging as much of the
contextual information is irreversibly lost during excavations, which are inevitably
invasive and destructive (Kotsakis, 1997). Although the emergence of “reflexive” approach
(Hodder, 2005) aimed at mitigating the irreversible effects of field work, and though both
archaeological theory and analytical methods have been progressing, the outcome is still
said to be strongly affected by the initial assumptions and the decisions made during
excavations (Conolly, 2000).

Besides the scarcity of material evidence, studies aimed at comprehensive
understanding of architecture as a dynamic and interactive social setting need also to
overcome the still dominant artifact-oriented paradigm of archaeology and the mostly
form-concerned history of architecture. Researchers point out that historical studies about
built environments tend to leave out references to human activity, behavioral patterns, and
cultural context. For instance, Gamble remarked that in both architecture and archaeology
the human body was regarded merely as a static measurement unit, a “yardstick.” Lawson
(2001) observed that architectural space was mostly discussed as “some entirely abstract
substance.” The situation was further aggravated by what Sheller and Urry (2006) had
called “a-mobile” attitude of social sciences, which tended to ignore the element of
movement inherent to any human setting. Lastly, studies of built environments were hindered by the discipline-based structure of involved sciences and their frequently exclusive paradigms (Karns-Alexander, 2012). Under such circumstances, the interpretation of material evidence tended to be partial and tentative, while kinetic architectural elements were largely ignored.

3.2 Evolving Paradigms and Perceptions of Architecture and Its History

Our intuitive perception of architecture invokes an image of an enduring structure. Such an image is rich with expressions that long transcended the technical context of the construction trade. For instance, the foundation and the cornerstone epitomize an act of irrevocable initiation and establishing a permanent presence. Thus, the concept of a static, firmly embedded composition became not only the paradigm of architecture, but also a cultural symbol of stability and endurance.

This undeniably structure-biased mindset can be traced to the continuing legacy of antiquity. Vitruvius, a Roman architect and engineer, asserted architecture as an art of composition rooted in the Hellenic tectonics. When defining the key attributes of buildings, he specified “durability” before “convenience and beauty” (15 BC/1914). Knights (1994) suggested that the symbolic and phenomenological aspects of architecture were left out by Vitruvius because these were the universal facts of life for his contemporaries, hence detailing such facts would have been nothing more but “stating the obvious.” Instead, Vitruvius focused on the art of engineering and architecture:

Proportion, geometry and construction, on the other hand, being more specialized artisanal skills, were perhaps more specifically architectural and less immediately obvious, and therefore more appropriate to the context of his books. (ibid.)

By embracing the technological perspective, Vitruvius had challenged the ancient “contempt for practical skills” and the then dominant ideal that “only a life guided by purely intellectual activity is truly worth living” (Boden, 2006). Later, generations of theorists kept echoing his words when referring to architecture while perhaps being unmindful of their original radical contribution: “lasting in structure” (Alberti, 1485/2006),
“duration” (Palladio, 1570/2006), “firmenes” (Wotton, 1624/2006), “solid” (Blondel, 1675/2006), “firmness” (Wren, 1881/2006), and “solidity” (Hübsch, 1828/2006). Certainly, the enduring backdrop of magnificent ruins of antiquity was conducive to such thinking. Although stripped of all the purpose and finishes after the Empire’s collapse, and further ablated by over a millennium of dilapidation, material extraction, and erosion, the imposing carcasses of Roman architecture dominated the landscapes of post-medieval Europe and Middle East. They set off two major stylistic epochs: the Renaissance in the fourteenth century and the Neoclassicism in the eighteenth century. They inspired generations of artists who, like da Sangallo and Piranesi, surveyed and chronicled them; who, like Breenbergh and van Bloemen, delegated them to incidental roles of scenic accents in romantic landscapes; who, like Panini, Clérissette, and Hubert, promoted them to be the uncontested centerpieces of attention; and who, like de Nomé, Coccorante, and also often Piranesi, surrendered to their mystique to the point of obsession and blurred the boundaries between the actual and the surreal.

Yet, the austere and abstract anatomies of ancient buildings, besides being an enduring tribute to the mastery of their creators, remained rather inscrutable about their actual streetscapes or their daily routines. For almost two millennia, architecture epitomized a static and solid composition, in which beauty meant the art of proportion rooted in the Hellenic tectonics while the architectural thought was eviscerated from all that disagreed with such image: action, spontaneity, exuberance, transient decors, and makeshift furnishings. Like an uncharted wasteland, this intellectual divide between architecture and its unruly alter ego lied unexplored until, in the nineteenth century, Gottfried Semper began reviving it with truthful visual detail and credible behavioral narratives. In 1834, Semper (2006) challenged the then unassailable canon of the stark white marbles of the Hellenic architecture and, instead, substantiated the historically accurate account of ancients indulging in rainbow polychromies. Furthermore, he ascertained the historical importance of transient and lightweight architectural elements. Wickerwork, ropes, skins, and textiles were, according to Semper, not only the earliest means of protection, but also the primordial architectural elements used for shaping habitable spaces (2004). He reasoned a conceptual continuity from such simple implements to more advanced architectural forms:
Wickerwork was the essence of the wall. . . . Hanging carpets remained the true walls, the visible boundaries of space. 
(Semper, 1989)

Most importantly, Semper argued that these lightweight elements have never vanished from the landscape of evolving architectural tectonics, but instead they have become the inseparable attributes of human interaction with rigid structures of buildings. Semper’s inspired inference transcended the classical paradigm of architecture as a static form and pioneered the principle of architecture as an interactive setting to human action.

Such notion of architecture as a complex system encompassing material artifacts, their cultural meaning, and human behaviors became discernible in writings by architects and historians much later in the nineteen-nineties. In 1993, Markus acknowledged buildings as primarily “social objects.” Evans (1997) stated that architecture embodies the “nature of human relationships.” Hillier (1996) noted that the concept of space could only be meaningful in the context of “human behaviour or intentionality.” The trend continued as, in 2001, Lawson argued that built environments were the reflections of “human spatial behaviour” and, in 2006, Hill theorized architecture as a trans-physical phenomenon, in which the immaterial and the tangible structures were equally important. Such discourse regarding the material-social duality of human culture had a broader interdisciplinary context as exemplified by Segal’s pioneering work linking technological progress with human cognition (1994), and Massey’s notion of space as “constituted through interactions” (2005).

Concurrently, archaeological theory also had embarked on developing conceptual bonds between the material and the social. In 1994, Renfrew and Zubrow declared that understanding “about what and in what manner did prehistoric people think” was one of the most challenging problems in archaeology. In 1999, archaeologists Brück and Goodman theorized built environments as the outcome of “social construction.” Jones (2004) stressed the importance of transcending the fixation on “what” in order to understand “why.” In 2006, Cutting identified studying “human patterns of movement” as essential for understanding the built environments of the past. Miller (2007) proclaimed that, although challenging, the comprehensive understanding of technology within its social context “is one of the most exciting trends” in archaeology. Also in 2007, Gamble asserted that all material culture and technology “is pre-eminently a narrative about human
identity,” thus building upon Segal’s premise and establishing a universal human-centered framework for integrating the psychological, the social, and the corporeal. According to Abramiuk (2012) “cognitive archaeology,” the distinct effort directed at “studying the mind of the past,” began in the mid-nineties.

The last decade has marked a new trend in archaeology aimed at reconstructing behavioral patterns of past human settings. According to Mlekuž (2010), seeking the understanding of movement coincided with archaeologists taking notice of Lefebvre’s model of society as a dynamic cognitive, physical, and temporal system, and of Hall’s work on human behavioral dynamics. In 2009, Bjur and Santillo-Frizell presented a novel approach aimed at understanding “the intangible underlying systems of space, movement and artefacts” while studying ancient urban settings. In 2011, Newsome reported a surge of “interest in movement” as the key to understanding the built environments of the past and their societies. Furthermore, he asserted that “movement makes space.” Laurence (2011) concurred that this trend marked the continuing “shift from the study of space to a study of movement.”

The tradition of intellectual effort aimed at overcoming the artifact-biased doctrines and enlivening the past has provided the inspiration for this project, and it has outlined the cognitive challenges we encounter when studying history. Gamble expressed such challenges straightforwardly:

The past is remote because it is un-peopled and definitely un-gendered. (2007)

3.3 The Beginnings

Neither the skill of constructing shelters nor the act of dwelling is unique to humans (Hansell, 2007). Still, we are curious about the primordial spatial practices of early hominids:

The idea of the first house ever built has enchanted artists, architects, philosophers and psychologists as well as archaeologists. (Parker Pearson and Richards, 1994)
Regardless of the purpose, which could have been sheltering from elements, protection from real or perceived danger, marking territory, or perhaps any combination of these, such practices resulted in artificial boundaries and their inseparable conceptual antitheses, entrances. A boundary is the act of creation while an entrance is the means of control. Together, they form the elemental system of space utilization and the conceptual underpinnings of built environments. The very act of entry is the epitome of motion, it is a dynamic transition through a boundary. At the same time, the act of entry asserts control: it defines where, how, and by whom a boundary can be breached. Doors, the universal devices of controlled motion and the defining points of our built environments, have been known for at least five millennia. However, it is a relatively short period spanning only the most recent one-thousandth of the known history of mankind. Although the first ever doorways and gates are the subject of as much conjecture as the earliest houses, for this thesis they are the conceptual nucleus of kinetic architecture and therefore deserving careful consideration.

Figure 3.1 Terra Amata site (Photo by Henry de Lumley; courtesy of Musée d'Archéologie de Nice)

A continuously growing body of archaeological evidence enlivens the Vitruvian “men of old” (Vitruvius, 15 BC/1914). Remains of Ardi substantiated the existence of early hominids as early as 4.4 million years ago. The oldest known stone implements marked the origins of prehistoric technology 2.6 million years ago, and “they are likely to get older,” perhaps back to the first hominids (Gamble, 2007). Yet, living “on savage fare” (Vitruvius) might have remained a cold and dark affair for much longer. For Vitruvius, it is the fire that marked the beginning of human societal progress. The earliest circumstantial evidence of humans using fire dates back 1.6 million years (McIntosh, 2006), while the conclusive findings confirming man-made fire are, according to Goren-Inbar et al. (as cited in
Gamble), only 780,000 years old. Hundreds of millennia later, we encounter the first clues about human appropriation of space. The 380,000 years old Terra Amata site is considered the earliest evidence of a purposefully fashioned shelter. Unfortunately, a weathered assemblage of stones at Terra Amata has not yielded too much to work with (Figure 3.1). This could have been a simple hut as proposed by de Lumley (1969) (Figure 3.2 left), or merely a wind break similar to the ones being constructed in the fields of New Mexico not long ago (Figure 3.2 right). The discovered artifacts are tentative to the point of some researchers doubting their anthropogenic origin (Villa, 1983).

Figure 3.2 Left: The Terra Amata hut, a conjectural reconstruction as proposed by de Lumley (Illustration by Marion Bernhardt; courtesy of Marion Bernhardt, Studium Integrale Journal); Right: Uncovered shade kishoni of Tusayan (Mindeleff, 1891; work in Public Domain)

Interpretations of relicts like the Terra Amata site are further hampered by the traditional overly cautious approach toward reconstructing the behaviors of the past. Even the popular media, which are expected to be much less constrained by academic rigors, show little courage in imagining the past. For example, an artistic interpretation of the Neolithic site Göbekli Tepe, published in the renowned journal National Geographic (Mann, 2011), focused primarily on the technology of construction as if the methods of ancients were easier to untangle than their social interactions, thus reminding us of Gamble’s warning: it is difficult to re-populate the past. What if the very act of constructing Göbekli Tepe was a
ritual rather than merely technically necessitated laboring? The illustration leaves us unconvinced and feeling let down. By contrast, a snapshot of a circumstantial artifact provides much more intrigue (Figure 3.3): a drilled hole in the horizontal slab might have been propping a device controlling ingress.

![Figure 3.3 Göbekli Tepe site (Courtesy of Klaus Schmidt, Deutsches Archäologische Institut)](image)

Nevertheless, the difficulty in interpreting such singular clues may be insurmountable. Although affordances of modern analytic methods often amaze with detailed reconstructions of diet and health of our distant precursors, disappointingly, the same cannot be said about spatial practices or the involved accessories. However, Donald suggested that primordial spatial practices may still be around us:

> The strategy adopted here must be, in part, reconstructive; early human cultures can be evaluated not only from archaeological data but also from the extensive literature on surviving human hunter-gatherer societies. (1991)

We still use some simple and timeless gestures of space appropriation. A blanket spread on the ground or a sheet draped over a branch, they are acts of domesticating space and making it comfortable. Such devices and actions are so simple that they quite elude any intellectual attention. Unfortunately, because of their material insignificance, they also remain elusive as archaeological evidence. These conceivably most archetypal gestures of subjugating space are merely extensions of the Semperian concept of textiles as the
primordial means of architecture. Whether woven textiles or animal hides, they share similar properties and purposes. The most important for this thesis is their inherent shape fluidity. They can be repeatedly folded, rolled, or draped over. Such fluidity of form is the essence of being kinetic, thus affirming animal hides and textiles as the prototypes of kinetic architecture.

What if a hide draped over an entrance was replaced in an instant of engineering elucidation, or in an urgent and widespread need for a better solution, with a solid, plate-like assemblage, the precursor of a door leaf and the first rigidly operated kinetic architectural component? This conjecture establishes a conceptual perspective for this thesis. While it remains unprovable in archaeological terms due to the notorious perishability of such lightweight artifacts (Venclová, 2006), it will provide a reference for discussing available material evidence and iconography. Although a technically mature door design dominated since Roman times, the Semperian motive of a flapping drape proved to be persistent and accompanied architecture through all times. On a mid-18th century painting depicting the church of San Pietro in Castello, which was until the beginning of the 19th century the cathedral church of Venice, the main doorways are protected with textile curtains (Figure 3.4).

![Figure 3.4 Studio of Canaletto, Venice: San Pietro in Castello, 1734-1742 (detail)
(Photo © The National Gallery, London, UK; used in accordance with “Terms of use” http://www.nationalgallery.org.uk/terms-of-use/)](image)

Churches Santa Croce (Figure 3.5 left) and San Simeone Piccolo (Figure 3.5 right), shown on other works from the same period, have similar curtains in their doorways. Whether it
was economy of the moment or other circumstances, textiles and kinetics had demonstrated immediate and organic interchangeability.

Figure 3.5 Left: Follower of Canaletto, Venice: The Grand Canal facing Santa Croce, after 1738 (detail); Right: Follower of Canaletto, Venice: San Simeone Piccolo, after 1738 (detail) (Photos © The National Gallery, London, UK; used in accordance with “Terms of use” http://www.nationalgallery.org.uk/terms-of-use/)

The theorized here invention of door would have been merely a successor to a more primordial concept, an entrance, which in turn is inseparable from the realization of a boundary. While entering we cross a boundary which demarcates two distinct realms. Such realms, besides tangible physical attributes, can also have profound symbolic meanings. Researchers indicated that the hunting-gathering era could be considered as a time of relatively effortless life. The effort needed to sustain communities while foraging and hunting the plentiful available resources was only a fraction of that involved in agriculture. Assumingly, spatial practices of hunters/gatherers might have been driven primarily by the need for protection from the elements. Yet, the notion that the corporeal is inseparable from the symbolic reminds us that we should not adopt our modern meteorology-driven understanding of the elements as universally applicable. According to Neustupný:

To explain enclosures and fortifications exclusively or predominantly by means of practical function and/or social meaning (the military hypothesis) seemed to be a reasonable assumption as long as it was believed that prehistoric societies had been ruled by principles of rationality, something that modern people assume in their own case (while the reality is often different). (2006)

Renfrew discussed the cognitive fusion of the material and the perceptual, and the resulting relativity of principles of rationality:
What is believed and what is agreed, that is to say the perceived reality, is as powerful as what one might today judge to be the real, physical reality. (Renfrew, 1998)

Podborský and Kovárník (2006) pointed out that “the dangers of the surrounding world” can be either “real or imagined.” They referred to Venčl’s (1997) discussion of the symbolic role of early Neolithic fortifications, which primarily served as boundaries between a “clean and sacred space inside from an unclean and demonic outside.” Neustupný identified the “unnecessary number of entrances,” which defeated the defensive role of many fortifications, as an evidence of their ritual function. While building upon Neustupný’s arguments, Podborský and Kovárník concluded that this was even more true for “simple enclosures.” Therefore, the function of Neolithic doorways and passages was, very much like the lives and spatial practices of Neolithic people, an inseparable fusion of the practical and the symbolic. Not surprisingly, such fusion is difficult to interpret while using our modern cultural perspective. Furthermore, according to Banning, our contemporary comprehension of the sacred and the profane is much different from that of past cultures, thus adding a challenge of understanding the actual functions of Neolithic built environments:

The interpretation of every Neolithic building that shows any evidence of spectacular art or unusual architectural features as a specialized shrine is problematic. (2003)

The depletion of resources and the dawn of agriculture brought along the necessity to maintain reserves of crops. Perhaps the ensuing change from universal availability to a localized differentiation of resources had promoted a notion of ownership in the prosperous, and an unavoidable and complementary sense of envy in the less prosperous. Venčl remarked that this transition had brought “the economic explanation of the causes of enclosure,” as the functional program of dwellings needed to incorporate the means of storage and protection from intruders. Such need intersected contradictory requirements: an easy access for normal use versus secure protection. Doorways, besides their ritual function, had to address also the practical aspects of safeguarding goods.

The Çatalhöyük archaeological site reveals a prospering Neolithic hunting-gathering and agricultural society, and continuous occupation of an elaborate settlement-city from 7500 to 5700 BC. Although Çatalhöyük may be holding clues about some of the
earliest devices controlling ingress to human dwellings, untangling the archaeological evidence of this site is difficult as indicated by cautious and often contradictory interpretations of its artifacts. According to initial interpretations, the access to the multi-storey dwellings was exclusively using ladders and through openings in the roofs (Mellaart, 1967; Leick, 1988). Yet, the recent research indicates that an image of Çatalhöyük contemporaries as roof-hopping aerialists is not entirely convincing. Most of the spaces were kept “spotlessly clean” and were frequently “renovated” – having their floors and walls completely re-plastered (Hodder, 2010). The effort of regular transportation of debris and finishing materials only through holes in the roofs raises doubts. Burning the fires in windowless and doorless spaces is also problematic because of smoke levels and the risk of carbon monoxide poisoning. Such systemic inefficiencies and hazards are difficult to reconcile with an image of a community prospering for two millennia.

Unfortunately, the site epitomizes all odds stacked against unraveling subtle aspects of dwelling construction. The two millennia of continuous occupation have layered and fused together the surviving evidence of countless additions, alterations, and demolitions into an intermingled and fragile puzzle. From the very onset, ‘lightweight’ artifacts were obfuscated or perhaps re-used. Ultimately, the very process of excavating was inherently destructive as it could only pursue a certain target, a conceptual point of focus, while other evidence was irreversibly altered or destroyed (Reich, 1987). Hodder (1995) provided an example of how the decisions regarding the extent of invasive excavating affect the delicate balance between the revealed and the destroyed:

In the Mellaart area, 'doors' and crawlholes had been blocked. This blocking was often not seen by Mellaart because he did not systematically remove plaster from the walls. The presence of a 'door' between houses 2 and 12 suggests that roof entry may have not been the only form of access, at least in some houses. (ibid.)

Such a combination of doorways and roof access reminds of Zuni pueblos in New Mexico (Figure 3.6). Perhaps the both architectures evolved under similar local conditions, thus resulting in their likeness. According to Gamble, “comparable adaptations” are a result of “similar selection pressures from the environment.” Still, there is no evidence of universal
use of doorways at Çatalhöyük. Therefore its doorways may for long remain solely the subject of conjectures and ‘proxy’ evidence. On the one side, it seems that Çatalhöyük was in a momentous need for a well-functioning door, and that this need existed for over a millennium. Should we then consider that such prolonged vacuum between the needs and technology is difficult to explain? On the other side, we may take a critical look at our interpretation of the cultural context at the prospering Çatalhöyük and at our notion of what is practical and functional: perhaps the inhabitants did not use doors because they choose not to.

![Figure 3.6 Zuni pueblo, circa 1887 (Mindeleff, 1891; work in Public Domain)](image)

### 3.4 Architecture of Entry

The Neolithic transition from hunting-gathering to agriculture and the evolving role of built environments had necessitated effective access control, thus leading to the inception of a rigid door. The oldest known artifact is a single piece wooden door from the Robenhausen site in Switzerland (Sherratt, 2001). Dated at 4000 BC, it trails Çatalhöyük by over two millennia. The leaf of the Robenhausen door has a series of holes along one edge, thus suggesting that it was hinged using cordage or strips of leather (ibid.). However, a protrusion at the bottom of the hinging edge could have played a role of a pivot, thus
resulting in a unique hybrid design combining flexible articulation of hinging with a bearing socket supporting the door’s significant weight (Figure 3.7 left).

Another Neolithic door has been excavated in Zürich in 2010. Dated at 3063 BC (Neolithic Door Found in Switzerland, 2010), it is by a millennium newer than the find at Robenhausen. The leaf is an assembly of planks held together with an intricate interleaved joinery. The door was held in place by two locating pivots, which can be clearly identified in this well-preserved artifact (Figure 3.7 center). A wooden door from the tomb of Khonsuhotep in Egypt (Figure 3.7 right) dates around 1285 BC (Quirke, 1992). It is a multi-plank, pivoting design. At 204 cm of total height, its dimensions are up to our modern standards. By comparison, the Neolithic doors are rather short at approximately 150 cm. Figure 3.7 shows the doors at the same scale.

Figure 3.7 Left: The Robenhausen door, circa 4000 BC (Sherratt, 2001; photo courtesy of Oxford University Press); Center: The Zürich door, 3063 BC (Photo courtesy of Stadt Zürich); Right: The Khonsuhotep door, circa 1285 BC (Photo © Trustees of the British Museum; used in accordance with “Standard Terms of Use” http://www.britishmuseum.org/about_this_site/terms_of_use.aspx)
These rare artifacts span a period of three millennia and mark quantum leaps in door millwork starting with the massive organic-shaped wood shake of the Robenhausen door, through the elaborate but coarse tab-and-strip joinery of the Zurich door, and ending with the precise concealed joinery and faultless flat surface of the Khonsuhotep door. They mark the emergence of the most important and the most common kinetic architectural component, which, after six millennia, is still in use in a conceptually unchanged form. Noteworthy is our cognitive and behavioral adaptation to using doors. We do not dispense too much of conscious attention when operating them. We do not receive formal safety training in door handling. Neither we buy a door usage insurance. The millennia-long conditioning of our reflexes guides us safely while we slip by the moving shear, crush, and impact zones. Yet, doors remain the most dangerous devices we operate every day as asserted by the sobering statistics of head injuries, crushed digits, and even amputations (Conner et al., 2010).

During the Bronze Age, doors were the definitive expression of social status and authority. Only elites could afford the expense of materials and fabrication. For instance, stone sockets bearing the door pivots, by today’s standards merely crude pillow blocks, were a luxurious commodity and often adorned with reliefs or at least engraved with dedications. Made of stone, thus much more resilient and less likely to have been repurposed than the wooden leaves they supported, they are the sole surviving physical evidence of the Bronze Age doors. A socket from the Archaic Temple in Hierakonpolis, dated at 3000-2675 BC, is a true object of art (Figure 3.8 left). It represents a captured and bound enemy subjugated to the perpetual torture of a pivot stem grinding into its back. An inscription on a millennium younger Sumerian stone socket from the Ur temple commemorates a military success over the Amorites (Figure 3.8 right).

The prosperity and manufacturing efficiency of the Roman Empire has made doors a common item. These simple pivoting devices have become the dynamic effectors of human intentionality and access control, thus enlivening the static masonries of Roman streets. As rigid mechanisms, doors integrated in a more substantial manner with the structures of buildings and they were much tougher than, for instance, textile curtains. Doors became the architectural components, while textiles remained merely decorations or impromptu partitions. Doors expanded the functionality of Roman streets as the stage for
social interaction and the display of social hierarchy. Hartnett (2011) described an exquisite case of using doors as the effector of social status. Through his position of influence, one Valerius Publicola was permitted, contrary to standard practice, to have the doors of his house open outward, thus swinging right into the faces of pedestrians. In Publicola’s house, the doors, or rather their movement, became the expression of power, prestige, and perhaps arrogance. While in the Bronze Age Egypt or Mesopotamia the mere act of owning a door was a measure of social status, in Roman times, the kinematics of doors and their functional application, especially when in contempt of local rules, became the signifying aspects.

Figure 3.8 Left: Door socket, Archaic Temple at Hierakonpolis, Egypt, 3000-2675 BC (Photo courtesy of The University of Pennsylvania Museum of Archaeology and Anthropology); Right: Door socket, Ur temple, Mesopotamia, 2150-2050 BC (Photo courtesy of The Spurlock Museum, University of Illinois at Urbana-Champaign)

Roman doors were not only a product of technological capabilities, they were also a realization of an elaborate system of the supernatural. Janus was said to be the god of doors (Taylor, 2000). However, Janus represented more than simply a mechanical device:

Celebrated in literature as the god of beginnings and of transitions, Janus seems to be a personification of transitional spaces through which one must walk in order to begin an undertaking. (ibid.)

Therefore, Janus signified the prehistoric and performed without doors ritual of entry, an act of breaching a boundary. Interestingly, door hinges were assigned their own goddess Cardea, as if Romans specifically recognized the significance of door kinematics. The architectural elements framing doors also were assigned their deities: Limentinus for lintels
and Forculus for thresholds (Donaldson, 1833). Therefore, Roman doors seemed to symbolize the entire universe as they comprised earth as the threshold, heaven as the lintel, motion as the hinges, and the act of transition from one realm to another.

Another device of entry, the portcullis, advanced the aspect of physical interaction to a violently enforcing level. Quite different from doors in that it was a sliding rather than a pivoting mechanism, and it was intended to be used only under extreme circumstances rather than casually. A massive assembly of vertical poles, usually spiked at the bottom and interlinked with horizontal bars, would be cocked high above the street level and latched in such Damoclean position ready to be unleashed in a moment of need. While doors were used in buildings, portcullises guarded entire cities. Yates (1843) detailed an installation of a cataracta, which was a Latin onomatopoeic term for portcullis, at the principal entrance to Pompeii. A building housed both the main gate and the portcullis located a distance behind. The portcullis was guided between two vertical masonry slots. It would be raised and concealed in a gap between two parallel walls except for its jagged edge of downward spikes, thus adorning the entrance with a Roman take on ‘this area is under surveillance.’ Yates referred to Vegetius’ ‘Epitoma rei militaris’ when recognizing the portcullis as an “ancient contrivance” rather than a Roman invention. Though we can theorize doors as a concept derived from folding a flap of textile or animal hide, no such casual analogy can be construed for a portcullis. Rather, the utterly violent and singular mode of its operation reminds a trap for a massive beast. Not surprisingly, every aspect of a portcullis evokes hunting and military analogies: ambush, trap, strike, block, cocking.

A different door solution utilizing planar rather than pivoting kinematics were large rolling stones. Conceptually, they appear to borrow from rocks moved over cave openings, and they share the essential functional features with such an archetype like the ungainly operation unfit for casual use and good defense once deployed. Although they are common throughout archaeological sites in Near East, no systemic research on these curious devices is available. Cave cities in Cappadocia, Turkey, are known for their rolling doors. The underground city at Derinkuyu is said to date back to 8th century BC (Emge, 2011). Figure 3.9 shows one of its doors.
Designs by Santiago Calatrava often explored the aesthetics of kinematics derived from arrays of simple linkages. The folding doors for Ernsting Warehouse, completed in 1985, are a lyrical and de-spiked interpretation of a portcullis motive (Figure 3.10). Another Calatrava’s project, the entrance to the conference room at the Abbey of Sankt Gallen, completed in 1999, was a successful high-tech intervention within a sensitive historical context. When lowered, the structure forms an unobtrusive platform serving as a sitting bench. When raised, its arched array of linkages transforms into an expressive, somewhat zoomorphic and alluringly ingestive presence amidst the delicate architectural fabric of Sankt Gallen (Figure 3.11), as if the sleepy town got its own mild-mannered and yawning dragon. The Sankt Gallen entrance epitomizes the ideal of kinetic architecture: effortless morphing from one shape and purpose into another.
3.5 Business of Kinetics

The business of kinetics traces the pragmatic approach toward integrating motion (engineering dynamics) and architecture – solutions that if practical, technically viable, and revenue-effective, were constructed and successfully operated.

3.5.1 Harvesting Wind

The archeological evidence indicates that the oldest known windmills were constructed in Persia approximately 1,500 years ago. However, their vertical axis of rotation, and mostly constant, unidirectional wind typical for the region, required no positioning movement from the corresponding building. The only moving part of the entire mill was the vertical vane assembly.

The European windmills needed to adapt to less favorable conditions: intermittent winds of varying force and shifting direction. The invention of a vane assembly having a
horizontal axis of rotation significantly improved the efficiency. However, such design required orienting the rotor with the direction of the wind thus spurring various schemes where the entire building of the mill or only a part of it could be rotated. The first European windmills date back to the 13th, perhaps even to the 12th century (Hills, 1996). They were of so-called post construction where the entire building of the mill was revolving around a central supporting post. The size of the towers was often large enough to possibly accommodate modest habitable quarters. Without much of historical fanfare and out of pragmatic necessity, a rotating building was born.

3.5.2 Harvesting Air – Rotating Shelters

Tuberculosis became nearly an epidemic in the 19th century thus prompting the search for effective treatments. The idea of accommodating patients in a controlled, pollution and contagion free environment has led to the inception of an open-air therapy and sanatoriums (McCarthy, 2001). The architecture of sanatoriums maximized the opportunities for patients to remain outdoors for extended periods. Characteristic were deep verandas encircling the buildings and providing an ample space for arranging the beds and for servicing the patients. In 1888, the first “rotating pavilions” were installed at the Falkenstein sanatorium in Germany (The Dettweiler Method of Treating Pulmonary Consumption, 1888). The pavilions were simple rectangular huts having one wall removed thus allowing the continuous circulation of fresh air. They could accommodate up to two patients. The entire hut could be rotated to keep the open side downwind and protect the interior from drafts. The “revolving rest huts” gained rapid popularity and soon became available as mass-produced catalogue offerings by entrepreneuring industrialists (Campbell, 2005). Boulton and Paul, a major British manufacturer of construction kits for houses and commercial buildings, posted ads for rotating shelters for “the open air treatment” as early as in 1907 (Graham-Smith and Purvis, 1914). The open-air therapy proved to be the only effective treatment for tuberculosis until the introduction of an actual vaccine (McCarthy) thus distinguishing the simple rotating sheds of Falkenstein as an important architectural contribution to the medical history.

During the first decades of the 20th century, the commercial success of rotating shelters has quickly transcended the health-care applications. 1930-ties ads by Boulton and
Paul touted such shelters as a “necessity to full open-air enjoyments in the Garden,” as “the room which can be turned to face any point,” as a “Revolving Sunshine Room,” and as a “revolving garden room – always with its back to the wind.” Outdoor shelters of all kinds were an indispensable part of the “open air craze” during the first half of the 20th century (King, 1984). A humble rotating shelter constructed by Bernard Shaw and used as his writing studio (Bernard Shaw's Rotating House Is an Aid to Health, 1929) became an icon of such garden architecture as well as of a sustainable and healthy lifestyle.

The universal implementation of the tuberculosis vaccine in the mid-20th century (McCarthy) marked the twilight of open-air shelters. Nevertheless, the concept of a tiny rotating shelter interacting with its environment has proven to be irrepressible. Architects and entrepreneurs continue to re-interpret the basic principle of such shelter while using new technologies and exploring new purposes. The kubus project by sturm und wartzeck, conceived in 1996, was intended as a cluster of small rotating units housing different functions. The units could be rotated to suit the desired purpose or the weather. The minimalistic design of the cube-shaped units resulted in a whimsical fusion of two seemingly discordant themes from the early 20th century – the Victorian garden architecture and the modernist avant-garde.

Currently, rotating garden shelters seem to be the specialty of the UK market where companies of long tradition as well as novices explore the potential of such idea. Scotts of Thrapston, a company of almost a century long tradition, offers optional turntable bases for their Victorian-styled octagonal summerhouses. A fleeting appearance by the Garden Sun Studios brought along a traditionally styled Revolving Summerhouse with a curiously located corner door. A very recent design by the Farmers Cottage Lamps has breached the stylistic conservatism. Their rotating Garden Pods are minimalistic ribbed spheres providing a virtually unobstructed view of the surroundings. The choice of materials further emphasizes the divergence from tradition – a laminated wood structure is clad in stainless steel and polycarbonate panels. The persuasively biomorphic quality of thick arching ribs helps the pods to assume the role of giant hi-tech pumpkins bulging over gardens in an assertive yet harmonious symbiosis. The largest version can accommodate up to fourteen guests seated around a central table.
3.5.3 Harvesting the Sun – Rotating Solaria

The hot springs facility in Aix-les-Bains became the focus of modernization efforts led by Saidman. The entrepreneurial doctor proposed a revolving solarium for actinotherapy treatments. A 25 meters long revolving platform equipped with ten insolation chambers was mounted atop a 16 meters tall tower. The rotating platform assured maintaining the best exposure to the Sun. The facility opened in 1930 and soon became a resounding commercial success. Seizing the opportunity, Saidman built two more similar facilities: in the coastal Vallauris and in Jamnagar, India. The charismatic doctor was the sole driving force behind actinotherapy and the operation of solaria – the facilities were closed right after his death in 1949. Both French solaria were demolished later. The revolving structure in Jamnagar has survived and is being considered for restoration as a historical curiosity.

3.5.4 The View and Prestige – Rotating Restaurants

Recent archaeological work at the site of Domus Aurea has corroborated the writings by the Roman historian Suetonius: Nero’s palatial complex had indeed comprised structures with revolving floors (Villedieu, 2011). Villedieu concluded that a revolving platform having a 12 meters diameter was installed high above ground over a circular colonnade, thus offering panoramic views of the area (ibid.). According to Villedieu, the Macellum Magnum shown on the reverse of Nero’s dupondius coin may just be the structure housing the revolving platform (Figure 3.12). Curiously, the central round structure is flanked with buildings of uneven height. If the stage was being rotated by a water-powered mechanism, this would have been a proper arrangement for realizing the water supply and the height difference. Tomei noted that “the spinning room is considered a very important architectural prototype, imitated for centuries.” Although Nero’s ‘spinning room’ would hardly qualify as a commercial venue in the modern sense, while overlooking the main market, it certainly was in the business of asserting the social status and grandeur – a dimension the contemporary revolving restaurants still exploit. Tomei also indicated the most important prerequisite for such facilities: “always localized in elevated positions to allow the 360-degree views,” thus confirming the role of ‘enthrallment,’ in this case experiencing spectacular scenery in motion, in many human endeavors.
Owing to Nero’s grand aspirations, around 65 AD, kinetics combined with a choice vantage point created an illusion of moving across the landscape thus challenging the architectural canon of static inevitability of the same. Architecture, like Icarus, breached the established norms of spatial constraints and gained an engineered dimension of freedom. Together with the business of status assertion, Macellum Magnum heralded the rotating restaurants of the future.

The first modern revolving restaurant was a consequence of hindsight knowledge. A few years earlier, designing merely a stationary restaurant for the TV tower in Stuttgart turned out to be an obvious omission as such exclusive vantage points do not come along too often. Designers of the Florian TV tower in Dortmund did not repeat this mistake. The Florianturm, opened in 1959, comprised a fully rotating restaurant thus marking a soon-to-follow race of cities to commission their own rotating attractions.

The second rotating restaurant was constructed on the top of a 120 meters tall silo building, a part of Henninger’s brewery in Frankfurt, in May 1961. An account by one of the patrons frequenting the Henninger Turm revealed an intimate experience with the rotating kinetics. Since only the turntable floor with the seating sections was rotating, the exterior walls and windows would slowly move past the tables completing a full cycle in one hour. Patrons would place notes on window sills and wait the full cycle to see what others had replied (Otoupal, n.d.), thus engaging in a spontaneous social interaction realized through exploration of an unusual setting. Such an outcome was unscripted by
designers and it was an indication that only the users of new environments could fully unravel their potential in often surprising ways.

3.5.5 The Thrill of the Ride – Giant Ferris Wheels

Giant Ferris wheels are a curious case of psychology of perception. Although their behavior is discernibly dynamic, their presence within the urban fabric is permanent and conspicuous. They are usually much larger than their horizontal cousins, revolving restaurants. Often they are the iconic accents in the silhouettes of cities like the London Eye, and they are capable of hosting dining or cocktails like the Viennese Riesenrad. Yet, there is some reluctance to call them architecture. Their vertical motion provides an advantage of generating scenic views merely by the merit of their large diameters. The vertical plane of rotation makes the experience of motion much more visceral – Ferris wheels are vertigo inducing machines. Furthermore, the vertical trajectory limits the access to a narrow localized segment of the wheel. Participants cannot enter or exit as they wish what adds an element of entrapment. Perhaps this is why vertical wheels do not integrate easily with other architecture or other functions. Rather, their purpose is limited, at least for now, mostly to the thrill of the ride. The concept of a Ferris wheel large enough to become a centerpiece of an amusement park can be traced back to 17th century. The first ‘giant’ wheel was built in Chicago in 1893. Within the next seven years, London, Vienna, and Paris had their Ferris wheels constructed. Then, it took almost nine decades before another giant wheel was commissioned in Yokohama in 1989. Since, five more giant wheels were built across the globe. Ferris wheels, unlike revolving restaurants, never became a subject of fashion craze. However, unlike the revolving restaurants, they have not faded away. Therefore, their full functional potential seems still waiting to be explored.

3.5.6 Rotating Detention

The idea of holding prisoners in a circular array of rotating cells having only a single access point was patented by Americans W.H. Brown and B.F. Haugh in 1881 (Brown and Haugh, 1881). However, the later patent issued in 1887 had only W.H. Brown’s name on it (Brown, 1887) thus perhaps indicating an authorship dispute as the drawings were almost identical except for detailing of the partitions between the cells and the access doorway.
The touted advantages included continuous surveillance of all inmates from a single fixed point and the security of a single doorway. The first rotary jail was completed at Crawfordsville in 1882. At least eight more, perhaps as many as eighteen, were constructed across the US. Unfortunately for the inmates, the inadvertent close encounters with the structure’s kinematics were resulting in frequent limb injuries (History of the Rotary Jail, n.d.). A somber record was entered in 1904 – the first recorded fatality due to operation of kinetic architecture (“Squirrel Cage” Jail Served County since 1885, n.d.). In spite of this, the longest-serving rotary jail in Pottawattamie County was operational until 1960 (ibid.). W.H. Brown’s keen eye for opportunity and a marketing flair have commercialized kinetics as a solution for detention. Although its use was controversial right from the onset, it remained in use for the astonishingly long eight decades.

3.5.7 Solar Opportunities – Solar Fringe

Subsidies aimed at promoting alternative/green energy solutions have spurred experimental projects and market-ready solutions like the Sündreyer – a photovoltaic panel-clad revolving roof, the Heliotrope – a rotating house with an orientable photovoltaic array mounted on the roof, and the Gemini house – a rotating cylindrical house having one side equipped with photovoltaic panels. However, at the end of the first decade of the 21st century, the global economic slowdown has put an end to most of the alternative energy subsidies. Without this additional support, the kinetics combined with the photovoltaics proved too expensive for the potential buyers, thus delegating these engineering feats to the commercial fringe even before a broader consumer feedback could be evaluated. The solar-powered, eco-friendly kinetic houses provided yet another example of the complex socio-economic circumstances governing the development of new technologies.

3.6 Architecture of Weather

The motion of the solar system is defining our environment through daily, seasonal, and tidal cycles. We exist in a tightly linked system of cause-and-effect interactions where the Earth’s ecologies are finely attuned to the effects of planetary motion. Archaeological evidence indicates a long history of humans mastering the ability to observe the celestial
motion, advancing the knowledge of its principles, and employing this knowledge in architecture. Built environments became a part of natural ecologies driven by celestial cycles – they needed to react to the changing weather and to adapt to the evolving climate. They became complex systems intersecting the human activity with the dynamics of nature. Architecture was not merely a static composition but a governing and reacting organism, the conveyor of human desires and the means for moderating the nature. Consequently, the stubborn Galilean “eppur si muove” applies equally to architecture. This section traces the history and the role of devices that enabled the buildings to fulfill such complex functions – the devices that were adjustable and configurable, the kinetic elements of architecture. While using the tentative notion of architecture as a dual purpose device, a tool of human culture and a weather shield, allows us to consider the architectural kinetics from these two perspectives. This distinction is meant as merely a working assumption, an initial reference to get a bearing on the largely uncharted history of kinetic elements in architecture while heeding the caution that in human culture the mundane is inseparable from the ritual (Banning, 2003).

3.6.1 Architecture of Shadow

Architecture and the Sun co-exist in a state of a negotiated truce. Buildings harvest sunlight to illuminate and sometimes to warm up their interiors. They also shield the interiors when sunlight becomes too intensive. Sunshades are dealing with the most apparent consequence of the celestial motion – day and night. Sunshades are the squinting eyelids of the buildings. They animate architecture and transform it into a responsive homeostatic system. It seems reasonable to suppose that simple shading devices accompanied humans from the earliest prehistory. Foliaged branches, animal skins, and wickerwork are the conceivable archetypes for modern canopies, screens, awnings, and blinds. When combined with architecture, such devices form the kinetic layer of buildings – the adjustable shading systems. Though merely shading devices, they often become the expressive faces of buildings and the showpieces of designers’ skills.

Roman velaria were used in amphitheaters to protect spectators from sun. Velaria were large sheets of canvas deployed over rope riggings suspended from masts reaching above the uppermost rows. Although modern depictions and reconstructions tend to
interpret velaria as tightly stretched membranes, they were rather draped with a generous slack thus following the logic of catenary physics. A tight stretching would require an insurmountable force as for a straight line the catenary equation is nearing an infinite stress. A Pompeian fresco from the house of Actius Anicetus shows a loosely draped velarium over the seating area of an amphitheater. A conceptual equivalent of raising a hand to shade eyes while squinting against the Sun, velaria were simple yet effective devices and forerunners for modern deployable shading systems over large public venues.

Santiago Calatrava’s Quadracci Pavilion at the Milwaukee Art Museum, completed in 2001, responds to light with its body. A conceptual opposite of Nouvel’s reactive surface, it gestures its grand sculptural wings over the central skylight. The Institut du monde arabe explores the micro-scale, the skin effects. In contrast, the Pavilion’s structure is an articulated skeleton of an animated beast. The expressive form establishes a landmark that can be seen from far (Figure 3.13 Left).

Figure 3.13 Santiago Calatrava, Quadracci Pavilion, Milwaukee Art Museum, 2001 (Left photo by Michael Hicks; used under a CC BY license; source http://en.wikipedia.org/wiki/File:Milwaukee_Art_Museum_1_(Mulad).jpg) (Right photo by T. Canaan; used under a CC BY-SA license, source http://en.wikipedia.org/wiki/File:Interior_Milwaukee_Art_Museum.jpg)

However, the kinetics of the building remains distant and unapproachable – a consequence of the scale and the composition. The external wings contribute little to the ambience of the
interior (Figure 3.13 Right). Although grand and expressive from afar, the awareness of the kinetic form vanishes if near or inside, overtaken by the curvaceous excesses of the building. The moving wings are a decoy, an attractor to lure the curious; then the building sheds the kinetic pretense and ingests them into the baroque of its concrete entrails.

Designed by Santiago Calatrava in the mid-1990s, the skylight over the cantonal emergency call center in Sankt Gallen is an example of pragmatic and balanced use of kinetics. A folding sunshade over the ridge-shaped skylight hints at the noteworthiness of the place in an intriguing yet minimalist way (Figure 3.14). The folding structure can be seen from many directions, but it cannot be approached up-close, which is appropriate for the sensitive function of the center. The structure, without becoming intrusive, adds an element of intrigue to the picturesque townscape of Sankt Gallen. It is a successful insertion of a large kinetic feature into subtle historic urban fabric.

![Figure 3.14 Santiago Calatrava, the skylight over the cantonal emergency call center, Sankt Gallen (Photo © Madalina N. Wierzbicki).](image)

The Villa Girasole transcends using auxiliary devices like sunshades for negotiating with the Sun. Instead, the entire building turns away to keep its courtyard in a persisting shadow. This radical vision of seeking a shadow refuses to be regarded in terms of practicality or sanity. Because of its obsessive surrender to a single goal and its grand scale, it bypasses the objections of a reasonable mind, and instead it commands a humble
and reverend submission to its logic precisely in the same way the Mének megalithic alignment or the Stonehenge does.

![Figure 3.15 Angelo Invernizzi, Villa Girasole, 1935 (Photo courtesy of Fondo Angelo Invernizzi, Archivio del Moderno, Mendrisio, Switzerland)](image)

Unlike many other rotating buildings, the shape of the Villa is not a symmetrically revolved volume. The pivot point is the very corner of the L-shaped building, its wings being swung around like the arms of a colossal clock (Figure 3.15). The massive concrete complication was executed with unstoppable determination as if resources and technologies had no limits (Figure 3.16). A round four-story tall building, partially buried into a hillside, formed the pillow block to locate and to support the revolving part. A tower-pivot housing the staircase marked the corner of the two storey L-shaped moving superstructure. The tower reached the full four storeys down into the base building to rest on a mill-sized roller bearing. Circular tracks guided the carriages supporting the revolving wings. Diesel motors supplied the torque to rotate the upper building. This fusion of a dream and mundane industrial hardware was completed in 1935, thus marking the inception of the first artificial shadow-seeking ecology.

The adage that kinetics demands reliability became the persistent fact of this ecology. The concrete finish of the exterior developed cracks after the first revolutions. It was replaced with aluminum panels. With time, it became clear that the tolerances of the entire complication exceeded the absorbing capacity of its structure. Although cast from lightweight fiber-reinforced concrete, the structure began to gradually crumble.
Lewis et al. skipped the technical finesse to deliver a somewhat blunt verdict, as if reinforcing the inevitability of the Icarian tragedy:

> By constructing a “machine-for-living” that arrests the temporal cycle of a day, Invernizzi’s villa is, in effect, a time machine in the process of destroying itself. (2005)

However, arresting “the temporal cycle” may not be necessarily at fault here. Rather, challenging simultaneously architectural paradigms and the limits of technology while breaching the boundary between whimsy and engineering proved too much for the designers of the Villa. In a way, the Villa Girasole echoes the Icarian allegory of getting too close to the Sun. Yet, we know that the fall of Icarus has not precluded the prospect of flight.

### 3.6.2 Modern Public Venues – Architecture of Weather

Although they are the abstract descendants of Roman velaria, the contemporary retractable roofs perform a more complex role than that of just a sunshade. This role varies depending on the local conditions. For instance, the air-conditioned arena in Pittsburgh functioned best when covered regardless of the outside weather. However, the very recent roof over
the Wimbledon Centre Court is intended solely as an umbrella for serious rainfalls – when deployed, it is said to cause uncomfortably damp conditions inside.

The first modern retractable roof over a stadium was a consequence of using architecture to promote the image of a city. Although not exactly a new idea, it marked the post-war revival of cities asserting their prestige, and coincided with the increased use of kinetics. The arena in Pittsburgh, initially intended to be covered with a fixed fabric roof, became an instrument of advancing the status: “What better way than to build a massive, open-air structure unlike any other in the world?” (McConnell, 2010). The arena’s steel-clad dome, completed in 1961, was split into offset sections, which could slide under the stationary segment when retracted. The central common pivot point for all the segments was supported by a cantilevered structure extending over the roof. However, the usefulness of staging “performances under the stars” seemed to be limited solely to displays of the kinetic extravaganza as ideal weather conditions for open air events were rare. Toward the end of its service, the dome was kept just in a closed position.

The Olympic Stadium in Montreal was intended as a showpiece of Organic Modern Architecture – a symbol of status and technological sophistication. The retractable roof echoed the elements of Roman velaria such as the use of canvas and rope rigging. Its foldable sheet of Kevlar was to be pulled up or lowered from an inclined tower rising above. However, the completion of the tower and the roof’s membrane was much delayed. Once completed in 1987, the retractable roof proved to be unreliable and prone to frequent tears requiring costly repairs. Consequently, this conceptually poetic but technically unfeasible design was replaced, after 10 years of troubled use, with a fixed roof.

Later designs of retractable roofs for large stadiums relied mostly on non-intersecting kinematics of individual rigid sections. Furthermore, to avoid design complexities like an additional cantilevered beam of the Pittsburgh arena, the sections were designed to be self-supporting. The Rod Laver Arena in Melbourne, opened in 1988, featured a simple kinetics for its retractable roof comprised of only two large sliding plates. The roof over the Toronto’s SkyDome, installed in 1989, was a combination of two rotating and two sliding segments stacking over each other thus being more compact when retracted. Although more complex than two-plate designs, the SkyDome roof proved to be reliable. The two-plate design became the most popular with large venues. It was

The lightweight structures of the rigid segments in the Reliant Stadium’s roof were covered with translucent fabric thus hinting, in a symbolic way, at the possibilities of foldable fabric-and-frame structures. Such designs have already been realized before on a smaller scale. In 1999, Escrig designed a retractable roof comprising an articulated arched lattice and fabric cover for the Jaén Auditorium. In 2000, Tillner used an array of articulated frames for a foldable roof over the Inner Courtyard of Vienna’s City Hall. The roof over the Wimbledon Centre Court, installed in 2009, is a large size installation using a combination of foldable fabric and articulated frames.

In half a century since their inception as the exponents of status and technological abilities, and after having experienced its share of Icarus-like projects, retractable roofs over public venues have matured into functional and reliable solutions. The innovation in kinetics is mostly directed at the folding fabric-and-frame designs, while rigid retractable concepts have regressed to the simplest two-plate sliding configuration, thus demonstrating an evolution and a natural selection as applied to kinetics.

L’Hemisfèric in Valencia demonstrates that the large scale kinetics needs not be unapproachable. Designed by Santiago Calatrava, and completed in the mid-1990s, it has its folding sides and pivoting panels at the ground level and readily accessible (Figure 3.17). Intended as the giant wind-screens, the hinged and pivoting structures encircle the interior and determine its machinelike ambience. The incompatibility of human bodies with machinery in motion has been resolved by ensuring large clearances between all moving parts. Even with all elements in fully closed position, there is still enough room for an intrepid visitor to slip by (Figure 3.18). The kinetics of the L’Hemisfèric is entirely for the effect – its functionality is tentative. The revolving glazed panels at the ends of the building were meant to control the ingress (Figure 3.19). However, in the closed position, they leave a space generous enough for even a tall person to enter with a minimal bow. More importantly, the clearances combined with the playful form and the lightweight feel of the panels are hardly an intimidating barrier. Rather, they invite to explore. The glazed folding sides provide no benefit as sunscreens. They are effective as windbreaks, but they let rain in (Figure 3.18) because of large clearances between the individual panels.
Figure 3.17 Santiago Calatrava, L’Hemisfèric, Valencia, details (Photos © Madalina N. Wierzbicki)

Figure 3.18 L’Hemisfèric, interior (Photo © Madalina N. Wierzbicki)

Notwithstanding the functional symbolism, the expressive zoomorphic rendition of openable nostrils and foldable gill covers delivers an unforgettable visual treat. The zoomorphism is tentative too, which is rather desirable – too literal of a metaphor loses its timelessness and the flexibility to engage. At night, the illuminated sphere of the auditorium becomes visible through the exterior glazing. Reflected in the surrounding pool, it becomes the entire pupil of a gigantic eyeball complete with foldable eyelids (Figure 3.20). Unmistakably, the L’Hemisfèric is architecture of enthralment.
3.7 Architecture of Celestial Motion

The motion of the solar system is defining our environment through daily, seasonal, and tidal cycles. We exist in a tightly linked system of causality in which the Earth’s ecologies are finely attuned to the effects of planetary motion, and so are we:

The astronomical phenomena of alternating day and night and the succession of seasons regulate the life of man since the origins. (Lequeux and Vigroux, 2011)
Our ancestors were never passive in this relationship as they acknowledged, from the earliest times, celestial choreographies through one of the primordial expressive media available to them:

At first human beings imitated the movements of the stars, in dance: they participated in a celestial motivation that had its origin beyond the province of comprehension, so they appropriated it through the agency of the body and made it their own; they made a representational alternative that carried its celestial reference physiognomically and by doing so held within itself an opening onto cosmic truth, to be experienced each time the representation was encountered. (Knights, 1994)

Furthermore, humans were expressing the awareness of celestial phenomena in their material culture. The earliest known artifacts include the Ishango bone believed to be over 20,000 years old and the paintings at the Lascaux cave dated to be 19,000 years old (Magli, 2009). Archaeological evidence indicates a long history of humans mastering the ability to observe the celestial motion, advancing the knowledge of its principles, and employing this knowledge in architecture (ibid.). According to Lequeux and Vigroux, “astronomy was the first science, and a very useful one.”

Astronomical observatories are a unique category of buildings – their kinetic structures can purposefully synchronize with the apparent movement of planets or stars. They literally are the architecture of celestial motion. Although nowadays astronomy is merely one of many sciences, and it is abstract in nature (Lequeux and Vigroux), the situation was much different before the technology of an atomic clock. The atomic clock has revolutionized the metrics of our world by being more accurate than time calculations derived from planetary motion. The accuracy and reliability of atomic clocks has enabled a purely artificial spatial indexing of the entire globe – the Global Positioning System. Precise navigation without referring to landscape or to stars became possible. However, before atomic clocks, astronomical observatories were instrumental in supporting the navigation – they provided the time reference and charts for calculating the position using observations of celestial bodies. Astronomical observatories were the providers of the global temporal and spatial metrics. Not surprisingly, the Edinburgh Encyclopaedia (Observatory, 1832) asserted that astronomy is “the noblest and most sublime of all the
“The same source noted the cultural importance of astronomy and the reflection of this importance in material culture throughout the history:

Though the information which can be drawn from ancient history is often imperfect; yet we find that all nations, among whom astronomy has been cultivated, have had their observatories at a very early period. (ibid.)

The megalithic structures of the Goseck Circle, Stonehenge, Kokino, and Arkaim sites span a period from 4900 to 1700 BC. They index astronomic events like lunar cycles, solstices, and equinoxes using architecture as a permanent imprint of celestial motion, and creating an eerie branding of the ephemeral in the hardest of matter. The massive static geometry became a metaphor for expectation, for patient awaiting to witness the inevitability of celestial cycles. Until the 19th century, architecture remained merely a static companion to the practice of astronomy – a solid referential platform and an affixed protective shell for the instruments. Such an approach was well suited for the 18th century’s observation methods, which were confined exclusively to the meridional plane thus requiring no horizontal mobility of the instruments.

Although meridional observations were a significant progress at that time, their affixed plane of view has become a hindrance later (Chapman, 1995). The invention of an equatorial mechanism addressed this shortcoming by the end of the 18th century (ibid.). Equatorial sectors could take angular measurements between any arbitrarily chosen points on the celestial sphere. Equatorial mounts could point large telescopes at any point of the firmament and keep that point in sight by counteracting the apparent motion due to Earth’s rotation. However, these instruments required horizontal mobility – they needed to be swung around. Furthermore, these complex, precise, expensive, and difficult to procure instruments needed protection from the elements. Therefore, they required enclosures that were effective as shields protecting the investment, yet capable of following their horizontal motion. But, the very first rotating cupola constructed for astronomic observations predated the equatorial mounts of the late 18th century, it predated even the dawn of optical astronomy. The earliest rotating enclosure integrated into a building structure was conceived by Tycho Brahe around 1581. Brahe, the last and the most significant name in the naked-eye astronomy, designed and supervised construction of his instruments. He also designed the buildings to house these instruments (Brahe,
Brahe’s ultimate realization was the Stjerneborg, an ideal observatory equipped with individual subterranean chambers capable of isolating the instruments from vibrations. Brahe described the rotating roof installed over a chamber housing the Revolving Azimuth Quadrant,

This instrument with its small crypt-turret is covered on top by a roof, made of small, smooth beams, ingeniously joined together and connected, below the horizontal top of the wall and outside the azimuth circle, by a strong, round wooden ring. Hidden inside this ring are wheels, placed opposite each other in four places. With the aid of these wheels the roof can be turned around, with little effort, as may be desired. (Brahe, 1598/1946b)

as well as similar roofs over other instruments. The chambers $D$ and $E$, the smaller red-walled structures on the left side, and the chamber $F$, the middle-bottom one, (Figure 3.21) were equipped with the rotating roofs. The largest of them, chamber $C$, instead of a rotating one, had a “roof which can be opened towards any desired direction” (ibid.).

Figure 3.21 Tycho Brahe, Stjerneborg, circa 1581 (Brahe, 1598; digitized by Det Kongelige Bibliotek, København; used under a CC BY-NC-ND license; source http://www.kb.dk/en/nb/tema/webudstillinger/brahe_mechanica/toc.html)
Brahe’s brilliance, personal wealth, and determination carved out a unique niche in the scientific landscape of the 16th century. However, his observatories “were destroyed in the course of a few decades after his death” (Strömgren, 1947). Although his writings have survived together with the defining contributions in astronomy, nothing has remained of his instruments and movable enclosures, the unique feats of engineering that transcended his times. Brahe “broke with his family’s traditions” and “quarrelled with his king” (ibid.). His relationship with the neighboring villagers was not much better because of the demands he placed on them regarding the construction of his observatories. Sadly, being out of touch with such social contexts resulted in the erasure of Brahe’s material legacy as if his contemporaries merely smoothed out an anomalous wrinkle. The ensuing administrative land divisions disregarded the location of Stjerneborg entirely and resulted, by the end of the 18th century, in a road passing over the site’s corner. The unmindful outline of the road was still clearly visible after the reconstruction in 1950-ties (Figure 3.22 Right). By the beginning of the 20th century, the scant remains of Stjerneborg’s foundations (Figure 3.22 Left) resembled the obliterated by millennia enigmatic relics of Neolithic settlements.

It took a century-and-a-half for astronomers to adopt Brahe’s pioneering enclosures. Airy’s brief note indicated the earliest possibility of a “moveable” roof at the Greenwich observatory:
In 1779 ( . . . ) the sliding shutters were placed upon the Advanced Building. It appears, however, that before that time there had been a moveable roof of some kind, probably constructed in 1749. (1845)

In 1769, the first rotating dome in a modern sense was installed on the King’s observatory at Richmond (Lambert, 1806), thus heralding the iconic leitmotif for observatories of the 19th century. Another Airy’s entry confirmed the first revolving structures at Greenwich:

About 1770 . . . the two turrets H and L, or summer-houses ( . . . ), were covered with revolving domes. This date is confirmed by a carpenter’s inscription which I have found cut upon the chain of rollers (which was discovered upon taking off some of the internal lining); the year there marked is 1773. (ibid.)

In 1785, a new observatory complete with a rotating dome, the first in Ireland, was completed in Dunsink (Ball, 1895). In 1790, two more observatories with rotating domes were established: the second Irish observatory at Armagh (Moore, 1967) and the first one in the mainland Europe at Palermo (Foderà Serio, 1993). The decades-long lead of the mainly British engineering was not by a chance. According to Turner (2003), the then divided Germany “did not create the political, economic, and social conditions for many precision instrument workshops to flourish,” while

In France, too, the economic and social climate was less favorable than in England to innovation in precision instrument-making until the last decades of the eighteenth century. (ibid.)

Not surprisingly, the observatory at Palermo, and many other in Europe, commissioned their instruments from “London’s leading maker Ramsden” (McConnell, 2007). The examples of Brahe’s inventions and instrument-making industries in England, Germany, and France demonstrate the long-lasting, many decades and even centuries, effects of political and social decisions on the development and acceptance of new technologies.

By the beginning of the 19th century, the classic form of an astronomical observatory as a “building with a dome” became universal (Wolfschmidt, 2009). In the analogy of buildings as bodies for human bodies (Gamble), the orientable cupolas were the extensions of human eyes; they became the sense of sight for the architecture of cities. Today, although light pollution has banned stargazing from cities and highrisers obstructed
vantage points, these cupolas are still easily noticeable artifacts of the era when an observatory was the measure of a city’s prestige (Figure 3.23).

![Figure 3.23 Left: Observatory, Department of Advanced Geodesy, Czech Technical University, Prague; Right: Observatory, Physikalischer Verein, Frankfurt (Photos © Madalina N. Wierzbicki).]

The function and the underlying philosophical motivation of astronomical observatories have changed since the inception of an atomic clock. The astronomy of the 18\textsuperscript{th} and 19\textsuperscript{th} centuries was concerned with mapping the visible universe and determining its motion for the immediately practical purpose of reliable navigation. The modern astronomy peers beyond the corporeal and seeks the understanding of the reasons for celestial motion:

> Although astronomy was a directly useful science in the past, it is at present essentially pure science. (Lequeux and Vigroux)

In a curious way, the modern astronomy, by becoming abstract, highly theoretical, and freed from the mundane of practical applications, seems to be more distant and mystifying than the tangible cosmology of the Age of Enlightenment. The massive kinetic architectures of the latest observatories (Figure 3.24), deported to remote locations and equaling in size the largest of sporting venues, are closer in their enigmatic purpose to the megalithic structures of Goseck and Stonehenge rather than to the urban-fitting and architecturally mainstream observatories of the past centuries. Regardless, the business of astronomy remains steady and new facilities are being continuously developed:
The last three decades have seen almost exponential growth in the numbers of large and very large telescopes, with the unanticipated current situation that there are almost as many VLTs as there are 4m-class telescopes. This growth in numbers has been curiosity-driven, but obviously technology-led. (Charles, 2011)

Observatories can be, like the W.M. Keck, the expression of a human dream. They can be, like the Gran Telescopio Canarias, the purveyors of a national prestige. They also can be, like the Subaru Telescope, the measure of a corporate status. Such multitude of agendas appears to be unified in a single goal, the ultimate obsession of unraveling the secrets of cosmogony, possibly a contemporary metaphor for the flight of Icarus.

Figure 3.24 The European Extremely Large Telescope (E-ELT), Cerro Armazones, Chile (Image by ESO, the European Southern Observatory; used under a CC BY license; source http://www.eso.org/public/images/elt_plane/)

3.8 Architecture of Spectacle

Arenas of Roman amphitheaters were complex systems of trap floors and elevators to support fast-paced stagings of their days. The amphitheater of Pompeii dates back to 70 BC, and it is considered to be one of the oldest known. The mechanical installations of Roman amphitheaters were the precedents for modern elevators and movable ramps.

19th century’s Parisian entertainment industry proved that enthrallment is a potent force driving new technologies by contributing spectacular examples of engineering fused with architecture. Almost half of the cavernous building of the Palais Garnier (Paris
Opera), completed in 1875, was an intricate mechanism of movable backdrops, adjustable stage platforms and lifts that could transform the interior to dazzle audiences. The conversion of the Salle Valentino hall into an aquatic circus in 1886 was an impressive achievement of engineering (Figure 3.25). A large movable circular iron stage was installed over a pool. The stage could be, within seconds, fully submerged under water (The Nautical Arena, or Aquatic Theater, 1886).

Figure 3.25 Salle Valentino aquatic circus, Paris, 1886 (The Nautical Arena, or Aquatic Theater, 1886; digitized by Google; work in Public Domain)

The Winter Olympic Games in Salt Lake City and in Vancouver both illustrate that enhancing the spectacle with kinetic installations brings along the statistical inevitability of the Mean Time Between Failures (MTBF). Salt Lake’s Hoberman Arch, installed in 2002, used overlapping metal-framed panels arrayed into a circular linkage assembly operating like an iris. It was used as a visual stunt during the Winter games, but it remained inoperational since. It was a unique concept that attempted to integrate an array of rigid articulated plates with a foldable linkage assembly. In 2010, four unfolding cauldrons were intended as the centerpiece of the opening ceremony in Vancouver. However, one of them failed to deploy.
3.9 Kinetic Façades

A latticework of mechanical irises patterns the entire façade of the Institut du monde arabe. It forms a vast slab of glittering clockwork viscera levitating over the main court and bonding the entire space in a spectacle of reflections (Figure 3.26).

Figure 3.26 Jean Nouvel, Institut du monde arabe, Paris, 1987 (Photos © Madalina N. Wierzbicki)

Inside the building, the mechatronic vitrail permeates the interior with light effects and imposes the dominating leitmotif. It is accessible and can be examined up-close thus inviting to an intimate encounter with the exotic aesthetics (Figure 3.27). Designed by Jean Nouvel in 1980’s, the installation was intended to automatically modulate the irises according to the intensity of sunlight. However, kinematics has proved that it demands reliability. While fulfilling the logic of the weakest link, the prone to fracture mounts of actuators immobilized the entire installation soon after the opening. In Nouvel’s design, the slim iris assemblies were permanently sandwiched between sheets of glass. They were inaccessible for repairs, thus proving that kinematics also demands serviceability. The incredulous gaze of irises immobilized at various apertures invites now to imagine the play of blinking and squinting metal and building-organism being alive – like an abandoned rail track that is invoking dreams of thundering locomotives.

The Institut du monde arabe has become a curious dichotomy of architecture – the iconic landmark, and kinetics – the epic ruin. Though affixed, it is a metaphor for motion. Nouvel’s project delved into the potential of new technologies – the expressive filigree of
embedded mechatronics and the façade as a live and instinctively reacting skin. It interpreted the technology as an implant, a reactive texturing enhancing the function and the expression of building’s shell. It established the direction and the milestone for exploring the scales, the functionality, and the aesthetics of the future embeddable technologies like regenerative materials, MEMS, or Metal-Organic Frameworks.

Figure 3.27 Institut du monde arabe, interiors (Photos © Madalina N. Wierzbicki).

Ned Kahn’s kinetic scale-like façades are the wind-catchers. The vast surfaces of freely pivoting plates react to wind-blown eddies, thus transforming the orderly array of articulated metal into a giant mechanical drape, a modern incarnation of the Semperian archetype, textile.

Chuck Hoberman’s adaptive shading system for the POLA showroom in Japan, completed in 2009, is an example of pragmatic application of simple appliance-like kinematics while achieving a spectacular visual effect. Curved and patterned polycarbonate panels can pivot 90 degrees from a position forming a continuous undulating skin to being recessed into the corresponding niches of the elevation thus providing maximum of unobstructed view.

3.10 Kinetic Residences

Kinetic residences exemplify the fulfillment of personal dreams and visions. They accomplish a variety of purposes: energy efficiency, changing scenic views, promoting
ideas, being the expressions of social status, and being the means of flexible living and enthralment.

The “Revolving House,” constructed for the Parisian Exposition de l'Habitation in 1903 (A House that Turns with the Sun, 1903) was a traditional house tucked onto a rotating platform. Although most of the visitors might have regarded it as merely “an architectural curiosity, with no practical value whatever,” it was a demonstration of the then popular “doctrines of heliotherapy” (ibid.). In contrast, François Massau’s three rotating houses, constructed at Wavre in Belgium in 1950-ties, proved to be functional and enduring till now (Tagliabue, 2008). Massau’s entire life epitomized personal perseverance at the cost of being at odds with most of the local community:

“There’s total indifference,” said Guy Otten, a retired journalist who often wrote about Mr. Massau. “He was always seen as eccentric. He was never appreciated here.” (ibid.)

Massau’s houses were unusual in that only the cylindrical living area rotated while held between the fixed foundation and roof slabs. Although reliable and effective in exploiting the precious moments of the often scarce Belgian sunlight, they were shunned by locals (ibid.), thus proving, in an unfortunate way, that even successful and viable technologies require a network of social relationships in order to succeed.

The Sliding House designed by de Rijke Marsh Morgan Architects and completed in 2008, stands out from the crowd of rotating pod-shaped houses of the last decades. The external shell comprises three segments sliding over each other, thus exposing or shielding various parts of the glazed interior (Figure 3.28). The house stretches or folds its exterior shell in

Figure 3.28 de Rijke Marsh Morgan Architects, the Sliding House, 2008 (Photos by Ross Russell and Sally Morris; used in accordance with the conditions http://www.therussellhouse.org/html/hi_res_images.html)
response to changing time of the day or weather, much like a flower sensing the environment and revealing or hiding its unusual glazed bud.

3.11 Closing Remarks

Each of the designs discussed in this chapter represented an encompassment of addressing functional requirements (real or perceived), seeking means of unique expression (to express status, authority, or to impress), and getting ahead of the competition. According to Smail, technologies change fast, while the human psychology and the essential needs tend to evolve much slower. Therefore, we can expect to keep closing and opening doors in the foreseeable future. Changing technologies can provide entirely new solutions to old challenges. However, in case of architecture, the human scale is the reference. So, even embedded MEMS (micro-electromechanical systems) based technologies will not alter the reference scale of human habitats. For instance, a door will need to provide a certain clearance based on the typified size of human body; also, the sizes of stadiums did not quite change since antiquity, only so many people can be seated while providing a reasonable view for all of them. The cultural context also affects built environments. For instance, we do not build gates to cities anymore. Such means of access control lost their defensive value a long time ago. Furthermore, they would not be compatible with modern transportation networks and available technologies. They also lost their symbolic value: we simply do not acknowledge entering a city as a culturally significant moment. Technologies not only evolve, they also fade away and vanish. For instance, we doubt whether we could build the Egyptian pyramids today. Though there are many examples of technologically advanced kinetic solutions, they fulfill mostly isolated functions appended to otherwise traditional static structures. Consequently, despite all the technological and computing progress, little has changed in the way architecture interacts with its users (Ataman, 2005).

The vision of a morphing space that interacts with users and responds to their requirements has not materialized quite yet. Yet, the historic landscape is marked with relics of visions once materialized by the determined effort of a few individuals who transcended the limits of available technologies, who disregarded mainstream practices,
and who often ignored social realities. Nero’s rotating dining terrace, Tycho Brahe’s Stjerneborg, W.H. Brown’s rotating prisons, Angelo Invernizzi’s Villa Girasole, and Saidman’s rotating solaria are examples of projects that, although they were the groundbreaking achievements of engineering, they were so out of context of their own times that their respective societies could not or would not assimilate such legacies. Inescapably, they faded away together with their creators.

Nevertheless, the progress of kinetic architecture, though not as dynamic as envisioned by Zuk, is being continuously marked by daring experiments like the Walking House and pioneering projects like Santiago Calatrava’s entrance at Sankt Gallen. These projects indicate that, technologically, kinetic architecture and interactive synthetic environments are already possible. Therefore, the lack of social demand together with the political and economic circumstances seem to be currently the dominant obstacles on the path toward the proliferation of kinetic architecture.
CHAPTER 4 Kinetic Architecture – The Solution

This chapter first explores the current state of built environments in conjunction with the role played by the construction industry in reaching this state. Next, with the objective integrating kinetic architecture into built environments, some new paradigms are presented. Within the theme of the present thesis, which integrates human-centric considerations and digital technologies into the architectural and engineering considerations of the design and development of kinetic built environments, some innovative concepts, design methods and tools are presented. Advantages of the introduced methodologies and the underlying challenges are discussed. Social acceptance of the proposed architectural innovations and rather abstract ethical considerations are indicated.

4.1 Current State of Built Environments and Construction Industry

Researchers express growing concern about the performance of buildings, the quality of built environments, and the state of the construction industry. Although it has been identified as the largest industry in the world (Prieto, 2009), the largest consumer of energy and materials (Kibert et al, 2002), and the largest source of waste globally (EPA, 2009; Stenis, 2005), it continues to be outdated (Ozorhon et al., 2010), lacking “systemic innovation” (Prieto), and “reluctant to change” (Anumba, 1998). Koskela and Vrijhoef (2000) blamed its underlying concepts for being “a hindrance for innovation,” while others pointedly critiqued its culture:

The widespread culture of the construction industry is a demanding, confrontational one, which has underpinned the inefficiency and the ineffectiveness of its processes. The strong resistance to change could be partly attributed to the strong and rigid culture of the construction industry. (Aouad and Arayici, 2010)
Consequently, its efficiency and productivity are poor (Doran et al., 2009) and continuously declining (BRANZ, 2010).

Better design approaches have been discussed for decades. Zuk and Clark (1970) theorized that kinetic structures would be essential for meeting the increasing needs of rapidly growing population. Menges and Reichert (2012) emphasized that the efficient material use needs to be based on “interaction with, rather than protection from” environmental conditions. A report by the Building Research Establishment (BRE, 2006) asserted that adaptability is essential for improving energy efficiency and reducing construction waste. Kinetic architecture could offer better space sharing, adaptive and secure access, efficient off-site fabrication, ease of deployment, flexibility of usage, enjoyment and emotional fulfillment, and safety during catastrophic events. Furthermore, on-demand adjustable structures could transform the construction paradigm from the traditional inefficiency of construct-and-demolish into the lean flexibility of assembly-and-reconfigure. However, in spite of the broadly discussed potential advantages of kinetic architecture, the industry has shown little interest in it and has made no significant progress (Ataman, 2005).

4.2 New Paradigms for Built Environments

The milestone that initiated the co-evolution of technology and architectural paradigm toward environments capable of interacting with occupants may perhaps be attributed to Le Corbusier. His declaration that “the house is a machine for living in” (Le Corbusier, 1923) used the bright and minimalist palette of modernism to redraw a passive picture of cozy surrender to architectural scenography as a dynamic and efficient process – the exhilarating feel of modern living. Fifty years later, Negroponte filled in the open-ended and provocative vagueness of Le Corbusier’s line with new technology. Cybernetics, computing, automation and artificial intelligence imbued built spaces to project a vision of robotic environments at occupants’ service – “architecture machines” (Negroponte, 1969). Within few decades and under many guises, the pursuit of new architectural paradigms ensued to explore and harness the emerging technological affordances. Negroponte (1975) theorized “architecture machines” as “intelligent” and “responsive.” Others joined and
formed a broad research front aimed at “intelligent” (Bowen-James, 1997), and “reactive” (Cooperstock et al., 1995; Buxton, 1997) environments. Mostly, researchers viewed such environments as automated appliances capable of sensing and interpreting occupants’ actions in order to purposefully adjust or engage appropriate functions. Wireless technologies spurred a distinct research thread. “Mediated spaces” (Renò, 2005) and “augmented spaces” (Aurigi, 2008) focused on the behavioral and social implications of ubiquitous connectivity.

The underlying thread of the majority of this research is the focus on the “typical” and “usual” – the focus on enhancing and facilitating programs, activities and conditions that are the repetitive daily routine of a particular setting. It is important to realize that architecture has been accompanied by similar, in concept at least, enhancements aimed at facilitating the routine for millennia. Delivered by trained and ready ranks of servants, slaves, maids, butlers, doormen, messengers, musicians and waiters, such enhancements were a part of responsive, intelligent and mediated experience to the social elites of the past. What is then different about the current pursuit of ‘enhanced’ environments? The industrial revolution seems to provide a fitting analogy. A wealth of sophisticated fabrication methods was known and used for millennia (Wright, 2005). However, only mass production has made the manufactured goods easily accessible and affordable. Similarly, the comforts of on-demand personal service and attention, previously accessible only to some, are now theorized as a mass offering of technology available soon to everyone.

An opportunity to expand the functional, performative aspect of architecture was hinted at by Zuk in 1970: “An evolutionary trend toward kinetics in building is becoming evident and this trend may be inevitable”. However, 35 years later, Ataman (2005) conceded that “to date architecture has failed to utilize the vast amount of accumulated technological knowledge and innovations to significantly transform the industry.” Traditionally, the architectural canon holds that building forms are static, non-adaptable infrastructures developed to support social processes.

Decisions regarding function, aesthetics and lifecycles of buildings and the resulting urban grid are seen as a part of the initial planning and design process. Once buildings are erected they form a permanent and unchangeable manifestation of these
decisions. From that moment inhabitants and managing authorities have to conform their needs to such fixed infrastructures. The inertia of these systems is obvious when exposed to changing social demands or functional conflicts and exclusions. In this context the potential benefits of structures that are configurable and functionally adaptable are immediately apparent. Ultimately, they can more effectively address the extended set of contemporary requirements. These requirements call for better safety when faced with natural and man induced disasters. They encourage meaningful environmental responsibility. Foremost, they define the functional and comfort expectations of societies that are far more dynamic and complex than 35 years ago. The increasing emphasis on building performance and the underlying digital simulation technologies are fundamentally redefining expectations of the building design, its processes, and practices. In such context, performative architecture is understood as a design paradigm driven by comprehensive economic, cultural, functional, and physical performance (Kolarevic, 2003).

Built environments that are morphing, interactive, and ‘intelligent’ can challenge our traditional understanding of the controlling role of humans-inhabitants. Lister et al. discussed the tentative and often illusory nature of being in control:

Let us then consider that while it may seem self-evidently true that humans put machines together, does it automatically follow that humans and their cultures remain in control of them? The view that human beings (or human cultures and societies) are in control of their machines works well as long as we consider simple machines or tools, but it works less well when we consider complex machines or systems of machinery. (2009)

Other researchers identified the importance of built environments in shaping behaviors, and attitudes. Interactive environments of the future will significantly expand this role, thus becoming the embodiment of technology that is “physically constructive of a vast array of cultural phenomena” (Lister et al.).

4.3 Advantages

Built environments are immediately noticeable and, in a physical sense, most representative of human activity, which is dynamic and transformative. They define the
human ecosystem. Unprecedented technological, economic and demographic dynamics of mankind is putting to test traditional building codes and construction standards. The question is if building structures could better address increasingly complex requirements of the modern world. Could they offer increased comfort under adverse climatic conditions? Could they afford functional advantages in densely populated areas? Could they mitigate ecological footprint of new construction? Most importantly, could they provide better protection under extreme circumstances like natural or human-caused disasters? Could they assure means of easily deployable, robust and adaptable sheltering under emergency conditions? In the end, could they more effectively serve and save human lives?

The unique features of foldable structures may change the traditional building maintenance and lifecycle models and offer reconfiguration as an option to demolition. In general, configurable structures will provide lesser environmental impact than traditional technologies as they are better suited for re-using, modifications and re-location. The technologically enhanced architecture forebodes built environments that could adapt to climatic changes, that could manage urban crowding, and – most significantly – that could moderate human behaviors. Such environments could facilitate or inhibit, they could liberate or constrain, they could become a meaningful and indispensable component of urban fabric or they could inconspicuously slip into insignificance. Intelligent and adaptive urban systems will be critical in addressing the exponential demographic growth, impending climatic changes, and better manage the ecology (Weinstock, 2011). Ultimately, they could alter the traditional paradigm of architecture as merely a passive backdrop to human activity. However, even though many experimental projects highlight the possibilities of new technologies (Cronin, 2011; Haque, 2007), the vision of ‘robotic architecture’ is still only at an innovation stage. Foldable structures may offer features that are beneficial while responding to the extended set of contemporary requirements. These requirements call for better safety when faced with natural and man induced disasters. They encourage meaningful environmental responsibility. Foremost, they define the functional and comfort expectations of societies that are becoming more dynamic and complex.

These new properties would expand, in a significant way, the traditional principles of permanence and determinism in architecture. Most importantly, they would also
challenge the common notions about space ownership, its use and sharing. Dynamic environments have the potential of providing a passive comfort or, if needed, aggressive control. They realize the concept of space that has to be negotiated and reckoned with. The constantly increasing dynamics of human actions builds favorable conditions for taking into consideration novel features and possibilities of performative architecture. However, the delivery of practical solutions depends significantly on co-development of adequate design workflows. Ultimately, the future success and acceptance of performative architecture may be determined mainly in a social dimension and depend on the ability of providing effective solutions in the context of demographic, economic and ecological challenges.

Kinetic structures can facilitate augmenting existing infrastructures with additional functions, for example commercial and institutional environments to include residential use. They can provide means of flexible expansion. They can also improve comfort, emotional fulfillment, and energy efficiency during extreme weather conditions. A variety of free standing, easily deployable kinetic structures could serve as adaptable, on-demand exhibitions, markets, exploration stations and public event facilities. Such structures are well suited for quick deployment in emergency situations.

Environments capable of actively engaging occupants can offer significant advantages in several scenarios. First, urban public spaces, where such technology offers the means to better manage user comfort and safety under extreme occupancy scenarios like overcrowding or high transiency. Increasing urban crowding raises serious behavioral and safety concerns (Regoeczi, 2002) and may be difficult to address using the traditional architectural strategies. Second, isolated environments where occupants remain confined for long periods. Whether research, exploration or military, such settings pose risks of emotional fatigue and breakdown. Claustrophobic confines of submarines remain submerged for months. Arctic outposts may be inaccessible for most of the year. Space station details last for years. Third, imposed isolation environments, whether detention or quarantine, are particularly challenging because of an inherent element of un-cooperation. ‘Reactive’ environments may provide means of increased participatory involvement while assuring safety and security.
4.4 Challenges

Although scholars endorsed the advantages of reactive environments decades ago (Zuk and Clark), practical solutions have not evolved yet (Ataman). Kinetic architecture and the underlying technology of folding structures are still only initial vague ideas. Such early stage of concept development has been referred to as the “Fuzzy Front End” (Khurana and Rosenthal, 1998), a notoriously challenging phase hindered by uncertainties, risks, and lack of precedents.

4.4.1 Social Acceptance

Kinetic environments will introduce a level of unpredictability and control, to which occupants of traditional public spaces are not accustomed. A vision of a distributed, interconnected, ubiquitous, autonomous and automated supervisory network diffused inseparably within the fabric of built environments and capable of actively engaging the occupants raises questions: whether it will be a valuable contribution or a frivolous excess; most importantly, whether it will provide beneficial facilitation or, rather, easily dispatchable intimidation.

Notions of control, authority and social participation are co-evolving together with information and communication technologies. Scholars point out the complex nature of public spaces as, far from being merely static architectural scenographies, they also project intentional programming and restrictions of owners or local authorities. Furthermore, ubiquitous wireless access intersects public spaces with a much larger virtual domain, a mediated space. Understanding such multifaceted and evolving character of public spaces as a “behavioral setting” is an essential part of designing the future built environments. Progress in understanding the emotional perceptions of built environments will expand purely quantitative planning of architectural projects to include perceptual and behavioral considerations for the purpose of foreseeing and influencing human responses. Including human perception-based criteria is a logical step in developing increasingly more comprehensive architectural planning programs that already include environmental and lifecycle concerns. In view of the constantly increasing demographic loading of existing
urban resources, related crowding and high transiency, this new design approach offers means of emotional comfort management besides merely crowd management.

Several approaches, depending upon the severity of a situation, could be employed to moderate behaviors. Such approaches could range from reducing the attractiveness of a setting through degrading the microclimate, disabling user interfaces, or employing harsh lighting, and they could escalate, if warranted, to restricting access and deploying discomforting effects. The outlined methods may sound severe, hostile and alien to the traditional sense of public spaces. However, contemporary security and safety systems do already employ some of the effects. A fire alarm system, if triggered by smoke, will unlock the doors and sound the bells. Even if it is a false alarm and occupants are untrained in emergency procedures, the noise level is discomforting enough to force everyone to leave. Therefore, the transition to reactive environments of the future is already taking place, and its next phases would most likely be gradual rather than radical. Yet, understanding the mechanisms of social acceptance will be an important factor in developing kinetic architecture.

4.4.2 Ethics of the Inscrutable

The premise of built environments that can detect occupants’ behavior and are capable of responding with physical changes raises ethical considerations. Such reactive environments will introduce a level of unpredictability and control, to which occupants of traditional public spaces are not yet accustomed. To be able to detect, analyze and respond, reactive systems will rely on extensive monitoring that will constitute a high degree of automated surveillance. The paradigm of surveillance will shift from that of passive data collection to one of a real-time autonomous interacting system, which may pose questions of constitutionality. The size and the complexity of such systems will delegate human operator’s involvement to merely periodical maintenance. The reactive environments will depend entirely on their sophisticated controlling algorithms. Such algorithms need to be capable of learning, evolving and adapting in order to be effective when faced with the unpredictability and spontaneity of human actions. Researchers point out that modern algorithms capable of learning and adapting exhibit an inherent trait of inscrutability (Whitby, 1996). Consequently, it is impossible to disseminate the decision process of such
algorithms. This raises a very tangible prospect of large surveillance and control systems operating as a ‘black box’: once the general intent has been programmed and the algorithm activated, it is impossible to examine how exactly decisions are inferred. Ironically, bureaucratic processes involving humans also occasionally exhibit aspects of inscrutability. As such, the concept of inscrutability is not new. Nevertheless, coupling inscrutability with new and powerful technology may take some time getting used to. How then to conceptualize the dynamics between the occupants and the reactive environment in the traditional terms of privacy and civil rights? Scholars identify the evolving nature of both surveillance methods and ethical paradigm as ubiquitous monitoring tends to blur the traditional distinction between “the controllers and the controlled” (Aas et al., 2009) and introduces a participatory element to surveillance (Andrejevic, 2006). Ubiquitous wireless connectivity may provide an unprecedented communication platform between the occupants and controlling algorithms. Such interaction may provide a different dimension of empowering and informed participating thus negotiating new relationships between the exploratory user involvement and the authority driven control. Ethical rights of users in terms of privacy, consent, transparency and freedom of choice will be co-evolving together with the technological advances affecting public spaces.

4.4.3 Design Methods and Tools

Performative buildings of the future pose design challenges regarding the initial requirements, functional programs, and user expectations. On a technical side, the added element of motion exceeds the capabilities of current design tools. Researchers noted that only yet-to-be devised design tools (Kolarevic, 2003) and new design methodologies (Goel et al., 2012) could overcome the challenges facing built environments and facilitate developing new performative architecture. Designers would need to transcend crafting merely static and passive backdrops to human activities and they would need to learn the skill of composing behavioral and emotional scenarios. The lack of suitable design tools may explain the slow progress of built environments and construction industry, and why the transformation of architectural landscape has been mostly limited to the formalism of shapes and to engineering details.
4.5 Concepts

New concepts by young designers often tease the conventional paradigms of habitable spaces and challenge the perceived notions of physics while exploring the space-saving opportunities of motion. The Roll-it habitable unit, designed by Zwick and Jerabek in 2009, is a horizontal cylinder having furniture-like features installed all around the inside diameter. The cylinder rests on rollers and can be rotated a complete 360 degrees to bring a desired piece of furniture into a usable position. The Roll-it unhinges gravity, the bearer of our sense of order, and allows users to modify its direction as needed. A look from outside into the Roll-it’s interior invokes a weightless ambience of a space station. This extreme fusion of a treadmill and a living space does away with petty concerns about loose objects or cups with drinks. Instead, it demands an absolute submission to its austere and quirky physics. The idea of the Roll-it is not entirely original. Perhaps more restrained because rotating a mere half turn and still offering a sliver of a straight floor, Wout Fierens’ ‘tilthouse,’ prototyped in 2002, is an earlier concept challenging the unidirectional dogma of gravity.

Although the colloquial term ‘living space’ alludes to three dimensions, our existence unravels mostly on a two-dimensional plan and we use square rather than cubic footages to measure it. Only intrepid projects like the Roll-it or the tilthouse explore the third dimension as an instrument of extreme optimization of our spatial needs. Such projects engage the actual 3-dimensional space as a tangible and precious resource and make it accessible through cunning manipulation of gravity.

In the pursuit of optimal space utilization, these interiors are interacting intimately with the bodies of the inhabitants in a coordinated choreography of mutual spatial dependency. We are familiar with devices that interact even closer with our bodies: our dresses. At this scale, architecture is approaching a point at which it will become wearable, thus expanding Rybczynski’s (1986) notion that “the relationship between clothing and interior decoration is venerable.”
4.6 Closing Remarks

As the last few decades indicate, kinetic phenomenon in architecture does not quite possess the dynamics of a revolution. Its gradual progress is evolutionary in the most literary sense. The contextual complexity surrounding kinetic architecture is evident. Underlying engineering and technological challenges are significant and they need to be addressed in conjunction with the architectural considerations, in a unified manner. The development of feasible applications as well as assessment of benefits and marketability must adequately support the design effort. Safety and performance tests need to be conducted as well as appropriate changes to building codes need to take place. Different models of space usage and sharing may encounter social acceptance issues. Not surprisingly, it is difficult to imagine that urban landscapes would be swept overnight with kinetic extravaganza. However, pioneering effort of designers will certainly popularize the potential capabilities of kinetic structures. The unique features of foldable structures may change the traditional building maintenance and lifecycle models and offer reconfiguration as an option to demolition. In general, configurable structures will provide lesser environmental impact than traditional technologies as they are better suited for re-using, modifications and re-location. Inherently modular, they facilitate assembling of infinite variations from a limited set of prefabricated components. They may offer functional advantages over traditional solutions while constructing configurable habitable spaces in densely populated areas. In fact they may become the mainstream of tomorrow.

Progress in understanding the emotional perceptions of built environments will expand purely quantitative planning of architectural projects to include perceptual and behavioral considerations for the purpose of foreseeing and influencing human responses. We propose that including human perception-based criteria is a logical step in developing increasingly more comprehensive architectural planning programs that already include environmental and lifecycle concerns. In view of the constantly increasing demographic loading of existing urban resources, related crowding and high transiency, such design approach offers means of emotional comfort management besides merely crowd containment. Architects will face new opportunities and new responsibilities while
transcending the stage of crafting passive backdrops to human activities and while entering an era of scripting behavioral and emotional scenarios.

This thesis brings into focus two reasons for the relatively slow evolution of folding structures: design and engineering challenges such as modeling of folding shells and instrumentation of the kinetic mechanisms, and the need to consider the human-centric issues and social drivers in developing new architectural paradigms.
CHAPTER 5 Design Methods and Tools

This chapter addresses the design of kinetic built environments, particularly foldable kinetic structures from technological methods and tools, as related to architecture. Kinetic built environments provide new opportunities in architecture and also associated challenges. These challenges may be resolved through innovative methodologies of digital modeling and integrated digital workflows. In this context, designers’ needs versus marketing pressure are addressed. Building Information Modeling (BIM) is an essential aspect of modern architectural methods. The importance of BIM and interacting with digital methodologies are discussed. The history of digital design tools in architecture and its chronology are presented. Technology of collaboration is discussed and the technology of process is indicated. Collaboration is compared with standardization. The structure of BIM is presented, the role of BIM in modern architectural procedures is given, and possible future trends of BIM are highlighted. For overcoming the limitations of the current approaches in integrating the complexity of human cognition into architectural procedures, the traditional methods for developing design requirements are augmented with an innovative intuitionistic approach toward information modeling, which is developed in the present chapter. This method is based on fuzzy logic and human-centric decision making. In particular, the present thesis proposes adapting intuitionistic fuzzy logic for computational modeling of spatial relationships. The intuitionistic model is integration with design workflows. As a case study of the developments, intent-driven modeling of a foldable kinetic geometry using fuzzy logic is presented. Intent-driven design and the design objective, the method for solving kinematics of the kinetic structure, fuzzy inference system, and associated algorithms are developed. The method is implemented in the case-study problem, and the obtained results are discussed.
5.1 New Opportunities and Challenges

Traditional pre-digital drafting and drawing tools have remained largely unchanged for millennia. Their simplicity and universal accessibility provided a level playing field for all designers. Digital technologies, however, have altered this balance irreversibly by introducing a market-driven rivalry of proprietary solutions, restrictive licensing, and unending development race. Software tools range from “cathedrals,” expensive total solutions branded with major corporate insignia, to a “bazaar” variety of freeware and low-cost modelers often supported through collective effort of user communities. Consequently, the egalitarian and transparent nature of pen-and-ruler based workflows has yielded to the significant technological stratification and attention-demanding transiency of digital tools. For designers, knowing how to use a tool-method has become as important as solving a design challenge.

5.1.1 Digital Modeling

Digital modeling provided easy re-using and editing of components, the convenience of consistent numerical accuracy, and direct integration with Computer Aided Engineering (CAE) and Computer Aided Manufacturing (CAM). However, not all aspects of Architecture, Engineering, and Construction (AEC) workflows have benefited equally from 3D parametrics. In particular, underlying mathematics and rules of strict dependencies of 3D modeling impose a level of analytical rigor that is poorly suited for ideation or exploring vague concepts. Researchers agreed that, disappointingly, little effort has been invested in improving the mathematical models used in digital design tools (Vries, de, 2004). Consequently, progress is limited to “speed, size and resolution” (Hanna, 2011), while “even the latest developments in modelling are still based on the same underlying principle,” which, according to Hanna, dates back to Sutherland’s Sketchpad from 1960. Bettig and Hoffmann (2011) confirmed that the parametric underpinnings of digital modeling have not progressed during the last decade, a situation that has "severely" limited the usefulness of digital tools for design work. Current methods of parameterization place a significant burden on designers as they are only effective if "thoroughly untangled and precisely described" (Scheurer and Stehling, 2011).
Furthermore, researchers have been critical about the cognitive shortcomings of user interfaces. Erhan, Woodbury, and Salmasi (2009) noted CAD’s deficiencies in "facilitating and visualizing" changes to complex models. Picon (2011) observed "the lack of intuitive content" when using algorithmics for generative design. Liebing (2011), an architect and a writer, commented that designing in 3D is not necessarily faster or easier than designing using two-dimensional (2D) digital tools. He critiqued the current 3D modeling for not being "inherently intuitive to the casual observer." Shelden and Witt (2011) were more specific in their critique, pointing out parametric tools' excessive focus on constructing geometries. Consequently, according to Shelden and Witt, the resulting architectural forms integrate poorly with their own functions and are alienated from broader contexts. The cognitive shortcomings of 3D design tools are serious enough to "represent a crisis in the implementation" of digital technologies (ibid.).

Figure 5.1 Catenary model for Familia Sagrada (Photo © Madalina N. Wierzbicki)

A physical model devised by Gaudi for the Sagrada Familia project illustrates the cognitive deficiencies of current digital tools. Gaudi used a network of weighted strings to fashion the natural catenary tectonics of the structure (Huerta, 2006). The tangible and interactive properties of this analog model are remarkable (Figure 5.1). Other architects used similar devices for such exploratory "form finding" (Bechthold, 2008). Bechthold also cautioned
that, if used for further design refinement, analog models demanded significant preparation effort to minimize extrapolation errors. Nevertheless, he was also restrained about computational methods – although they are expected to be more convenient and faster, they "require extensive background knowledge in order to produce meaningful results."

5.1.2 Integrated Digital Workflows – Designers’ Needs versus Marketing Pressure

Digital technologies have brought significant changes not only to the way building layouts and their forms are modeled, but also to the entire process of the Architecture, Engineering, and Construction (AEC) industry (Kymmel, 2008; Eastman et al, 2011). The market-driven doctrines of software development have resulted in an opportunistic appropriation of design and other supporting processes, and creation of highly integrated comprehensive workflow tools – the ultimate “cathedrals” of design software. Known as Building Information Modeling (BIM), such total design environments aimed at managing all design and construction aspects across all involved disciplines. Consequently, BIM has intersected the traditions of two professions: that of an Architect who conceives the idea and that of a Master Builder who materializes this idea through the skill of construction.Liebing commented on the complicated relation between designers and the software industry:

The most troubling aspect of BIM is that architects don't need to be saved; they need software developers to listen to what they do, and understand how to make that process easier. (2011)

Although generally BIM is considered as a tightly integrated and coherent system, researchers note many issues originating from within its own structure. The process of designing is an iterative temporal activity while a 3d parametric construct is inherently modal (Shelden 2009). Reconciling these disparities involves always a work-around in a form of versioning, document and file management using database tools. In the process, the integrity of a 3D model is altered by adding an abstract dimension of changes and versions. Only a rigorous adherence to the supervisory versioning logic assures a coherent data representation across all involved AEC disciplines. Building Information Modeling is a composite of two technologies: parametric modeling and collaboration. Paradoxically,
although it promises interoperability and data sharing, it also restricts with proprietary data formats and locks users in an exclusive licensing of its respective software brand.

5.1.3 Symbolic Importance of BIM

The image of BIM is complex and bears signs of being an answer to the wishes of practitioners as much as being the result of marketing strategies. Besides being a tangible tool responsible for many documented AEC achievements, BIM plays an important role as an abstract concept of architectural activity. As such, it provides a far more resilient ideal of collaboration and integrated workflow than its practical incarnation. It transcends the boundaries of current professions and workflows. It engages the academic community in an explorative discourse about the future of the AEC industry and the architectural profession.

While building upon this notion, sections 5.2 and 5.3 of the thesis will examine BIM’s history and the potential of its future. Regardless of whether it will remain in its current form, whether it will be assimilated by other technologies, or whether it will disintegrate from within, BIM has already established an important milestone and laid out the direction toward collaborative integrated workflows. BIM has formed the nucleus of significant development potential for the future architectural workflows.

5.1.4 Interacting with Digital Technologies

Having software tools strategically incorporated into the vital design processes resulted in a sole gateway, an exclusive digital interface between designers and their work. Consequently, it is important to understand how such digital interfaces affect the cognitive effort of designers, and to seek solutions facilitating information exchange between humans and computers. Researchers have noted the challenges in conveying high level non-geometric concepts and the inherently incongruent human reasoning while using crisp digital inputs. They also have pointed out the difficulties in direct application of the learned and intuitive comprehension of the surrounding physical world to analytical formalism of digital models. In response to these concerns, sections 5.4 and 5.5 of the thesis present approaches aimed at overcoming the limitations of current digital design tools.
5.2 The History of Digital Design Tools

5.2.1 Chronology

Figure 5.2 maps the timeline of design software technologies in the context of market dynamics. The key industry players have followed different strategies. Some (Bentley, Nemetschek) have relied on their traditional main CAD platforms and built BIM solutions around them. Others (Autodesk) have developed entirely new modeling engines. In all cases, however, a complex blend of CAD and AEC technologies was used as the foundation for 3D parametric modeling. The late 1990s marked the convergence of key technologies needed to form what is now known as BIM. First, most CAD and AEC software became universally parametric. Second, four major Information Management (IM) solutions emerged. Once an AEC modeling platform was integrated with an IM system of choice, it became a market-ready BIM product.

This vigorous phase of software development coincided with many decades long period of exponential economic growth that continued until 2001. Afterwards, however, the development of software ‘cathedrals’ slowed down to merely incremental improvements. A year earlier, in 2000, the simple freeware direct modeler SketchUp debuted. It soon came to epitomize the ‘bazaar’ movement. In the 2000s, software market activity focused mostly on acquisitions. One such acquisition ended the independence of the major BIM software pioneer – Graphisoft.

5.2.2 Technology of Collaboration

Researchers agree that collaboration is essential to BIM. This collaboration expands in two directions. First, BIM is a CAD interoperability tool that links together design models and files throughout all the AEC disciplines. Second, BIM is an Information Management platform that enables synchronous co-operation between, as well as within, all involved teams. Although CAD interoperability is three decades old and is supported by standardized data exchange formats like SAT, STEP, or IGES, it still provides only a basic non-associative one-way translation. BIM is more demanding because it relies on two-way, interactive, and on-the-fly coordination of parametric data.
Figure 5.2 Chronology of computing technologies (Graphics © Madalina N. Wierzbicki)
Nevertheless, such expanded functionality of data exchange is an incremental improvement rather than a technological breakthrough. In contrast to the traditional 3D data exchange or linking methods, collaborative team environments are a fairly new technology that was pioneered by projects like TeamMate, Teamwork, O.P.E.N., truEVault, and NavisWorks during the second half of 1990s, thus coinciding with the emergence of Enterprise Resource Planning (ERP) tools, which integrated information flow across entire organizations. Furthermore, all these new collaboration tools relied on the newest networking technologies like the internet and the Gigabit Ethernet. The emergence of these collaborative technologies marked the tentative inception of BIM, as all major developers immediately integrated their collaboration tools with their respective AEC packages. By that time, 3D modeling was already universally parametric. Notable are different strategies adopted by the major industry players. Bentley and Nemetschek based their products on their traditional main CAD platforms, which they continued to develop, while Autodesk acquired and developed new CAD technologies. Furthermore, Bentley and Nemetschek diversified their market offerings by acquiring other AEC/BIM platforms. Such variety of strategies and component technologies highlights the fact that BIM’s touted integration, interoperability, and collaboration were a fragile compromise of very different technologies (Neff et al., 2010). In all cases, 3D parametric modeling underpinned the final products. Yet, even this essential component itself was a varying mix of surface and solid modeling methods.

5.2.3 Technology of Process

Is BIM a process? Although the term “process” is frequently associated with BIM, its use may reflect an ideal rather than BIM’s actual attributes. Scholars define a process as a sequence of actions aimed at transforming inputs into a desired outcome. Other attributes of a process are ‘decision,’ ‘purpose,’ ‘learning,’ ‘expertise’ and ‘quality.’ Furthermore, the term ‘process’ has a wide application ranging from industrial automation to entire business organizations. In all cases, a process is temporal in nature and involves sequences of actions. A tool can be considered as a low-level component of a process, and may imply some logical steps. Yet in itself, a tool reveals nothing about a goal, a decision, or expertise. Only within the context of a process, can a tool define such attributes. In its
current form, BIM exhibits more clearly properties of a tool than a process. According to Gauchat:

It is important to keep in mind that BIM is merely a tool, albeit a transformative one. (2009)

Nevertheless, a question remains whether BIM can become a process, how that might be accomplished, and whether a good reason to pursue such expanded function of BIM exists (Ottchen 2009). Also coinciding with the inception of BIM, Business Process Modeling (BPM) became a subject of vigorous research and development activity. The resulting emergence of BPM software developers like SIMUL8, Metastorm and CreateASoft has bolstered the growth of Information Management (IM) technologies. The potential implications of coupling BIM with BPM are significant as such comprehensive tool-process would be capable of governing all activities in an organization.

Yet, it is important to understand the conceptual differences between BIM and BPM. While BIM would need to remain a relatively flexible, open-ended and transparent production tool in order to handle a broad range of architectural projects, BPM, once implemented, would form a unique and relatively permanent expression of organization’s policies on efficiency, quality, purpose, and ethics. Therefore, an effective integration would have to merge these disparate paradigms into a synergetic system, in which BPM could assume a supervisory role as a project management tool to monitor the efficiency of project delivery, to administer project management details like human resources assignment, and to track the quality of communications between involved parties.

5.2.4 Collaboration versus Standardization

Although collaboration is an essential function of BIM, the competing brands and diverse market offerings have resulted in a troubling lack of cross-platform compatibility. Such compatibility requires universal acceptance of an agreed upon information exchange standard. However, researchers acknowledge that the very premise of standardization has drawbacks as it introduces a limiting effect of the lowest common denominator:

IFC is the ‘lowest common denominator’, which results with the most of the functionality found in proprietary applications being substantially reduced to the level of functionality carried by other interfacing applications. (Pniewski, 2011)
Therefore, the ease of cross-platform exchange is a tenuous compromise between innovation, brand control, and standardization. Furthermore, this situation is worsened by different approaches toward standardizing information exchange. The ISO STEP project, which aimed at facilitating information exchange within manufacturing industries, started in the mid-1980s. However, it was the International Alliance for Interoperability (IAI), a decade-later initiative that has delivered the Industry Foundation Classes (IFC) data exchange standard, which gradually became integrated into major BIM packages (Laakso and Kiviniemi, 2012). Although the IFC is targeted specifically at AEC industries, it lacks the key functionality of translating parametric geometries (Kiviniemi et al., 2008). Consequently, other specialized translators need to be used in conjunction with the IFC (Pniewski). Researchers agreed that the process of adopting the IFC was slow. Although all major AEC software developers launched their flagship BIM packages within three years, adopting the IFC by the same developers took nine years (Figure 5.2). Kiviniemi et al. identified “the complexity of the IFC specification” as the reason for this delay. The combination of the IFC’s complexity together with the slow pace of its implementation has negatively affected the standardization effort:

Comprehensive standards such as the IFCs are not generally understood and are not being adopted. The IAI has been around so long that people have forgotten it or become bored. (Howard and Björk, 2008)

Furthermore, Kiviniemi et al. noted low demand for the means of effective collaboration and unwillingness to improve the project delivery processes:

The awareness of the need for an enabler for collaboration is not high. There seem to be no real interest in the industry to change its business processes. (Kiviniemi et al.,)

In conclusion, BIM’s interoperability is tentative and fraught with challenges. The incompatible paradigms of collaboration and market-driven competitiveness raise a question of how much interoperability is really necessary:

The single BIM has been a holy grail but it is doubtful whether there is the will to achieve it. (Howard and Björk)

Therefore, the divide between the BIM’s ideal and its practical incarnations can be viewed simply as a reflection of complex cultural circumstances influencing all technologies.
5.3 Future Trends

5.3.1 The Structure of BIM

Researchers generalize information management and CAD technologies as Information and Communication Technologies (ICT) (Aouad and Arayici, 2010). BIM is considered as the main component of ICT used in AEC industries. As such, it is aimed at streamlining and integrating numerous, traditionally disparate AEC workflows (Aouad and Arayici; Kymnell, 2008; Penttilä, 2006; Eastman et al., 2011). Though BIM definitions are diverse (Aranda-Mena et al., 2008), researchers acknowledge that BIM systems are built around parametric and object-based 3D modeling (Kymnell; Penttilä; Eastman, 2009). The built-in interoperability of various AEC workflows is the source of BIM’s effectiveness (Kymnell; Penttilä; Shelden, 2009).

5.3.2 Possible Trends

An emerging trend among researchers is to view social interactions and human ecosystems as coupled systems rather than as closed-loop repeatable and predictable processes (Dubois and Gadde, 2002; Liu et al., 2007; Orton and Weick, 1990). Blocks in coupled systems exchange actions and reactions without necessarily having predetermined constraints or external regulating mechanisms. The outcomes of such iterative exchanges (interactions) defy algorithmic determinism. Consequently, coupled systems are open-ended, continually evolving and often unpredictable. Conceivably, the trans-disciplinary nature of BIM could grant it an important role in influencing the delicate balance of the human-environment coupled system, hence the motivation to examine the broader context of BIM and its peripheral processes. Being a fusion of CAD, information management, and collaboration technologies, the current BIM extends over various building delivery workflows: architectural, structural, electrical, and HVAC (heating, ventilation, and air conditioning). Furthermore, these AEC workflows are immersed in a broader context of geography, local regulations, social sciences, and material engineering. Together with the temporal dimension of workflow phases such as planning, delivery, commissioning, and operation, this context forms a conceptual plane of possibilities for BIM’s engagement and expansion. The cross-disciplinary direction charts BIM’s continuing expansion of
collaboration and information sharing across increasingly diverse workflows. The temporal
direction maps the relevant ‘before’ and ‘after’ phases, which are often referred to as
“upstream” and “downstream” (Shelden). Along this direction, BIM provides support for
various project phases, such as initial design, detailing, design verification, construction,
and operation. Figure 5.3 sketches out the potential spheres of expansion over a backdrop
of workflows and processes that are technically, administratively, and theoretically related
to building construction. The sphere ‘I’ highlights the scope of the current BIM. The
sphere ‘II’ shows BIM’s expansion over civil engineering and GIS. In fact, BIM-GIS
integration is currently very active (Berlo and Laat, 2011) and indicates the trend toward
global infrastructure modeling. The sphere ‘III’ engages abstract cultural processes such as
governance, policies, sciences, and theories. For instance, linking BIM with material
engineering would provide designers access to the newest materials and participation in
developing new technologies. Material engineering would benefit from systemic data
collection from actual buildings. BIM’s integration with social sciences would help
designers to include perceptual criteria and to employ behavioral analysis tools. Since
buildings play a critical social role as behavioral settings, BIM could become a tool of
behavioral engineering.

The horizontal axis along the workflows is a subject of considerable academic
interest. Scholars agreed that, at this moment, BIM offers poor support in the ‘upstream’
direction: early design stages and ideation (Penttilä, 2007); and the ‘downstream’ direction
involving post-construction operations also needs much improvement. This indicates that
BIM has not yet evolved beyond its CAD underpinnings. Processes that need non-CAD
methods therefore tend to be poorly supported by BIM (Sturts Dossick and Neff, 2010). In
order to support the ‘upstream’ early design stages, BIM will have to transcend the
limitations of the current explicit numerical modeling and be able to process ‘soft’
qualitative data. Furthermore, the ‘downstream’ processes such as building operations
require data structures capable of recording temporal variability. In contrast, CAD relies on
modal representations. Numerical 3D models do not ‘age,’ since they lack a natural
temporal component. The outer extent on the horizontal axis indicates BIM’s expansion
beyond production workflows and into higher-level regional governance. BIM could
potentially handle the comprehensive lifecycles of built infrastructure on urban and
regional scales. When directed toward the future, BIM could become a tool for planning and decision-making. In such function, BIM will benefit from access to the operational records of existing infrastructures. If employed over large geographical and temporal scales, BIM may therefore become a tool of global governance.

![Figure 5.3 Design computing trends (Graphics © Madalina N. Wierzbicki)](image)

5.3.3 The Role of BIM

Achieving efficiency in integrated workflows involves eliminating duplicate and non-contributing (non-value-adding) tasks, as well as process bottlenecks. Therefore, BIM
exposes traditional workflows to a scrutiny, which, in its procedural and unemotional pursuit of productivity, often questions the established wisdom and habits: for instance, whether BIM can empower architects or diminishes their role, or whether it streamlines the job of engineers to make a concept-to-construction project delivery a reality. Such questions flex the boundaries of traditional professions and facilitate discourse on their future. In this role, BIM is a catalyst for change, a source of new capabilities and skills. BIM has gained this important position thanks to its tremendous potential as an efficient project-delivery tool (Pniewski). Nevertheless, it is important to point out that BIM is far from becoming a universal remedy to AEC ailments. BIM’s success depends on the intersection of its functionality and the operational processes of an organization, thus further confirming BIM’s role as a complex and potent, but merely a tool rather than a process. Therefore, a skillful fusion of technology (based on BIM) and process (an organization or dynamic system) is a necessary yet elusive and difficult to formalize step in BIM’s implementation. Architectural projects are complex and notoriously diverse thus further complicating matters. The efficient delivery of one project does not necessarily assure the efficiency of the next. This opens yet another debate: whether BIM is a vehicle of typification aiming at merely consistent efficiency, or whether it enables uniqueness and innovation.

5.3.4 The Future of BIM

Current BIM is built around 3D modeling, or CAD. What then are the practical limits of numerical 3D representation? The entire globe can be represented as a 3D model (in a static sense) using, for instance, cloud computing. However, other vital global characteristics, which can be dynamic in general, require different methods. The already developed and in use Global Climate Model is based on Computational Fluid Dynamics. The modeling of social activity relies on studying the movement of the population (and associated motivations), locational indexing, and agent-based programming rather than 3D detailing. On a global scale, a 3D model is one of many components of equal importance.

As BIM is a result of one strong technology (CAD) becoming an attractor and a binding nucleus for many supporting satellite technologies, new strong technology transcending the current limitations may form an entirely different nucleus and assimilate
BIM in the process. Although speculative, such a scenario has a few plausible candidates. For instance, strong Artificial Intelligence is a machine-based intelligence that equals or surpasses human reasoning (Karray and de Silva, 2004). In contrast, Synthetic Intelligence (Gros, 2013) is a hypothetical concept of a sentient system that is entirely different from human mind. Machine-based knowledge-making and reasoning would open unprecedented possibilities:

> The prize for unbundling those issues might be a new industrial, economical and societal revolution. (Bonsignorio, 2013)

However, it could also pose unprecedented problems:

> This poses serious safety issues, since a superintelligent system would have great power to direct the future according to its possibly flawed goals or motivation systems. (Armstrong, 2013)

Nevertheless, such technology would be capable of absorbing BIM entirely for use as merely a task-oriented effector.

5.4 Overcoming the Limitations – Integrating the Complexity of Human Cognition

The challenges of linking nuanced and multi-layered human reasoning with the analytic and explicit formalism of computers have been noted by many researchers. In particular, the areas of capturing design requirements, architectural programming, and early conceptualizing are still in need of much development (Eastman; Manning and Messner, 2008; Penttilä, 2007). According to Kymmell, improving BIM effectiveness will rely on how well complex information can be inputted and accessed. Ottchen (2009) agreed that BIM must transcend simplistic data quantification and become able to use “soft data.” She warned against simplifying the complexity of available information whilst fitting it into the limited templates of BIM inputs. Sturts Dossick and Neff (2010) asserted the importance of loosely structured information, “messy talk,” for the early design stages. Researchers pointed out that digital technologies have not changed the mechanism of designing, which remains an iterative process of comparing an evolving concept with the initial intent (Kymmell; Shelden). However, since BIM provides easy access to design reviews, it has
become increasingly more important to capture and then to provide access to the initial design requirements in as much detail as possible (Howard and Björk; Ottchen, 2009).

Recent advances in both intuitionistic and mediative fuzzy logic indicate a growing interest in information modeling that is increasingly sophisticated and capable of analyzing a complex interplay of alternative solutions while engaging subtle traits of human reasoning such as hesitation or contradiction (Montiel and Castillo, 2007). Furthermore, researchers have voiced the importance of incorporating such ‘soft’ qualitative data into digital design workflows like BIM (Shelden, 2009; Kymmell; Ottchen, 2009).

The present section of the thesis focuses on the cornerstone of any design project: preparing initial requirements. Formalizing design requirements is the critical transition step from an unstructured idea residing in a human mind to the rigor of the collective design process. Furthermore, discussed is the impact of the dominant mathematical concepts on how design requirements were handled in traditional pre-digital workflows and how these concepts have affected today’s mainstream digital tools. A novel approach toward interfacing qualitative and inherently inconsistent human reasoning with workflows driven by crisp data is then presented, along with an original computational method and the results of a simulation.

5.4.1 Traditional Methods for Developing Design Requirements

In architectural projects, one of the most common goals of design requirements is to capture the desired functional dependencies between spaces. Such dependencies are usually expressed in qualitative terms and then tabulated as “spatial relationship matrices” (Voordt and Wegen, 2005), which are the essential input for driving early design stages and layout conceptualization.

Spatial relationships are often expressed using phrases like connected, strongly-connected, isolated, separated, neutral, positive, or negative. When arranged in matrices, they provide flexible and easy-to-read snapshots of general spatial dependencies (Figure 5.4). They use qualitative, open-ended descriptors listed in a table-like format that avoids unnecessary topological assumptions. Accordingly, they are considered as an objective tool capable of capturing initial design intentions (Voordt and Wegen; Duerk, 1993; Evans and Wheeler, 1969). Yet, the commonly used matrices of spatial relationships exemplify
how tools, which are considered to capture initial design requirements in their most unprocessed form, often apply significant data discrimination, filtering and interpretation. A detailed examination reveals the complexity and the extent of interpretative process that is involved during preparation of such matrices (Figure 5.4).

![Figure 5.4 Traditional spatial relationship matrix (Graphics © Madalina N. Wierzbicki)](image)

In reality, each space represents a usage program, a function. The highlighted relationship requirements between spaces B and E (Figure 5.5), if considered through specifics of program B, may be different from the corresponding requirements arising from the specifics of program E. Yet, the graphically concise traditional grid of a half-square – actually, a half-matrix – provides only the limited means of assigning just a single attribute to each spatial relationship. Furthermore, the resulting mapping does not reveal which
specific needs of the program influenced the corresponding relational attributes. These attributes are thus the outcome of an arbitrary synthesis of initial considerations into singular values, all recorded within the constraints of a simplified grid.

Transposing such mapping onto a full-square, table-like grid (Figure 5.5 center) reveals the extent of the simplifications of the half-matrix. The same relationship, between B and E, is highlighted. The full matrix allows mapping the relationship requirements between each pair of spaces as two distinct attributes derived from individual specifics of corresponding spaces. The blue highlight indicates the relationship between B and E as derived from the specifics of program E, while the pink highlight indicates the same relationship derived from the specifics of program B. Such a distinction is not possible when using a half-matrix grid – the yellow highlight (Figure 5.5 left). These separately derived relationships need not be identical. This is precisely the advantage of a full-matrix scheme: different source considerations yield different results. In this example, the specifics of B yield a ‘connected’ relationship, while the specifics of E yield an ‘isolated’ relationship.

Reducing this mapping to a half-matrix scheme results in interpreting a pair of differing relationships by a single best fitting assignment – a ‘separated.’ If such half-matrix mapping is then used for design development, the initial complexity of the source information is lost. Instead, the design is driven by simplified data. The obvious advantages of the simplified data are the ease and the convenience of dealing with consistent and coherent data. On the other hand, the full-matrix’s ability to capture the complexities of initial considerations is also responsible for the inherent element of ambiguity and contradiction. Figure 5.5 (right) illustrates disagreements between the differently derived relationships.

The fully developed spatial relationship matrix can be considered as a complex data model (Castillo and Melin, 2012). Although such data cannot be readily utilized in traditional workflows since they only can accept inherently consistent and unambiguous inputs, researchers point out that considering the entire complexity of initial requirements is important for successful ideation (Barton, 2000; Stokes, 2006). Therefore, it is necessary to improve tools for modeling design requirements (Lubart, 2005).
5.4.2 An Intuitionistic Approach Toward Information Modeling

The present thesis proposes that recent advances in intuitionistic mathematics and intuitionistic logic (Montiel and Castillo) open the way for the effective integration of complex data structures into design workflows. This will further require a mechanism to incorporate “human involvement and thinking” which may come from knowledge, experience, natural intelligence, intuition, common sense, social factors, tradition, and so on. The traditional dominance of binary logic further engrained through proliferation of computing technologies brought along certain intolerance toward ambiguity and indetermination. This intolerance, pointedly expressed as ‘the law of excluded middle,’ (Karray and de Silva, 2004) has been generally accepted as the underlying norm for creative, industrial, engineering, and research workflows. Obvious benefits of such approach include convenience of simplicity and processing efficiency. However, this systemic, virtually transparent bias against information that is ambiguous or contradictory encourages simplification to the point where potentially important data may be discarded (Linsey et al., 2008). According to Foucart (2010), using such “quantified” data models for information describing social systems and human behavior results in “illusory objectivity” which “considerably reduces the richness of the information processed.”

Fuzzy Logic

Interestingly, traditional soft computing exemplifies the omnipresence of crisp discrimination as fuzzy logic duly obeys the law of excluded middle: although multi-valued and non-binary, fuzzy logic variables are still deterministically tied to their negations in a mutually exclusive complement, as exemplified by a proposition such as “all my statements are false” (Karray and de Silva, 2004). If the value of an entity is known, its opposite is automatically assumed also to be known as the simple product of mathematical negation. For example, the answer to a question if a given object is LONG, a so-called fuzzy assignment, can be any value between 0 and 1 and is typically represented as a plot versus the range of actually measurable property (Figure 5.6 a). Naturally, the answer to a question if the object is NOT-LONG can be derived as a mirrored plot. If the NOT-LONG plot is then inverted, it coincides perfectly with the LONG plot (Figure 5.6 b). In qualitative terms, this means that a given property will always yield the same value.
regardless of the perspective from which it is examined. However, it is clear that there is a region where there is some degree that both LONG and NOT-LONG are possible, which is the “fuzzy” region.

**Intuitionistic Fuzzy Logic**

The intuitionistic approach breaks with the limitations of exclusive and complementary treatment of the opposites. Instead, it introduces a dimension of other options. Mathematically, it does so by defining the negation as entirely independent from its original statement (Atanassov, 1999). The answer to a question if the object is NOT-LONG is not anymore a mirrored image of the LONG plot (Figure 5.6 c). The increased complexity of expressing a statement and its negation by means of two independent plots allows to model subtle and computationally elusive aspects of human reasoning (Torres et al., 2007). If such mutually independent functions are superimposed like before, they do not coincide. Instead, they form gaps and overlaps (Figure 5.6 d). The gaps (blue areas) represent a cautious assignment – hesitation. The overlaps (yellow areas) represent a simultaneous assignment of opposing values – a contradiction. It is important to realize that intuitionistic approach requires doubling the inquiry effort as subjects need to be considered from two different and mutually opposing viewpoints.

![Figure 5.6 Fuzzy and intuitionistic fuzzy assignments](Graphics © Madalina N. Wierzbicki)

**Mediative Fuzzy Logic**

Recently, computable methods for solving intuitionistic datasets have been developed (Montiel et al. 2008). The approach is based on constructing two traditional fuzzy
inference systems (FIS): one for the initial statements and one for their negations. The final outcome is computed as a weighed product of both FIS where the weighing is controlled by the nature of the differences. The advantage of the approach described by Montiel et al. is the application of the traditional and widely available fuzzy logic computing for solving intuitionistic datasets.

**Intuitionistic Model of Design Requirements**

The present thesis proposes adapting intuitionistic fuzzy logic for computational modeling of spatial relationships. The complex fuzzy datasets are well suited for capturing the qualitative and intuitionistic richness of real life dependencies and the inseparable contradictions or vagueness (Karray and de Silva, 2004). To solve the intuitionistic sets computationally, a recently developed mediative algorithm has been adapted. The thesis employs a generalized approach for developing intuitionistic datasets, whereas a strict mathematical negation can be substituted with any logically complementary information. The discussed earlier spatial relationship diagram provides a good example of how a complementary yet inconsistent in the traditional sense datasets can be derived. Translating the qualitative terms describing the spatial relationships into numerical values (Figure 5.7) allows processing the data using computational tools.

The two complementary spatial relationship queries form independent data paths with two intermediate outputs: ‘Results I’ and ‘Results II’ (Figure 5.8). The differences between these datasets are then analyzed and used to combine the intermediate outputs into the final result. Two Fuzzy Inference Systems (Figure 5.9) are used for deriving the intermediate results (Distance FIS) and for deriving the final output (Mediative FIS).

![Numerical Relationship Coding](Graphics © Madalina N. Wierzbicki)
Figure 5.8 Using intuitionistic dataset and mediative inference (Graphics © Madalina N. Wierzbicki)

Figure 5.9 Fuzzy inference systems (Graphics © Madalina N. Wierzbicki)
5.4.3 Testing an Intuitionistic Model

To test an intuitionistic model of design requirements, two simulations were set up using MATLAB. First, a simple radial arrangement of spaces around a central node was specified to observe the effect of mediative inference derived from an intuitionistic dataset. Results of a straightforward single input query representing a simple average of both input queries and a product of mediative inference were compared (Figure 5.10). The mediative inference produced a weighed result based on assessing both the variance of the input queries and the assumed importance of spaces. Figure 5.11 shows the superimposed results to highlight the differences.

![Figure 5.10 Mapping spatial relationships (Graphics © Madalina N. Wierzbicki)](image)

An important feature of the developed in this thesis implementation of the mediative inference is the adjustability of the weighing algorithm. Such adjustability allows negotiating the input queries according to, for instance, the evolving knowledge of the weighing criteria. Consequently, a variety of solutions can be derived and evaluated. The second simulation tested the flexibility of the mediative inference on a sample architectural plan.

**Simulation Setup**

The actual architectural context has necessitated the inclusion of size and topology for an abstract and dimensionless matrix of spatial relationships to be translated into a realistic floor plan. The assumptions about the sizing of spaces are another layer of the initial design requirements, while the choice of topology is an interpretative boundary between the requirements and a physical layout.
The simulation requires therefore two groups of inputs: functional requirements such as number of spaces, their sizes, and the relationships between them, as well as initial conceptual decisions regarding the global topology. Figure 5.12 details the flow of the simulation. Since a diversity of architectural layouts cannot be expressed as a computable algorithm, the simulation iterates through all unique and non-repeating permutations of possible topologies, which are then used to construct dimensioned layouts based on space sizes and their spatial relationships.

![Figure 5.12 Simulation Flow](image)

Figure 5.12 Comparing different mappings (Graphics © Madalina N. Wierzbicki)

The dimensioned layouts are used to compute access distances between all the spaces. The result is a matrix of distances, which is structured identically to the spatial relationship matrix. After normalizing, the spatial relationship matrix can be compared directly with the matrix of distances. After all layout permutations are compared with the reference matrix of distances, the best match is returned as the solution. The simulation was set up to take advantage of the adjustable mediative inference and to generate a variety of solutions for comparison and analysis (Figure 5.13).
Figure 5.12 Simulation flow (Graphics © Madalina N. Wierzbicki)

Figure 5.14 illustrates the simulation’s interface. The Spatial Relationship Matrix in the Design Requirements panel on the top-right stores both the initial and the complementary query results. Sample values of the initial set are circled red, while the corresponding values of the complementary set are circled green. The corresponding relationships are highlighted light-blue and pink. The bottom-right panel displays the mediative solution, circled blue.
Options for Deriving Solutions

Solutions were affected by two factors: the setting of the mediative inference and the method of computing distances between spaces. The following options were tested:

- Mediative algorithm, contradiction bias.
  A relationship between two spaces is influenced more by data associated with the space that has a lower overall contradiction score. The contradiction score list is pre-computed initially to sum up all the disagreements for all the spaces.

- Mediative algorithm, size bias.
  The relationship is influenced more by the data associated with a larger space.

- Single (traditional) query.
  Either the initial or the complementary query can be selected as the input.

- Distance computing options, Euclidean.
  A natural distance measuring metrics is suitable for a simple linear arrangement assuming a fairly unrestricted main hallway.

- Distance computing options, ‘Cityblock.’
  A rectangular grid metrics is effective for modeling access obstructed by partitions or furniture.
5.4.4 Results

The simplicity of a ‘brute force’ iterating simulation algorithm assured that results were not skewed by limiting the topology options through arbitrary assumptions. The simulation iterated through all possible permutations; therefore, solutions were based purely on the desired spatial relationship. The results revealed that layouts are sensitive to both the mediative inference and the distance computing options (see Figures 5.15 through 5.21).
Figure 5.16 Solution derived from an initial query using ‘Cityblock’ algorithm for computing distances (Graphics © Madalina N. Wierzbicki)

Figure 5.17 Solution derived from a complementary query using Euclidean algorithm for computing distances (Graphics © Madalina N. Wierzbicki)

Figure 5.18 Solution derived from a complementary query using ‘Cityblock’ algorithm for computing distances (Graphics © Madalina N. Wierzbicki)

Figure 5.19 Solution derived from an intuitionistic inference using contradiction bias and Euclidean algorithm for distances (Graphics © Madalina N. Wierzbicki)
Although this is a fairly simple architectural program with only ten spaces, it is virtually impossible to track all the spatial dependencies manually. A manual approach would most likely necessitate some interpretative simplifications, thus preventing consideration of all the options and associated complexities. The described approach demonstrated that ambiguous information can be used for driving digital design and that it can be retained in its full complexity throughout the design process “as ideas are iterated and refined” (Carleton et al., 2008), thus responding to the concern that “correctly designing for ambiguity remains an obstacle for AI” (ibid.) Most importantly, this project opens a way for applications capable of resolving ambiguity earlier, providing additional models to more effectively facilitate problem finding and problem defining when ambiguity is high, and augmenting early-stage team activities to either reduce ambiguity more rapidly or manage ambiguity more comfortably. (ibid.)
5.4.5 Integration with Design Workflows

The intuitionistic approach would allow designers to record and utilize a fuller spectrum of the initially available information. Furthermore, the ability to store a detailed account of design inputs would reduce the risk of oversimplifying the requirements, and it would allow better informed decisions throughout the project. Such approach toward capturing the complexity of initial design requirements is a logical step in matching the adaptive performance of modern parametric CAD tools and in developing comprehensive digital workflows. The structured and computable make-up of the intuitionistic algorithm and the mediative inference is well suited for integration with parametric design workflows. A systemic access to the high-level initial design assumptions and requirements can provide a governing process for the traditional, detail-oriented parametric design environments. Figure 5.22 shows an implementation of such governing process. Intuitionistic datasets can effectively retain contradictions and ambiguities resulting from approaching a design problem from many perspectives and from considering intentions of many stakeholders.

Figure 5.22 Using mediative inference for design review (Graphics © Madalina N. Wierzbicki)

This complex data allows deriving a range of conceptual solutions depending on user-chosen weighing criteria. Such criteria, referred in this section as ‘biases,’ can explore the richness of information that underlays design requirements, and they can drive the desired
design changes. For example, as in the simulation presented in this section, design requirements can be used to control the topology modeling algorithm and to enable data-driven modifications of layout topology, thus significantly expanding the traditional paradigm of parametric modeling, which is limited mostly to size adjustments. This highlights the significance of the approach presented in the thesis.

5.5 Intent-Driven Modeling of Foldable Geometry Using Fuzzy Logic

This section presents an original method for interfacing the complexity of human thought with the analytical inputs of digital design tools, and developed as an original contribution of the thesis. Furthermore, the method is employed for accomplishing a key objective of the thesis: how to make the designing of complex folding (kinetic) structures accessible to architects. A novel fuzzy logic-based interface allows solving the kinematics of a free-form folding geometry using intuitive human reasoning instead of inscrutable and difficult to formulate algorithms of motion.

5.5.1 Intent-Driven Design

Intent-driven design concerns accomplishing a goal in the most direct way. A notched stick is an example of a childishly simple object. In the analog world, we can fashion it in a matter of seconds. However, in the digital world, the amount of reference sketching needed for such simple feature is surprisingly quite extensive (Figure 5.23). Digital workflows tend to be more complicated than analog media. We need to realize that our mind was conditioned to deal with the analog world for millions of years. Perhaps the analog media is not that easy. But, we simply might have become very adept in using it. On the other hand, digital tools are only decades old. We may be facing an apparent initial cognitive barrier when dealing with the digital.

Parametric 3D models offer tangible interaction with shapes and their kinematics. Unfortunately, parametric tools impose a critical cognitive divergence between designer’s perceptions and formulaic abstractions of the software’s interface. 3D modeling is driven by complex mathematics of geometrical algorithms. A simple continuous path between two points is topologically, and conceptually, identical regardless of its shape variations.
However, each of these variations may require an entirely different mathematical representation. This means constructing entirely new reference geometry each time we change our mind. The world of mathematical representation is incongruent with our cognition. A simple example explains how the mathematics of modeling may diverge from the designer’s intent. A designer may consider various shapes for a walkway connecting two fixed points: a straight line, an arc, a zigzag, or a freeform weave (Figure 5.24).

Figure 5.23 Modeling a notch (Graphics © Madalina N. Wierzbicki)

Although topologically all these trajectories are identical – they are continuous and non-intersecting – their computable algorithmization in a digital model is very different (Figure 5.25). Consequently, once the designer decides on the trajectory, she cannot iterate through all other variants by merely using parameterization. Instead, each time he must construct an entirely new geometry. What we percept as a logical variation of the same, is not necessarily reflected as such in the computable mathematics of a digital representation. The above examples refer to designing objects that are static – architecture in the traditional sense. Expectantly, modeling challenges increase significantly when dealing with motion. For instance, constructing even a simple rigidly folding shell requires a copious set of constraints (Figure 5.26). Furthermore, motion of such complex constrained models tends to be unpredictable and often requires work-arounds like adding hidden reference geometries or replacing the trouble-causing constraints with formulas. This echoes the concern raised by Bettig and Hoffmann that the mechanism of complex
constraining algorithms is "not fully understood" yet, and that identifying problems in constrained models, and communicating them to users, is difficult.

Researchers agree that the cognitive side of digital tools needs to be improved (Deutsch, 2011). Shelden and Witt pointed out the importance of integrating high level design intent into the mathematics of modeling. According to Ottchen (2009), digital tools must interface with qualitative "soft data" in order to be useful for early design stages. Scheurer and Stehling (2011) critiqued the algorithmic approach for being inherently limiting because of the necessary a priori knowledge of "a general solution." These concerns prove significant when dealing with freeform foldable structures. Although such structures offer expressive possibilities for designers, they also pose significant design challenges. Even though the kinematics of a folding geometry may be computable, the actual formulas tend to be complex and not suitable for intuitive interaction with the geometry or for exploring topological variations. Consequently, it is difficult to establish a clear and comprehensible relationship between the visual attributes of digital models or their behavior, and their underlying parametric descriptions. Simply, the intent of folding, although cognitively tangible, cannot be expressed using parameters and constraints. Parametric modeling tools impose a critical cognitive divergence between designer's perceptions and formulaic abstractions of software’s interface. This is an obstacle for designers, who need interactive and tangible access to properties of a shape.
In response to these concerns, proposed in the present thesis is a human reasoning-driven tool intended for controlling parametric models. The tool can be easily ported to mainstream modelers and adapted to deal with any challenging geometries. The goal is to facilitate designing complex geometries using intuitive and interactive approach.

5.5.2 Design Objective

Irregular quadrilateral meshes are rigidly foldable under certain conditions. For instance, a 2x2 array is always foldable. Furthermore, continuous 2xn quadrilateral arrays are also always foldable, and so are two-directional 2xn arrangements such as a 3x3 array with one of the corner patches removed (Figure 5.27 middle-right).

Adding a ninth patch n9 fully constrains the geometry thus resulting in a rigid assembly. However, a so-called overconstrained motion can still be achieved under specific geometric conditions. The goal of this project was to devise an intuitive method of finding the geometry of the patch n9 (Figure 5.27 right) for a 3x3 array to be rigid-foldable. The geometry of the patch n9 is defined by two angles: an internal angle $\alpha$ and an orienting
angle $B$ (Figure 5.28 left). In order to fold the initial mesh, the patch $n9$ is only partially constrained: the red marked edge (Figure 5.28 left) can slide against its neighboring edge. Consequently, we can observe the effects of folding such as the drift angle $D$ between the sliding edges. The drift angle is being observed at two specified folded positions: Half-Fold (Figure 5.28 center) and Full-Fold (Figure 5.28 right). If the drift is eliminated at both these positions, the entire assembly becomes rigidly-foldable. The assembly can be folded using two driving patches (Figure 5.29).

Figure 5.28 Input parameters and output conditions (Graphics © Madalina N. Wierzbicki)

Figure 5.29 Folding the mesh (Graphics © Madalina N. Wierzbicki)
5.5.3 Method for Solving Kinematics

The method for solving the kinematics of a 3x3 quadrilateral mesh is based on the following:

- The target of the optimization is to reduce the drift angle below a preset value $D_R$. This value represents a residual drift that is below practical assembly errors and therefore does not affect the folding in an actual build assembly.
- Perturbations to accessible geometry parameters are used for understanding the behavior of a model and for drawing conclusions regarding dependencies between input parameters and output conditions.
- The geometry can be adjusted through changing the inner angle $A$ of the patch and/or the orienting angle $B$ of the patch.
- The adjustment values are be inferred from an intuitive set of rules using fuzzy logic.
- If both the half-fold and the full-fold angle drifts are below the preset threshold $D_R$, then the geometry is optimized and rigidly-foldable in practical applications.

The premise that a proper rigid folding can be achieved through adjusting angles $A$ and $B$ resulted in a system of two input parameters $A$ and $B$, and two output conditions $D_H$ and $D_F$ (Figure 5.28). The drift angle at half-fold $D_H$ is a function of both input parameters, the geometry angles $A$ and $B$:

$$D_H(A, B)$$

and so is the drift angle at full-fold $D_F$:

$$D_F(A, B)$$

In order to decide which geometry angle is more effective for controlling the particular drift angle, we need to compare the adjustment dynamics and select the most responsive coupling as the primary adjustment:

$$\max \left( \frac{dD_H(A, B)}{dA}, \frac{dD_H(A, B)}{dB}, \frac{dD_F(A, B)}{dA}, \frac{dD_F(A, B)}{dB} \right)$$

Since in this case (Figure 5.30) it is the geometry angle $B$ when used for controlling the half-fold drift $D_H$:  

$$132$$
the adjustment problem can be expressed as two concurrent optimizations:

\[
\frac{dD_h(A, B)}{dB} \quad (4)
\]

\[
\begin{align*}
\text{minimize} & \quad D_h(A, B) \\
\text{subject to} & \quad |B - B_0| < B_{\text{FOLD}} \\
\minimize & \quad D_f(A, B) \\
\text{subject to } & \quad |A - A_0| < A_{\text{FOLD}}
\end{align*} \quad (5)
\]

The conditions \(A_{\text{FOLD}}\) and \(B_{\text{FOLD}}\) specify the practical limits of adjustments, beyond which the geometry becomes unfoldable. Furthermore, both drift angle functions (1) and (2) are coupled because they share the same arguments \(A\) and \(B\). Therefore, we need to check, by comparing both the adjustment cross-talk paths, if concurrent optimizations will not cancel each other out:

\[
\frac{dD_h(A, B)}{dB} > \frac{dD_h(A, B)}{dA} \quad (7)
\]

\[
\frac{dD_f(A, B)}{dA} > \frac{dD_f(A, B)}{dB} \quad (8)
\]

For this and similar geometries, the adjustment separation is very good (Figure 5.30). Therefore, a simple adjustment strategy, whereby each of the geometry angles is used to reduce the corresponding drift, is sufficient.

Practical applications do not need the absolute accuracy of mathematical models. A solution is acceptable as long as the actual drift angles are below the relevant assembly and manufacturing tolerances. Once both the half-fold and full-fold drifts are reduced below the maximum allowable value \(D_R\):

\[
D_h, D_f < D_R \quad (9)
\]

the solution has been reached.
5.5.4 Algorithm

Once linking between inputs and outputs has been determined, in this case $B: D_h$ and $A: D_f$, the algorithm alternates between looping sequences of adjustments to the angles $A$ and $B$ until the drifts $D_h$ and $D_f$ are reduced below a preset threshold (Figure 5.31).
Optimization can only be accomplished if the maximum drift values $D_h$ and $D_f$ in each successive adjustment sequence show a decreasing trend. Figure 5.32 shows a plot of the drift angles $D_h$ (red) and $D_f$ (blue). Indicated are the adjustment loops, and switching points between the $A$ and $B$. Tested was the outcome of the chosen linking between the input parameters $A$ and $B$ and the output conditions $D_h$ and $D_f$.

![Figure 5.32 Output plot](Graphics © Madalina N. Wierzbicki)

Figure 5.33 (top) shows plots of the angles $A$ and $B$ normalized to have the optimized target value at 0. For the inverted linking, both $A$ and $B$ continued to diverge from the target values until the geometry could not be solved anymore (Figure 5.34 right). Also, the plot of the drift angles shows a diverging trend (Figure 5.33 bottom).

### 5.5.5 Implementation

Parametric 3D modeling programs offer an easy programmatic access to model properties using the Application Program Interface (API). Furthermore, different applications – modeling, computing – can easily communicate through the application’s server functionality. The main part of the adjustment algorithm was coded in the API of the modeler of choice (Inventor) and configured to access the computing application (MATLAB) from within the running algorithm (Figure 5.35).
Figure 5.33 The role of proper linking input parameters to output conditions (Graphics © Madalina N. Wierzbicki)
MATLAB is used for the convenience of setting up a Fuzzy Inference System. The API of the 3D modeler is the interface point with the user. This is convenient as users can control the entire adjustment algorithm from a single and familiar environment of the modeling software. Figure 5.36 shows the entire application mapped over the used software platforms. Two blocks, handling the geometry and computing the adjustments, make up the structure of the algorithm (Figure 5.37).
Figure 5.36 Software platform (Graphics © Madalina N. Wierzbicki)
Figure 5.37 The algorithm (Graphics © Madalina N. Wierzbicki)

The operator P detects the magnitude of the angular drift, while the operator D detects the change of the drift. The Fuzzy Inference System (FIS) uses these two values to derive adjustments. Once the drift angle drops below a preset limit, the optimization is complete. The red dotted block is essentially a PD – a Proportional-Derivative feedback loop controller (de Silva, 2009) using fuzzy logic as a computing aid. This is a unique feature of the concept: formulaic algorithmization of kinematics has been replaced with a signal processing-like approach. The dynamic behavior of geometry is being monitored, and typical signal processing and control tools are used to implement adjustments. A significant advantage is that only the key measurable aspects of motion are sufficient for optimizing the geometry without the need to involve its underlying mathematical model.

5.5.6 Fuzzy Inference System

The algorithm measures the drift angle and the change of the drift angle between iterations. The Fuzzy Inference System processes these two values using a rule base, which reflects the observed characteristics of motion using intuitive, human reasoning-like statements (Figure 5.38). Sugeno inference method (Karray and de Silva, 2004) was implemented in
order to assure smooth surfaces (Figure 5.39) and precise generation of adjustment values at the low end of the inputs.

Achieving a desired precision presented additional challenges. The basic algorithm performed well when reducing the drift angle up to 0.1°. Below this limit, the resolution of FIS of MATLAB became the limiting factor. This could be addressed by specifying a much higher computing resolution for the FIS together with a more elaborate system of input/output membership functions. However, such approach had considerable drawbacks. Most importantly, the more involved membership functions would result in a complex and much less intuitive set of inference rules. Furthermore, such solution would not be scalable if yet higher precisions were desired. Also, the needed significant increase in FIS
resolution would result in noticeably longer computing times. Instead, an additional supervisory FIS (FIS 2) was devised (Figure 5.40) specifically for managing the parameters pertinent to achieving a desired precision.

The second FIS implemented a concept of progressive drift limits, thus breaking the entire optimization into distinct phases governed by increasingly tighter limits for the drift angle (Figure 5.41). The added advantage, besides the clarity of the inference rules and scalability, was also the efficiency of optimization. Since the algorithm alternates between adjusting two mutually interfering output conditions, the progressive drift limits prevent overadjusting one condition before both of them are brought into a similar range of drift. Although the second FIS used a simple set of rules such as ‘if the desired precision is $X$ then adjust FIS 1 by $Y$, ’ the algorithm easily achieved precision of 0.0001˚, which is a magnitude below the most stringent theoretical CNC tolerances. Adding the second FIS allowed an easy and scalable increase of precision by magnitudes.
The algorithm was tested on a freeform, non-repeating, non-symmetrical, quadrilateral mesh. Folding of the initial mesh resulted in significant drifts between the sliding edges. The adjusted mesh folded with the edges properly aligned (Figure 5.42). Examined was the impact of FIS parameters on the behavior of the algorithm. The signal processing-like nature of the algorithm is evident when reviewing drift angle plots for various FIS settings. If the FIS generates excessive adjustments, the drift angles overshoot repeatedly before they are brought down to a desired level (Figure 5.43 top and Figure 5.44 top), thus resembling an underdampened feedback loop. Figure 5.43 displays plots using logarithmic scale to show the dynamics of adjustments across the entire optimization.
Once the FIS parameters are set to optimal (Figure 5.43 bottom), the first phase of optimization to reach the 0.1 drift limit is clearly the longest. This is caused by the initial asymmetry of the required corrections for the angles $A$ and $B$. An arbitrary initial location of the edges of the patch n9 results in one of these edges needing more adjustment than the other. Once both edges are brought into a similar error margin, which happens after the first phase is completed, then optimization progresses more efficiently and achieves an improvement of three magnitudes (from 0.1 to 0.0001) in less cycles than needed for the initial improvement of two magnitudes (from 8 to 0.1).

Figure 5.44 displays only the final phases of optimization using linear scale to show the undistorted plots of adjustments. If the FIS is not able to regulate adjustments according to the actual drift angle and instead keeps them constant (Figure 5.44, line A), the progress of optimization is slow, and it resembles an over-damped feedback loop (de Silva, 2009) (Figure 5.44 line B). Once the FIS membership functions were set to optimal values, adjustments were calculated accordingly to the drift level (Figure 5.44 line C) and the speed of optimization improved.
Figure 5.43 The role of the controlling algorithm (Graphics © Madalina N. Wierzbicki)
It should be emphasized that from the engineering perspective, the present thesis only concerns the kinematic problem of a kinetic (folding) structure. There is another important aspect that needs consideration in the design of a kinetic structure, which is ‘kinetics’ that encompasses the dynamics of the problem. Kinetics will involve forces, moments/torques, stresses, strains, and so on as well (de Silva, 2014) and is beyond the scope of the present thesis. However, kinetics may also be incorporated into the overall design problem of a dynamic architectural system, by giving due regard to the human-centric issues in the spirit of the present thesis. That however, will dominantly involve ‘engineering.’
5.6 Education

Not surprisingly, the diverse and often polarizing discourse on the role of digital technologies in re-defining architectural paradigms is also reflected in the search for new educational models. On the one side, contempt for the traditional “paper-based culture of design” (Oxman, 2008) promotes an unreserved reverence for the digital:

Beyond any doubt digital design appears to be a mainstream phenomenon, and the theory of digital design appears to be one of the most active and significant subjects of theoretical discourse today. (ibid.)

Consequently, a vision of the corresponding educational model is a reflection of such reverence:

Any new framework for design pedagogy must be responsive to conditions in which digital concepts are integrated as a unique body of knowledge consisting of the relationship between digital architectural knowledge and digital design skill. (ibid.)

The inevitable conclusion is that “architectural education appears to be in need of a make-over from the bottom-up” (ibid.). The guiding premise of this technology-centric approach is the focus on process, on “the concept of formation” (ibid.) rather than on the outcome, thus in a way demoting future architects to be merely craftsmen of the digital. Yet, such craft of digital synthesis results in an unprecedented richness of architectural forms. These spectacular structures explore the exotic aesthetics of clashing magnitudes whereby miniaturized humans are transported into a realm of giant organic sponge- and filament-like forms. Yet, such an approach seems to leave out the concern for the human scale as the subsequent computer-generated presentations generally avoid elaborating on the relationship between these enthralling structures and their occupants. Consequently, ‘digital designs’ are successful only at the “level of a superficial, mere appearance mimesis of the ‘novel aesthetic qualities’ of computational art” (Lostritto and Vardouli, 2012). More importantly, the excessive preoccupation with digitally generated abstractions prevents designers from “perceiving and operating on the inherent spatial potential” of their own ideas (ibid.), thus resulting in architectures that are in Gamblean sense “un-peopled.”
On the other side, the tangible, immediate, and intimate skill of hand drawing is considered as the yet unsurpassed media for ideation:

Drawn content and drawing as analysis isolate the spatial potential of the aesthetics unencumbered by overtly spatial conditions in a geometric model. Sketching with pencil and paper is still the best medium for the improvisational creation of drawings. (Lostritto and Vardouli)

Hand drawing, which is merely a physiokinetiс sibling of gesturing we use all the time and mostly subconsciously to emphasize our spoken language, is different from gesturing by only employing the simplest implement of all, a stylus or a piece of chalk. The technological elaborations such as pencils and pens have not altered the underlying concept of hand drawing or writing for millennia. The realization that literary works, art drawings, architectural plans, and mechanical designs were expressed using the same method is an empowering metaphor for our enduring culture: as long as we are able to point our hand, we can create and express our visions using the simplest of implements. In contrast, computers leave us feeling vulnerable and dependent as we are assimilating the fears of the digital era: power outages, discharged batteries, crashing software, and data loss. Not surprisingly, on this side of the argument the timeless virtue of hand drawing is complemented by the “integrity of the traditional disciplines” as the essential reference for developing new knowledge models and for integrating new technologies with existing practices and education (Mitchell et al., 2003):

Without a disciplinary frame, the richness of disciplinary practices, methodologies, and concepts can become lost, leaving an oversimplified crossdisciplinary knowledge domain. This danger exists when any practice is digitized in the absence of an appropriate model, as for example in arts education when young people have become wedded to the prescripted options of packaged applications and are only capable of creating PhotoShop art. (ibid.)

Accordingly, Gauchat (2009) warned against subjugating education to the fleeting fancy of new technologies:

Architectural education must not give in to pressures to trade off general education in favor of professional subject matter. (ibid.)
Furthermore, Gauchat argued that specialized technical knowledge becomes quickly obsolete while “good general education” provides a universal reference for continuing learning. Similarly, Chester (2007) emphasized the importance of developing “strategic knowledge” transcending the instructional level of using digital design tools. Such knowledge would help students to deal with the continuously changing digital technologies. The model of such “strategic knowledge” dates back to Vitruvius (15 BC/1914), who argued the importance of a comprehensive interdisciplinary expertise derived equally from theory and practice,

\[
\text{The architect should be equipped with knowledge of many branches of study and varied kinds of learning, for it is by his judgement that all work done by the other arts is put to test. This knowledge is the child of practice and theory, (ibid.)}
\]

and matured through years of experience,

\[
\text{I think that men have no right to profess themselves architects hastily, without having climbed from boyhood the steps of these studies and thus, nursed by the knowledge of many arts and sciences, having reached the heights of the holy ground of architecture. (ibid.)}
\]

Is it possible then to construct a consistent educational framework retaining most of both such opposing approaches? Interestingly, both approaches are united and governed by the inevitability of time. Educators have the experience and the expertise, or in other words, they know the past and they are skilled in the present. Students, however, represent the future. They will reach their productive peak in conditions that will be entirely different from the present ones. Therefore understanding such a temporal crossroads is important for transcending the entanglement of current circumstances and identifying concepts, which are timeless and which establish our social and cultural continuity. The primary goal is to empower students so they can take an active role in creating the future rather than just passively anticipate it. As the analog has yielded to the digital, so the digital will be surpassed by the quantum. First quantum computers have already been constructed. Quantum tools will bring to computing what the digital has brought to information: the scales of massive. For instance, such resources of processing power would allow to model qualitative phenomena like analogy and metaphor, thus allowing the use of truly human-like reasoning in design tools. We can participate in developing this future by learning the
concepts of modeling human-like reasoning, and experimenting with these concepts using the current digital tools as merely transient devices of convenience.

At the core of being able to experiment with design tools lies the knowledge of programming – the capacity to use the tools the way we want to. Proponents of both sides agree that the skill of customizing software is becoming essential in the digital era, thus establishing a common point regarding the most contentious issue, that of digital technologies. The ability to make sound judgment may be another universal virtue few would object to. Gauchat asserted that

Judgment is probably the most important yet elusive characteristic of a complete professional. With almost infinite amounts of information, judgment is needed to discern which information is relevant and which is extraneous.

The skill of using analogies is another essential and timeless cognitive mechanism, which according to Pask needs to be trained and educated to avoid its pitfalls:

Globetrotting may now be defined as the misunderstanding of valid analogies the use of vacuous analogies or both, while improvidence is failure to use valid analogies, failure to use a common principle, or both. (1976)

Perhaps such combination of understanding the demands of the digital with classical cognitive concepts will suffice to sustain the continuity of tradition through the volatility of cutting edge technologies. Or perhaps architectural education will “bifurcate”:

into the more traditional establishments that will continue to foist an educational programme on students that was modelled on the teachers’ own educational experiences, and the more progressive schools that are able to make the necessary investments and faculty adjustments to educate a new breed of architects. These two trajectories are also likely to grow further and further apart. (Gauchat)

In any case, the adversarial sides will be always unwittingly unified through the “boundary object” (Jones) of material culture, the built environments which will embody the respective theories, obsessions, and educational models, thus projecting these notions into the timeless domain of the “here and now” and the “everywhere and always” (Knights), so they would conclude all that was said in the past and then would surrender to the inquiry by everyone in the future. We expect education to reveal how to harness the unique
vantage point of ‘now,’ this singular transition between the past and the future, through choreographing our own unique trans-disciplinary networks and through employing our own combinations of digital technologies. Ultimately, such frameworks form our expertise and then become a part of our designs.
CHAPTER 6 Examples and Practical Applications

A foldable 3x3 quadrilateral mesh has been developed during the present research as reported in the thesis. This mesh can be considered as an elemental block of a crumpled geometry as it manifests analogous ridges and valleys while folding. While in motion, the mesh resembles mechanized textile. In a way, freeform foldable geometries are the modern incarnations of the Semperian architectural archetypes. The expressive shapes of free-form folding geometries provide rich media to be explored by designers. Some relevant examples are presented in this chapter.

6.1 Application Examples

![Figure 6.1 Foldable shade (© Madalina N. Wierzbicki)](image)

Some examples of the concepts of foldable kinetic structures as developed in the present research and their applications are presented now. A kinetic shade constructed using a 3x3 quadrilateral mesh can be adjusted on demand (Figure 6.1). Being a rigid and self-
supporting structure, it offers advantages over fabric-based solutions in terms of durability, robustness, simpler anchoring, and the variety of forms.

A similar foldable module can be arrayed over the entire elevation of the building (Figures 6.2 and 6.3). Coordinated, distributed control (de Silva, 2009) of the modules results in virtually infinite configurations to negotiate environmental conditions or to provide expressive choreographies (Figures 6.4 to 6.7).
Figure 6.4 Foldable elevation (© Madalina N. Wierzbicki)

Figure 6.5 Foldable elevation (© Madalina N. Wierzbicki)
Figure 6.6 Foldable elevation (© Madalina N. Wierzbicki)

Figure 6.7 Foldable elevation (© Madalina N. Wierzbicki)
6.2 Foldable Shades

Installing a folding module on an articulated anchoring stem significantly expands the repertoire of spatial postures and functions (Figures 6.8 to 6.12). Such stem can be constructed using a rigid variant of a harmonic drive (de Silva, 2007), thus offering slow movement, fine motion resolution and a very high holding torque, all desirable in kinetic structural applications.

Figure 6.8 Foldable shade (© Madalina N. Wierzbicki)

Figure 6.9 Foldable shade (© Madalina N. Wierzbicki)
CHAPTER 7 Conclusions

Researchers unequivocally agree about the urgent need to improve built environments and construction methods. Furthermore, researchers agree that such improvement can only happen through an integrated interdisciplinary effort aimed at the entire complex system of architectural and engineering professions, their education, technologies, and cultural circumstances such as economy, politics, and social expectations. As investigated in the present thesis, built environments need to become flexible, dynamic, and adaptable to both environmental conditions and functional changes. The thesis asserted that such objectives can be accomplished by developing kinetic architectural solutions. The presented review of the current state of the art and the examples developed in the course of the investigation revealed that, technologically, kinetic architecture is already feasible. However, lacking is the social demand, the support of the governing bodies, and the interest of the involved industries.

The historical analysis presented in this thesis indicated that movement is, and always was, inseparable from human spatial practices. Therefore, architectural profession must transcend the traditional disregard for the occupant activity and for the inherent element of transiency in human behavioral settings such as built environments. In this regard, a human-centric initiative is needed in the architectural and technological processes of the development of built environments, as proposed and investigated in the thesis.

In the present investigation, foldable kinetic structures were used to exemplify a dynamic built environment. The thesis investigated the challenges of designing folding kinetic structures and identified the inadequacy of the available design tools. In response to these concerns, novel design methods were presented for solving the kinematics of foldable structures.
7.1 Main Contributions

The present thesis employed a human-centered perspective to interconnect disparate disciplines into an inclusive framework aimed at understanding and designing built environments. Such approach connects scientific and emotional domains: engineering with curiosity, architecture with social awareness, and history with understanding the present. The goal is to empower designers in becoming contributing participants and a part of the solution, along with the users. This is an important and novel contribution of the thesis as it addresses the concerns of other researchers regarding the entrenched and obstructing divides between disciplines, for instance, between architecture and social sciences, between engineering and history, or between engineering and architecture. Furthermore, this thesis contributed an original and fundamental comprehensive understanding of kinetic architectural components: their history, and their functional and social significance. In particular, this investigation traced the historical understanding and the cultural role of mechanical motion as both a valuable functional technology and as a means of multilayered symbolic expression. Such knowledge is critical for the effective integration of kinetic components into architectural design practice, and for understanding circumstances affecting social acceptance of new designs. For instance, integral use of components such as adjustable shading, movable wind shields, or easily operable enclosures results in better energy efficiency, in increased comfort of users, and in functional flexibility.

This thesis established, while using a functional and behavioral focus, a recognizable historical continuity of artifacts, archaeological research, and architectural theory, thus grounding the contemporary architectural discourse in the context of historical precedents and social practices pertaining to space. This original contribution addresses the concern voiced by researchers about architecture and its history being asocial and ‘un-peopled.’

Another vital and original contribution of this thesis addressed digital design tools. First, the thesis presented a comprehensive history of architectural design software in the
context of computing technologies, economy, and competing marketing strategies. Second, it provided a detailed review of current discourse about digital design tools. This knowledge is necessary for design practitioners when dealing with the volatile software technologies and constantly changing design processes.

Most importantly, this thesis presented original solutions addressing concerns raised by other researchers that current digital workflows are unintuitive and not able to interface with human reasoning. In particular, the present thesis developed, presented and tested a novel method for modeling initial design requirements using an original implementation of intuitionistic fuzzy logic. The developed method allowed integrating into the initial design requirements “qualitative” information and knowledge along with such subtle traits of human reasoning as hesitation or contradiction, thus overcoming the traditional oversimplification of the initial data.

Furthermore, developed, tested, and described in the thesis was an original method for intuitive, intent-driven interaction with kinetic parametric models, whereby fuzzy logic was employed as a human reasoning-driven controller capable of adjusting kinematics of the model. Such approach is essential when designing folding geometries in order to overcome the, as critiqued by researchers, deficiencies of parametric tools stemming from their analytical and algorithmic nature.

Lastly, the thesis presented some original concepts of architectural examples applications employing rigidly-foldable kinetic geometries.

### 7.2 Future Research Directions

The broad interdisciplinary scope of this study has identified numerous new directions for further research in both engineering and humanities. Some of these are summarized now.

History of architecture and built environments needs to be reconsidered to integrate the wealth of kinetic and adjustable implements, and the dynamics of human behavior.
This thesis has defined the methodology, and has unraveled the key points; however, much still remains to be done to complete such a vast program.

This project has identified the importance of understanding the emotional interaction between habitants and built environments. This knowledge holds the key clues for improving urban settings and buildings, and it must be furthered using an interdisciplinary effort of both architecture and humanities. The thesis has identified possible directions for integrating the capacity of intuitive reasoning with human intent into digital design tools.

Concepts for kinetic folding geometries and for possible applications were presented. Rigid folding offers unique design opportunities and further research on such geometry is necessary to explore this promising direction.

It should be emphasized that from the engineering perspective, the present thesis only concerns the kinematic problem of a kinetic (folding) structure. There is another important aspect that needs consideration in the design of a kinetic structure, which is “kinetics” that encompasses the dynamics of the problem. Kinetics will involve forces, moments/torques, stresses, strains, and so on as well. However, kinetics may also be incorporated into the overall design problem of a dynamic architectural system, by giving due regard to the human-centric issues in the spirit of the present thesis. That however, will dominantly involve “engineering.”

The methods proposed and developed in the present thesis need to be further researched to include the missing aspects of dynamic systems, and in this manner improve the performance and versatility of kinetic built environments. Furthermore, virtual models need to be validated through concurrent engineering and fabrication of functioning assemblies.
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