Thinking Manual

A Digital Framework for Designing and Making

by

Anna Vasileiou

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Signature of Author: ____

Department of Architecture
May 8, 2020

Certified by: ____

Axel Kilian
Visiting Assistant Professor
Thesis Supervisor

Accepted by: ____

Leslie K. Norford
Professor of Building Technology
Chair, Department Committee on Graduate Students

Thesis Committee

Thesis Supervisor

Axel Kilian, PhD Design and Computation

Visiting Assistant Professor

and reader

Mark Goulthorpe

Associate Professor of Design

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ABSTRACT

In the wake of a new form of craftsmanship, we, architects and designers have adopted a new digital mindset. Design is considered not only a tool of making but also one of thinking, with us transitioning from inventing analog machines as thinking, drawing, and making tools to designing and fabricating with computer-controlled machines. Yet, although these digital technologies are conceived as tools augmenting certain aptitudes we have, they fail to communicate the creative and inventive aspects of the act of design.

We have embraced this new digital mindset, we use more and more computation-based software to solve even more challenging geometric problems and reach higher degrees of accuracy and efficiency in design and fabrication. However, computers' binary structural and representational logic focusing mainly on the symbolic and computational design aspects is neither similar nor fully understandable to our way of thinking. Hence, this very lack of understanding of the tools' operational logic repositions our creative role from making by thinking to making by calculating. Yet, can the computer as a digital tool augment the human mind and render design a pedagogical act of creative thinking?

In the course of this thesis, I aim to explore ways of introducing computational tools into design processes of advanced geometry for a more creative and open-ended human-machine symbiosis. To this end, I propose the Thinking Manual, a hypothesis in the form of a new design workflow enhancing and reconciling the designer's creative thinking with the computer's image processing and simulation capabilities. I use the problem of paper folding to question my initial hypothesis, test my proposal, and prove the necessity for a paradigm shift in design practice and pedagogy. Herein, design stands as the interface between unconscious and conscious thinking, doing, and making, driven by the triptych eye-mind-hand with or without geometric precision.

Thesis Supervisor: Axel Kilian

Title: Visiting Assistant Professor

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Anna Vasileiou, MIT, Cambridge, May 2020

To my mom, Marianthi Themeli,

my dad, Nikolaos Vasileiou,

and my brother, Chris Vasileiou.

“He who fights with monsters should look to it that he himself does not become a monster. And when you gaze long into an abyss the abyss also gazes into you.”

Friedrich Nietzsche

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PART I

Prologue

PART I
Prologue

As I phrase the prologue for my work, I situate design between conditions of both theory and practice. Instantly, I find myself strolling between how - if not if - drawing, computing, and making come together to articulate the inventive act of design. Soon, I realize that there are no clear division lines between the three of them but rather, an underlying driving force that fuels this very act from conceptualization to implementation. That is, thinking or, for me, an armature of seeing, imagining, perceiving, knowing, making, decision making, exploring, and learning. Later, I am able to understand that the only existing division lines can be traced in the way thinking is incorporated in designing, be it sometimes an embodied human act and some others a digital, discrete and binary process of computing executed by the technological tools and software we, architects and designers, use today for doing and making.

Saluting this last thought, I can only think of design in terms of the following five ennoiological axes that I blend syntactically and turn into the title of my work:

1. Thinking
2. Manual
3. Digital
4. Designing
5. Making

Here my thesis begins.

Thinking Manual

A Digital Framework for Designing and Making

While digital technologies have irrefutably inundated all instances of the contemporary design practices, the tendency I have identified in current approaches is to assume that these technologies enhance and augment former aptitudes we, architects, designers, and humans, have. At the same time, they set the foundations for a new state of affairs in design as a tripartite activity of thinking, doing, and making. The computer-aided-design (CAD) applications, for instance, are developed as the designer's computational and representational assistant changing, if not improving, what was formerly remembered as the drafting table. The rapid prototyping technologies help us fabricate physical prototypes faster allowing us to iterate, test, and, therefore, perfect our design solutions. At the same time, our identity seems to be shifting as we transition to a new form of craftsmanship.

Nonetheless, I claim that the problem with utilizing digital technologies in general and computers and softwares in particular is associated with the way they process any sort of input the designer might feed them with. That is, any input - even the unquantifiable ones, such as an idea or thought - is processed as bits of information, able to be discretized, reasoned, and computed. In these terms, in design in particular, the hands, eyes, and even the mind itself, are suppressed by the computational constructs articulating the process. Thus, the designer's assistant shifts from being a tool of thinking, imagining, and creating to one of merely computing.

In this context, I argue that the role and essence of the tool and the tooling itself needs to be redefined and thought of anew in relation to both its physical and digital dimensions. We do not interact with a computer's mouse or a piece of software's interface in the way we do with a hand tool, a pen, or a drafting table. While on the former a click by use of the mouse generates a symbolic representation on the computer's screen, on the latter what a pen generates on a sheet of paper is what is drawn.

The human dimensions of the problem I address here touch parameters such as creativity, perception, imagination, and consciousness. The computational aspects look into the limitations of the digital computers in the way they drive the creative design process today which, I claim, is something that still needs to be reexamined and resolved. For this reason, I choose to develop a critical outlook towards computers' inadequacy and misuse as well as the designers who blindly remain passive to these points of failure.

On the base of this speculation, I am concerned with bridging the gap between creative design practices and computing. To this end, I explicate the ways in which the former is altered by and tailored to the latter. I first try to articulate the relationship between the designer and their tools and then define the very essence of design as a thinking process of seeing, doing, and making. Although I identify that my quest comes with both intellectual and practical boundaries situated in human-machine symbiosis in design practices today, I concentrate and elaborate on rendering computers important, yet complementary agents in design's thinking, doing, and making apparatus, such as drawing and physical simulating. To this end, I outline how computers are incorporated in creative design processes and I reposition the designer, theoretically and practically, within these processes. To test my argument, I propose the Thinking Manual, as I call it, or else a hypothesis in the form of a new design workflow aiming to recentralize the designer's role and create the potential for new moments and ways of interaction and symbiosis with their digital tools. This workflow enhances the creative and critical thinking capabilities of the human designer and combines them with the image processing and simulation capabilities of the computer.

On the theoretical side, I question to which degree designing as a creative act can be codified in digital terms. I redefine the statement that thinking is the medium from designing to making by interrelating the notions of meaning seeking, meaning making, computing by seeing and making, and designing by seeing, computing, and making. I portray the designer as the interface between unconscious and conscious thinking, doing, and making and the tool as the interface between the designer's mental aptitude and their physical enacted act of thinking.

On the technical side, I propose a workflow enabling the designer to solve a geometric problem of high complexity via broadening the process by adding a level of computing. In this context, the Thinking Manual revolves around the following axes:

1. the types of visual understanding and meaning one comes up with while designing;
2. the ways in which this meaning can be computed, if any;
3. the ways in which these computed meanings can lead to an augmented version of the visual meaning anew.

In methodological terms, I start my research by framing a problem and then I go on to propose the aforementioned hypothesis as a solution to the very problem. In this context, this thesis is structured around two main parts: first, an interpretation of the tool – be it analog or digital – and the designer as different sorts of interfaces integrated in the design process; second, the proposed workflow targeting for a more creative, intuitive, and open-ended human-machine symbiosis.

Therefore, on a general basis with my research, I search for ways to incorporate the logic of computing into designing, thinking, and making in an open-ended manner and aim to make both theoretical and technical contributions to design. I aim to explore the very moment at which the human designer and the tool – both analog and digital - symbiotically interrelate as well as inform and augment each other's capabilities. To do that, I go into a design domain - that of paper folding with a focus on curved creases and origami tessellations – that is not yet adequately explored or understood by designers and architects, not only under the scope of geometry but also that of the symbiosis between physical and digital exploration tools. To this end, I associate evidence from the fields of architecture, design, computer and cognitive science, and philosophy.

Although there have been prior studies with an aim similar to this one redefining the roles of physical and digital computing in creative design processes, I hold that this thesis offers a different way of addressing the problem. Yet, my goal is not to address a problem and solve it. Rather, I intend to point readers to a different way of thinking about the following core inquiries:

- what computational design systems are used for and how they complement us in the act of design;

- how we can break the boundaries that the computation al process limits us within;

- what computational design systems are used for and how they complement us in the act of design;

- how can we utilize computational tools to create an open-ended creative process in which thinking stands as the interface between designing and making.

The workflow I propose is not meant to be a product or digital application in the commercial sense of the word. Rather, it is conceived as a hybrid tool to think with - a physical and digital manual for bridging the gap between designing, making, and learning by use of both analog and digital tools. The software and hardware parts of it activate, externalize, visualize, and augment the designer's mind, eyes, and hands which I aim to reposition in key parts of this workflow to enhance it as a creative, prob-lem-solving, and learning process. Even though there are current-ly applications and simulation software computing problems like the ones I address in this thesis, I don't intend to further develop this domain by proposing an improved device, piece of software, or application in place of what already exists. For a move like that would not overcome the deterministic, binary nature of these computers-devices and therefore contradicts with my trajectory's primary goal.

In this context, I believe that this study unfolds as a reminder that the human parameter is the very essence of the act of design and as such it should not be suppressed by the tools developed to augment it. I hold that it is essential that designers realize what the contribution of mere computing in creative thinking processes is and what each tool allows them to do, be it digital or physical, practical or intellectual.

PART II

Designing

PART II
Designing
1

The problem

In the era of ubiquitous computing, architects and designers have adopted a new digital mindset. Design is now more and more considered not only a tool of making but also one of thinking. With the hand technique and construction methods as a point of departure we transition today from the analog machines as thinking, drawing, and making tools to the building with computers and software-controlled machines. However, although these digital technologies are conceived as tools that can enhance and augment some of our aptitudes, I claim that they fail to communicate the intuitive, creative, and inventive aspects of the act of design.

Although up to a certain degree we have embraced this new digital framework as a tool for thinking rather than one for making, we are using more and more machines and computation-based softwares on every step of the design process to solve even more challenging mathematical or geometric problems and reach higher degrees of accuracy in design and fabrication. However, the way computers function focuses mainly on the symbolic and computational aspects of design in a deterministic way which is neither similar nor fully understandable to us. Consequently, this very lack of understanding of the tools' operational logic – which I call instrumental knowledge – suppresses design knowledge - or else the formal, spatial, and material organization principles. Thus, our creative role as designers is marginalized with us transitioning somewhat mechanically from the mode of making by thinking to that of making by digitally calculating.

Under these conditions, design knowledge - or else what in the context of this thesis I call the formal, spatial, and material organization principles – is suppressed by instrumental knowledge pertaining to the intentional understanding of a technological tool's operational logic (Witt, 2010). At the same time, we are unable to control by hand the logic that complex processes and geometric functions follow when carried out by computers. In these terms, the extent to which technology's integration into the design process is beneficial is questionable.

For if we assume that architectural knowledge is the sum of both design and instrumental knowledge, does the latter enhance or diminish architectural knowledge itself and the role of the architect in the design process? The question that emerges then is, has the design process itself become more mechanized and less humanized?

The technical logic of the 1960s and the early CAD implementations led to the idea that computers are informed machines with cognitive capacities that can augment the creative aspects of the act of design and help architects with tedious tasks like data processing, analysis, optimization, and simulation. However, this view of technology's role came to failure as it didn't consider the creative aspects of the design and ideation process. Rather, it only enhanced the representational, numeric or symbolic value that computers could offer (Negroponte, 1975, 7).

Consequently, it was soon proved that design is not an automated information process or a medium of digitization of the analog but a much more complex problem that can be only erroneously defined in terms of static rules and symbolic representations. With the subsequent focus of the fields of Artificial Intelligence and Human-Computer Interaction on the computer as an anthropomorphized assistant with capacities that can potentially surpass the human ones, the symbiosis between the designer and their digital tools has been examined as a way to complement and augment the designer. Yet, how can architects and designers interact with current technologies in a more creative and less representational way to bridge designing and making still remains unanswered.

In this very transition from designing to making by means of thinking, I identify three fundamental problems related to technology's role in the digital design process: the first one is linked with the so-called black-box processes, the second one refers to the generic processes, and the third one describes the consequent creative gap. The contemporary digital tools' focus on mainly the representational aspects of design from ideation to fabrication brings the 1960s' representation problem of design into question (Dreyfus, 1986, 12). Known as the problem of the black-boxed processes in software and machines, it leaves out the architect's creativity and control over the way the contemporary digital design tools execute computation-based operations to solve geometric problems among others.

The second problem, that of the generic processes, refers to the use of generic operations that are embedded into both software and hardware to implement a non-generic design idea. As a result of the former two problems in the transition from design to making, the "creative gap" emerges between the designer and the digital tool used, thus representing the marginalization and mechanization of the human aspect of design.

Hence, it is valid to ask at this point how the interaction between these two opposing systems – that of the designer and the other of the digital tool - should be designed in order to generate more intuitive and creative design processes. Next, I try to define the role of each system in the act of design before I understand the requirements of their symbiotic relationship.

PART II
Designing
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The tool: An analog instruction

Architecture has always been supported by the use of tools - both analog and digital ones - to reach precision and efficiency in design and fabrication processes. To this end, the pre- and post-Renaissance architectural and engineering manuals were developed as tools systematizing and democratizing instrumental knowledge for drawing or building purposes. Technical encyclopedias - like those by Vitruvius and Alberti among others - quantified and transformed natural-world observations into abstract taxonomic drawings of models, tools, and machines.

The importance of this interdisciplinary knowledge when it comes to architecture and design is explicitly phrased in the work of Leon Battista Alberti whose engagement with machines as fundamental tools of the design process links their role with the birth of architecture as a discipline. In his treatise De re aedificatoria (1452) and his description of the architect's role, Alberti considers the knowledge of technology to be the base of design and construction (Alberti, 1988, 3):

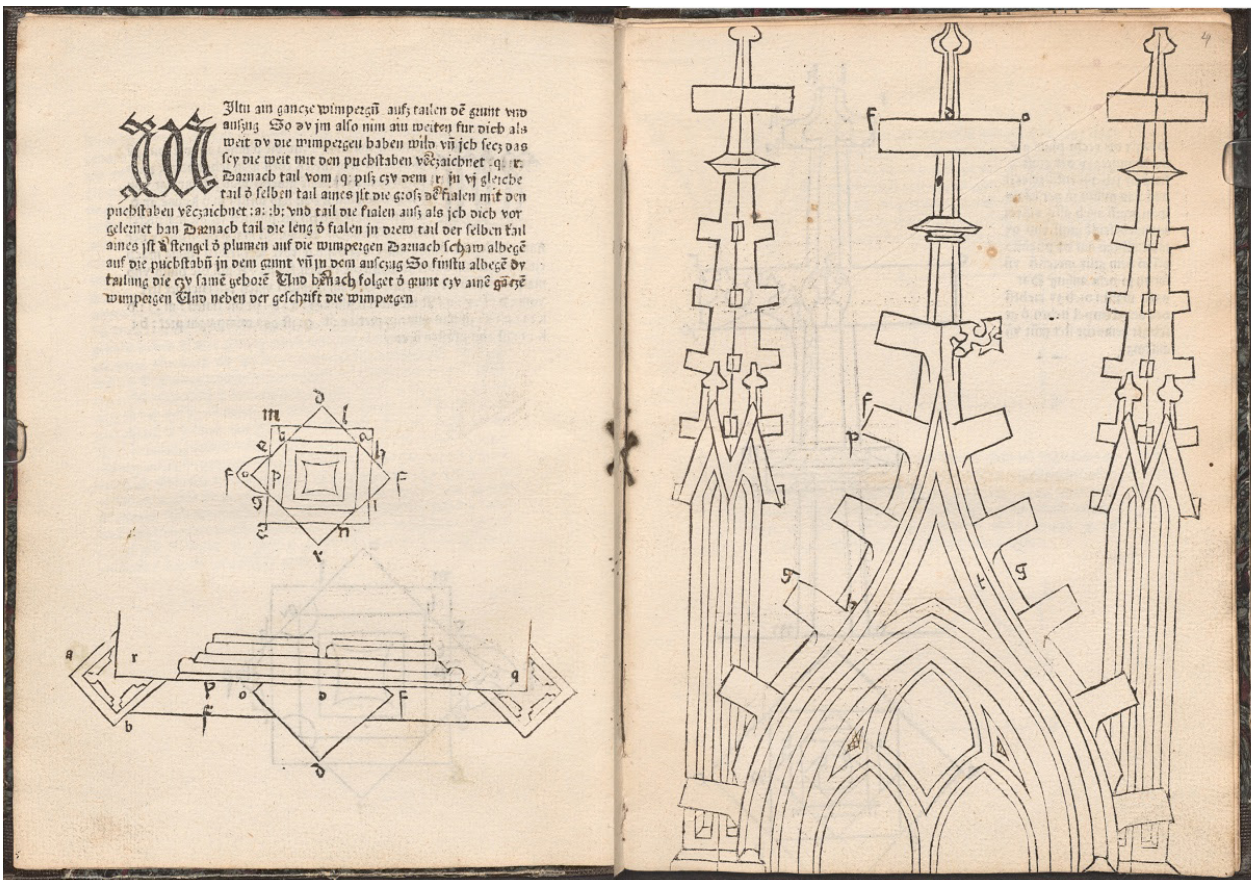
> "Him I consider an architect who, by sure and wonderful reason and method, knows both how to devise through his own mind and energy, and to realize by construction, whatever can be most beautifully fitted out for the noble needs of man, by the movement of weights and the joining and massing of bodies. To do this he must have a knowledge of all the highest and noblest disciplines."

In the Baroque period in particular, the design and construction of complex geometric forms with high degrees of accuracy, like dou-bly-curved vaults and intersecting arches, triggered the need for design operations that required interdisciplinary expertise beyond architecture's rigid boundaries. The architect as the Renaissance man incorporated the knowledge of these geometric processes in drawing machines and advanced tool making which by the 18th century had become a distinct discipline supported by a series of architectural and engineering reference manuals (Witt, 2010).

However, in an effort to reduce the number of design and building im-perfections, these very reference manuals were articulated as catalogs of instructions favoring only a single solution to the design or building problem every time. A reference manual of that logic is that by Mat-thäus Roritzer, a master builder of cathedrals, written in the 15^{th} centu-ry to reveal a proper way of implementing architecture and designing and building pinnacles for Gothic churches (Shelby, 1977). Roritzer's drawings are composed of lines that either describe geometric relation-ships between architectural elements or depict the form of the pinnacle itself (Fig. 1). As representational tools, they are explicitly instructional and immutably defined revealing Roritzer's aim to narrow down the range of the design solutions and give each of them only one feasible description.

Similarly, Neufert as a reference manual still in use today aims to pro-vide a broad pool of designers and engineers with a high level of tech-nical expertise and a pre-defined set of explicitly described design solu-tions (Fig. 2). As a consequence, this standardization of architecture and its processes leaves no space for customization. What is more, it turns the instrumental knowledge provided into a commodity not easily understood by unspecialized makers but only by well-trained profes-sionals. In this sense, these very reference manuals that democratize instrumental knowledge divide the social body into distinct entities, disciplines, and zones of power, sharpening the gap between special-ized professionals and unspecialized craftsmen (Baudrillard, 2006).

At this point, I transition from reading technical encyclopedias as gen-erative design tools dictating an analog instruction to computers and softwares prescribing a digitally programmed action. In the course of this thesis, I call the latter contemporary digital reference manuals.



Wiltu ain ganczē wimpergñ auſz tailen dē grunt vnd auſzug So dv jm alſo nim ain weiten fur dich als weit dv die wimpergen haben wild vñ jch ſecz das ſey die weit mit den puchſtaben vēczaichnet .q. .r. Darnach tail vom .q. piſz czv dem .r. jn vj gleiche tail ō ſelben tail aines jſt die groſz dē fialen mit den puchſtaben vēczaichnet :a: :b: vnd tail die fialen auſz als jch dich vor gelernet han Darnach tail die lēng ō fialen jn drew tail der ſelben tail aines jſt ō ſtengel ō plumen auf die wimpergen Darnach ſchaw albegē auf die puchſtabñ jn dem grunt vñ jn dem auſczug So finſtu albegē dv tailung die czv ſamē geborē Vnd hernach folget ō grunt czv ainē gāczē wimpergen Vnd neben der geſchrift die wimpergen

Fig. 1: Pinnacle design for Gothic Churches, Matthäus Roritzer, 15th century.

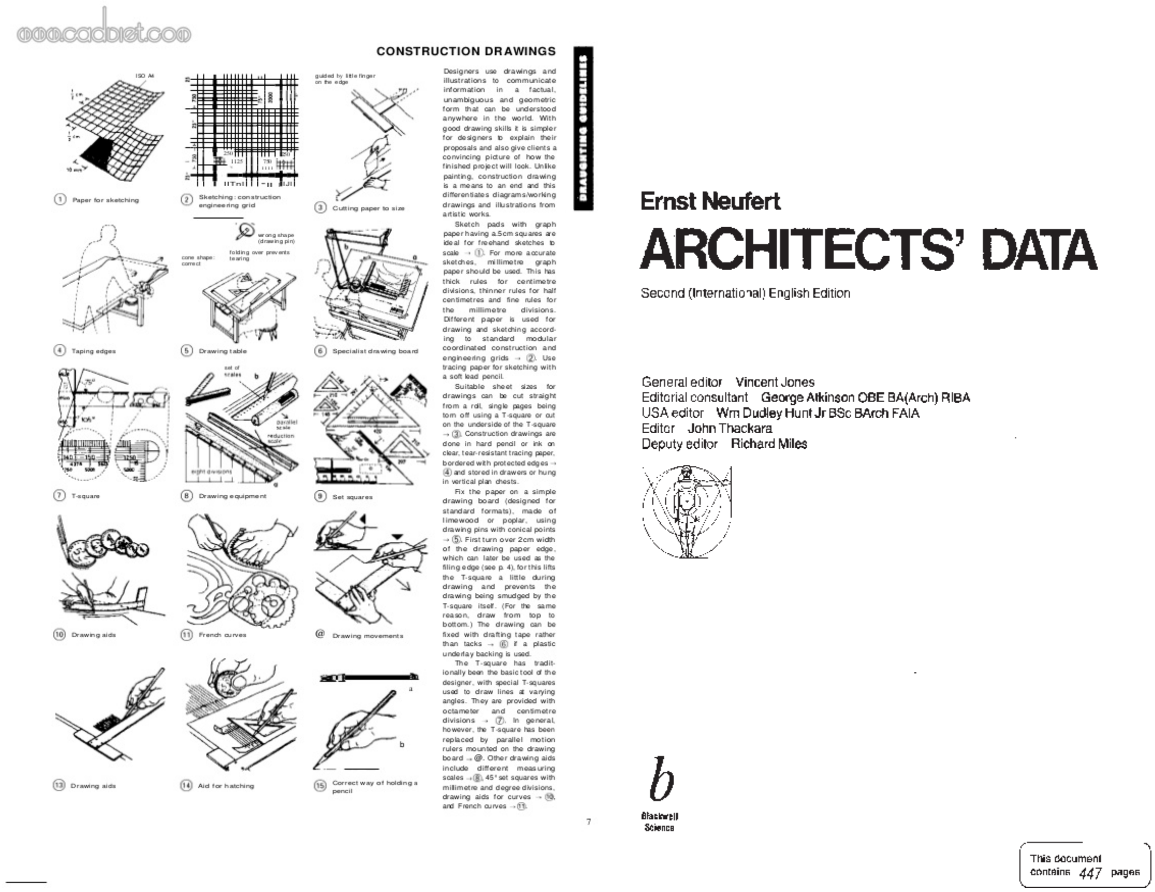


Fig. 2: Instructions for construction drawings, Ernst Neufert, 2000.

PART II
Designing
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The tool: A digitally programmed action

If the analog tools are highly described instructions aiming to train architects, designers, and builders for more precise and flawless building outcomes, the digital ones lie on the opposite standpoint. That said, they are machines trained to imitate designers in the way they think, decide, and act, to augment their capacities and automate the design process per se.

In 1950, the Turing test was developed to define and augment the presence and type of intelligence embedded in a "universal" machine that could be used by anyone. To this end, the machine was used as a way to trick a human and make them believe it is the human itself. In this context, the test examined whether human intelligence can be imitated by a machine which is programmed to have what in this thesis I call machine intelligence.

However, the test has raised a lot of criticism in that it doesn't reach any form of intelligence but only imitates the human one. At the same time, it is also argued that there is no form of intelligence in the way tasks are performed by computers. Though in the Turing test, if the machine imitated human intelligence by executing arithmetic calculations more slowly, similarly to the time humans need for calculations, the machine would achieve human intelligence but no other form of intelligence.

Therefore, I claim that there are many forms of intelligence, be-sides the human one, which a machine could encapsulate and there is great value in trying to incorporating some of that intelligence into the human way of thinking and designing. Yet, can we imitate the way computers work without losing our human properties? Or can we build computers that are not only digital?

It has been argued that all mental processes are goal directed, predictable, and capable of being imitated by a computer (Minsky, 1961). Computers are quicker and more precise than human beings when it comes to computation, iteration, solution optimization, and simulation. Yet, the design methods they drive are based on rational and algorithmic assumptions following a purely deterministic logic of operation. In these terms, the objectives, variables, and criteria of evaluation of the process itself are fixed in advance. The binary logic any computer language follows is based on the discretization of data into parts that sum up to but don't exceed the limits of a whole by use of configuration methods that generate design solutions. To the contrary, in human terms this cannot hold true as the semantics between all parts are equally important to the parts themselves.

In a parametric design system, parameters build up in a bottom-up logic to generate models that are defined by numeric or geometric constraints. This explains why a parametric design produced by a computer generates the same results if the same sets of parameters are used. Yet, I believe that the problem is not in the system itself but in the way parametric design is conceived and translated in the computational environment. For, unlike what happens in the contemporary cityscape, if more than one designers implement the same parametric logic in spatial terms without the use of a computer – Gaudi and his design for Sagrada Familia being one of the most indicative examples in this case – then the architecture produced by each of them will be considerably different.

What is left out of the computational way of thinking is what George Stiny describes in his theory *Shape Grammars* as the ability to compute while remaining human (Stiny, 2006). If the computer could be not only the explorer of many solutions but also the perceiver of all the ambiguities associated with them and the way they are conceived, then we would talk about a computer that goes beyond the digital.

Yet, can creativity, imagination, inventiveness, and ambiguity embedded in the human way of thinking and designing be codified in a computer? And if not, can the way this digital tool is programmed inform creativity itself?

PART II
Designing
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The designer

With the development of the CAD software, line drawings are composed by design elements structured based on topological and geometric relationships between all design parts which are bounded within definite drawing operations. On the one hand, this structured nature of computer drawings can be considered beneficial to design. As described by Ivan Sutherland (Sutherland, 1975, 19):

> "To a large extent it has turned out that the usefulness of computer drawings is precisely their structured nature… An ordinary [designer] is unconcerned with the structure of his drawing material. Pen and ink or pencil and paper have no inherent structure. They only make dirty marks on paper. The [designer] is concerned principally with the drawings as a representation of the evolving design. The behavior of the computer-produced drawing, on the other hand, is critically dependent upon the topological and geometric structure built up in the computer memory as a result of drawing operations. The drawing itself has properties quite independent of the properties of the object it is describing."

On the other hand, as I noted in the previous section, this very structured nature of computer drawings leaves no space for creativity, imagination, ambiguity in seeing, perceiving, thinking, and decision making. Design theorists Broadbent, Gordon, and Osborne argue that the most valuable part of design is what goes on inside the designer's head both consciously and unconsciously (Nadler, 1995). The lack of inherent structure found in paper drawings lets the designer decompose and recompose them in unanticipated ways modifying their symbolic representation. Designers do not follow a standardized, predefined logic when it comes to ideation and problem solving. Herbert Simon notes that (Simon, 1988, 72):

> "everyone designs who devises courses of action aimed at changing situations into preferred ones".

The way the designer understands and approaches a problem does not abide by a strict methodology but varies based on the different way they see, perceive, think, decide, and act. Therefore, they must be portrayed not as an intellect executing tasks and making decisions but as human being whose mental aptitude is shaped by historical or contemporary references, mnemonic recollections of previous individual experiences as well as archetypal and intuition-based ideas sheltered in the unconscious mental sphere. With these ingredients in mind, the designer develops a vocabulary composed of functional types, mnemonic references, spatial gestalts, and experiential archetypes, each of which affects the way design is conceived, developed, and implemented in specifiable ways (Schön in Design & Systems, 1995). Thus, design can bear more than one methodologies for the purpose of problem solving.

If we think of computers as programmed assistants facilitating the act of design by means of speed and precision, can we also claim that they can be programmed in such way as to take account of the human designer's ability to make and read spatial gestalts?

Can there be a computational system capable of translating experiential archetypes into a system of design constraints? And if not, can there be computation-based digital interfaces capable of responding to the way designers formulate their ideas based on such archetypes?

PART II
Designing
4

Design as an interface

Design is an activity of the mind which cannot be directly observed, described or structured. It is a constant meandering between the conscious and unconscious mind; the known and the ambiguous; the pre-conceived step and the unexpected encounter; the predictable and the unforeseen. For, if everything could be predicted and planned, there would be no need for a plan B to a plan A. Neither would there be any need for designing the transition from one to the other.

Though when design becomes a computer-driven process, initial parameters, constraints, and steps leave no or little space for the unexpected and unpredictable to emerge. Intuition, imagination, and creativity are suppressed by this deterministic operational structure. Although in the 1960s ideas like human-machine interaction and human-like machines emerged in the field of Human Computer Interaction, the failure of the early CAD implementations to consider computers machines with cognitive capacities that would augment the designer's creativity, obscured the innovation that these ideas promised.

In 1963, the SKETCHPAD by Ivan Sutherland was the first Graphical User Interface and was able to create highly precise drawings (Fig. 3, 4). A Sketchpad user sketched directly on a computer display with a light pen to position parts of the drawing. A set of push buttons controlled the changes to be made. The

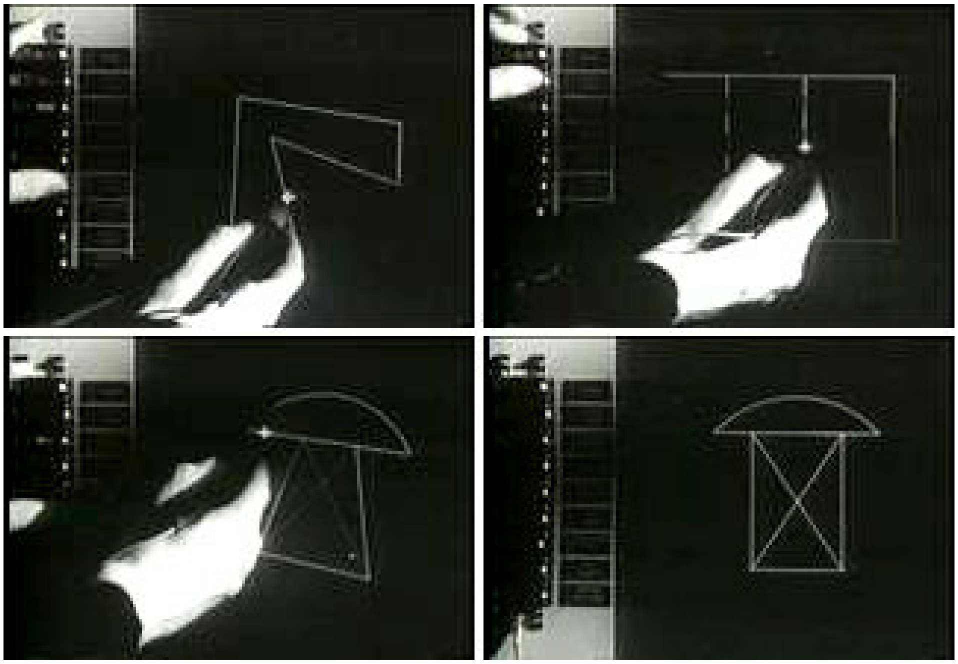


Fig. 3: SKETCHPAD's pen and screen system, Ivan Sutherland, 1963.

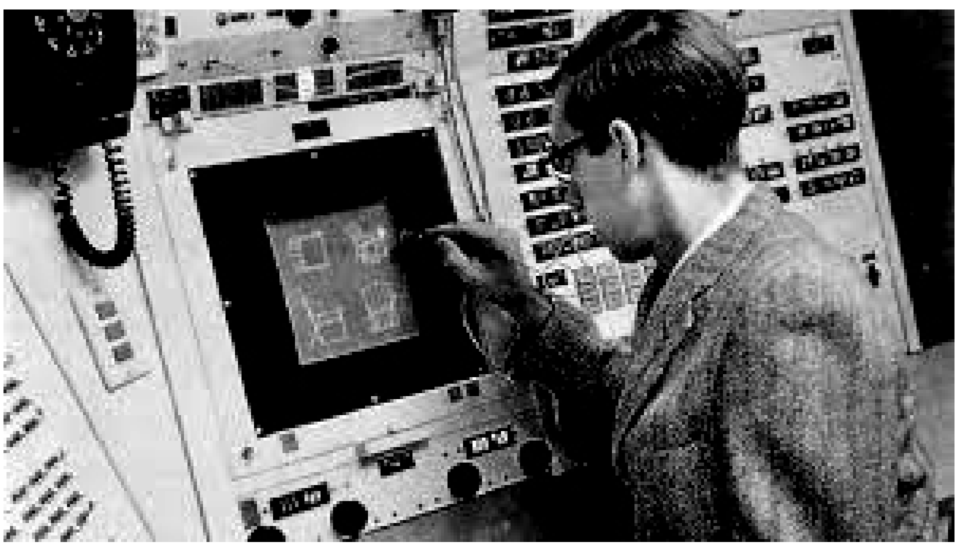


Fig. 4: SKETCHPAD, Ivan Sutherland, 1963.

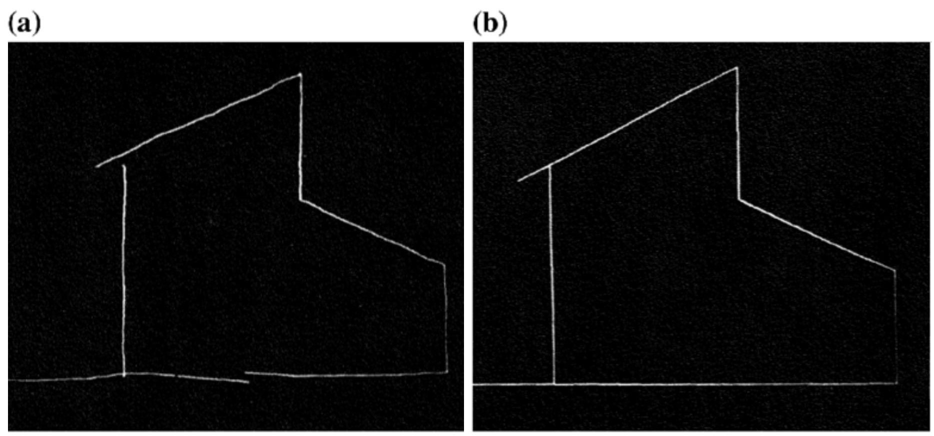
sketch could include only straight line segments and circle arcs.

Similarly, HUNCH was a project developed by James Taggart in 1972 inside the Architecture Machine Group at MIT (Fig. 5). It was a computational tool that aimed to combine the creative power of the designer with the computational power of the computer and allow the designer to be graphically free and inaccurate. The system used a pen as an input device and transformed this input only in digital lines or points.

However, both the SKETCHPAD and HUNCH failed to address the creative aspects of design partly due to the limitations of their pre-defined representational structure. Additionally, their black-boxed logic that dictates a certain mode of operation failed to engage the designer's intuition and imagination in the act of design, enlarging the communication gap between the tool and the designer per se. It was, therefore, proved that the notion of augmentation by automation promised by this computational approach to design was barely feasible because of this very logic of the digital interface that couldn't grasp the designer's intentionality.

In this system, the interface between the designer and the digital tool seems to be the act of design itself which ensures and augments the communication between the two parts. In the Oxford dictionary, the interface is defined in English as "a point where two systems, subjects, organizations, etc. meet and interact"[1]. In the era of digital supremacy we live in, an interface is a device or program enabling a user to communicate with a computer (McLuhan, 2011). As so defined, an interface can be the mouse and screen of the computer; a sheet of paper on which a designer communicates their ideas to the world; the human mind that wanders before seeing and perceiving.

1. "Interface | Definition of Interface in English by Oxford Dictionaries." Oxford Dictionaries | English, Oxford Dictionaries, en.oxforddictionaries.com/definition/interface.



sketch before the sketch recognition operation → rationalization through data compression of 4128 core locations

Fig. 5: HUNCH, James Taggart, 1972.

In this context, I find designing unfolding as the threshold between the processes of the mind and those of the computer; the in-between from seeing to perceiving, to thinking, to deciding, to making; a mediating device of thinking (Fig. 6). Though at this point, I find it essential to take a step back and attempt to touch what design per se stands for.

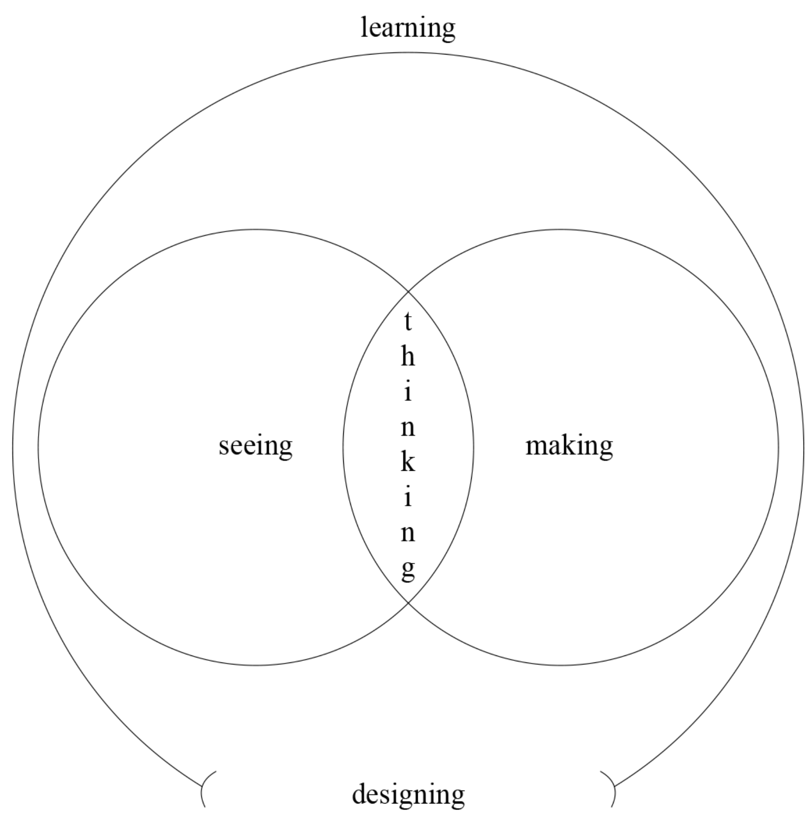


Fig. 6: Designing from Seeing to Learning.

PART II
Designing
5

The tooling: what is design?

Design is a mediating device of thinking.

As a derivative of the Latin *de + signare*, design pertains to the making of something distinguishable by a sign and therefore has a significance which designates and is designated by its relation to other things and users. In Klaus Krippendorf's words (Krippendorf in The Idea of Design, 1989, 156):

> "design is making sense (of things)."

If we assume that design pertains to the understanding of the semantics of something with its surroundings, then it can be considered an activity creating sense, one based on reasoning, perception, intuition, experience, aesthetics, and intention. At the same time, it is an activity creating meaning which is to be understandable to someone and expressed by various representational means - with drawing being only one of them. Design is concerned then with the subjective semantics of objective things.

If design rests on the interpretation the designer assigns to it, then it turns into an analytical mental activity seeking for an acceptable solution to a given problem by building up on assumptions about the way the parts of the problem are interrelated. Herbert Simon states that design means synthesis based on the analysis of objects, processes, ideas, and the ways in which these can be

to design[2]

late 14c., "to make, shape," ultimately from Latin *designare*

"mark out, point out; devise; choose, designate, appoint"

from *de* "out" + *signare* "to mark," from *signum* "identifying mark, sign"

2. Online Etymology Dictionary, https://www.etymonline.com/word/design.

realized to satisfy the goals, criteria and constraints set during analysis (Simon in Design & Systems, 1995). To the contrary, cognitive scientists consider design as a primarily problem-solving process which starts with a set of givens to satisfy the requirements of a goal by performing a series of operations.

In the context of this thesis, I approach design as a continually reconfigured process of problem-setting, problem-searching, and problem-solving in which there is no preset end-goal but only an iterative logic which is continually reshaped in the act of design. Through this lens, design becomes inherently computational – a matter of computing the implications of initial hypotheses and combinations of them.

To design is to gather and combine information about what follows from what one has proposed or assumed. A design task does not only entail finding a solution to a well-defined problem but also discovering and expanding interesting possibilities by means of critical thinking. Emphasizing on the importance of visual computing and perception in design, William Mitchell finds that design exploration is a trial-and-error process (Fig. 7) of defining and implementing sets of constraints to generate potential solutions which are evaluated next by computing predicates (Mitchell, 1990). Therefore, design proves to be an inferential procedure dependent on human reasoning, intuition, and creativity as opposed to algorithmic processes based primarily on the deterministic execution of computational tasks.

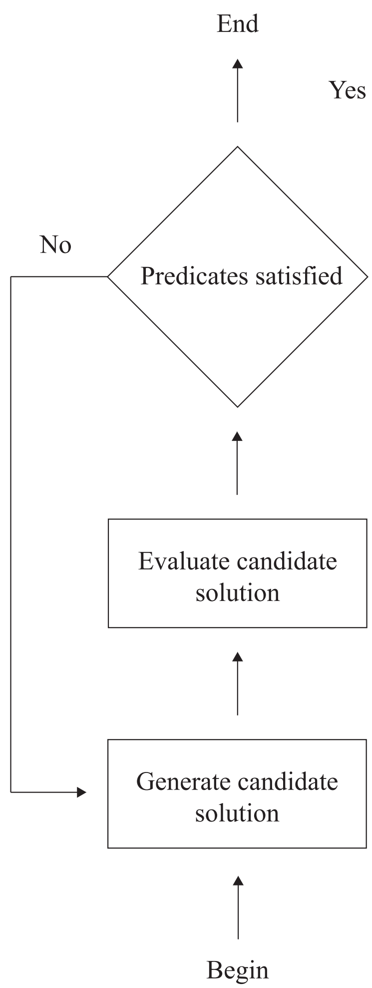


Fig. 7: Design as a trial-and-error process, William J. Mitchell, 1990.

PART II
Designing
6

Is any problem design?

Not all problems are design. Karl Duncker, a Gestalt psychologist, defines a problem as one that:

> “arises when a living organism has a goal but does not know how this goal is to be reached” (Duncker, 1945).

The majority of everyday problems can be considered *wicked* or *ill-defined* as their components are vague or not specified and their potential solutions are classified by a relative qualitative scale. For instance, if *well-defined problems* are board games or mathematics and logic problems, design can be considered “ill-defined” by nature.

In their definition of a *wicked problem*, design theorists Horst Rittel and Melvin Webber note that design can have only subjective and no objective criteria for solving and ending the process (Rittel & Webber, 1973). These criteria are continually reconfigured and can be classified not as true or false but only as good and bad. As such, design cannot be approached as a deterministic act of problem-solving. Similarly, in the case of architectural design a criterion can be considered preferred over another one based on visual, psychological, functional, or economical parameters, among others, associated with space and its programmatic requirements.

An architectural approach to design as an ill-defined problem can be traced in the work of Frank Gehry who sees design as an open-ended and experimental exploration with a seemingly vague, yet formally explicit and inventive underlying rule system. Combining creative thinking, physical making, and digital computing, he conceives his buildings as sculptural objects whose form emerges from a series of drawings and iteration-based physical models to be built eventually via digitally-heavy fabrication processes.

The Ray and Maria Stata Center at MIT was designed incorporating 3d CAD technology from design to assembly (Fig. 8, 9). Gehry developed Digital Project, a software to disseminate his CATIA-enabled design and construction methodologies to the rest of the design and construction world. The software enables information to be sent directly to the manufacturer rather than needing to be processed separately in preparation for sending out of house. Similarly to the workflow followed in all his projects, in the case of Stata Center, the design starts with physical cardboard modeling, then it is iteratively rationalized into developable surfaces before being brought into CATIA and refined. On the last step of the workflow, the design is brought back to physical dimensions. However, Gehry rejects the contribution of computer models at later stages in case he finds his vision not served by them. In the case of Stata Center in particular, which was based on a very collaborative model of workflow, one of the challenges he faced was the lack of instrumental knowledge that many of the engineers involved in the project had. This might also explain why Gehry's work can argue for and against the black-box processes problem associated with design.

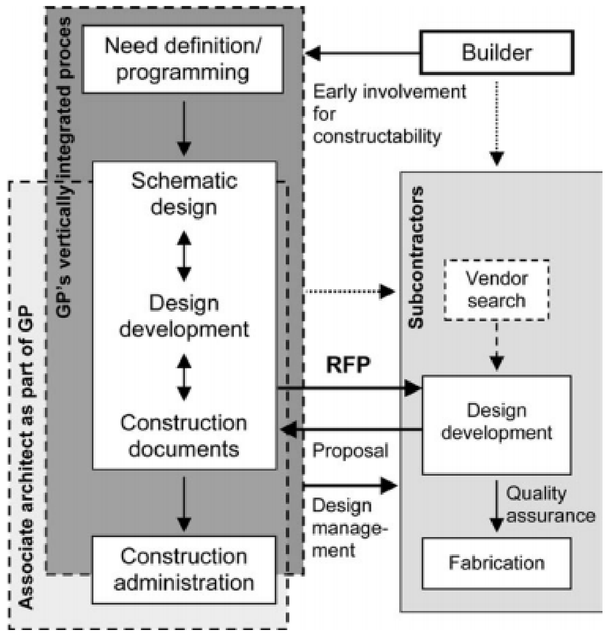


Fig. 8: Gehry's Project-Delivery method limiting the risk of producing construction documents without involvement of constructor managers and fabricators involved in standardized implementation processes, Maria Stata Center, 2014.

Fig. 9: Maria Stata Center's implementation by Gehry Partners.

PART II
Designing
7

The thinking manual: A mapping

At this point, I find myself binded by the hypothesis, terms, and constraints my thesis revolves around.

I claim that the design softwares we use today fail to communicate the creative aspects of the act of design and restrict our creative role as designers and critics. Nonetheless, my aim is not to define what designing by hand or on computer really is. Neither is it to unpack the black-box processes problem with regards to design. Rather, I aim to propose a new methodology to address the problem of open-ended creative design practices which remain poorly-understood and undermined in the era of ubiquitous computing we live in.

In addition, I aim to test the theoretical and practical gap between the analog and digital design tool and the designer. To this end, I will use the problem of advanced geometry of paper folding - and in particular that of curved creases and origami tessellations - as a way to question my initial hypothesis, test my proposal, and prove the necessity of a paradigm shift in design practice and pedagogy.

In what is to follow, I aim to theoretically unfold and practically map the question: can the computer as a digital design tool augment and challenge the human mind and turn design into a pedagogical act of creative and critical thinking? With regards to the research presented in this thesis, I propose three interrelated descriptions of the act of designing: an act of seeing, thinking, and making which I develop and explicate in practical terms in Part III. To this end, I will touch the subject of designing as an embodied and enacted act from a theoretical and practical point of view.

Finally, I aim to develop and read this thesis as a thinking manual, one utilizing thinking as the mediating device to seeing, perceiving, and making with designing in the role of inventive wandering and critical thinking. In this analogy, I map and plan the moments when the designer interacts with the mental, physical, and digital tools available in this act of pedagogy as well as the ways in which these interactions take place.

PART III

From Designing to Making to Learning

PART III
From Designing to Making to Learning
1

Technical, Practical, and Theoretical goals

The technical goal of this thesis is to explore alternative ways of introducing computational tools into design processes of advanced geometry like the problem of curved creases and origami tessellations. To this end, I propose a workflow that introduces a flexible methodology of designing through drawing, making, and computing. This workflow combines both physical and digital modes of drawing and making with digital image processing and physics simulation techniques. I present drawing studies that use Ron Resch's and Duks Koschitz's (Koschitz, 2014) curved crease folding methods to explore the outcomes of visual and tactile thinking that takes place during the emergence of these drawings.

The practical goal is to interact with digital tools to develop an open-ended design system in a way that enhances creative visual exploration and retains and expands intuition. I argue that contemporary computational design methods and digital simulation tools fall short in doing so due to their black-boxed operational and representational logic. In this context, on the one hand, my aim is to enable the designer to better understand the advanced geometry of paper folding by visually perceiving, physically simulating, and drawing the design system from scratch. On the other hand, I aim to enable the designer to control the degree and outcome of the interaction with the black-boxed digital interface I have developed for the purpose of this thesis.

Finally, the theoretical goal is to trigger a shift in the designer's mental aptitude and inform the way we interact with computational design tools today without losing control over the creative and inventive aspects of design.

PART III
From Designing to Making to Learning
2

Computing Visual Making: The case of paper folding

Parametric and computational design today fail in many cases to develop a discourse between space, users, and designers. Although they achieve higher levels of accuracy, efficiency, and freedom in design and formal terms, they rely on processes structured mainly on a representational and black-boxed approach to design and fabrication. The swift from the analog to the digital tools in the design and architectural culture assumes that visual percepts can be explored without the pen and paper as the traditional design interfaces. The computer's capacity to store high amounts of data and execute complicated tasks with speed and precision makes algorithmic thinking a promising part of the design process, yet not an essential one. In algorithmic terms, design is thought of as a system composed of many parts whose topological relationship to the larger whole determines the structure of the design solution. As part of the act of design, ideas emerge after their translation into a rule based system with a pre-defined syntax with bounded flexibility. Therefore, unlike a hand drawing, the digital one's potential is traced in its capacity to represent with great computational precision. However, for this precision to be reached instrumental knowledge achieved through intensive skill-building is necessary.

This problem is widely encountered in practices based primarily on designing by making in which a poor understanding of the design parameters before prototyping leads to fabrication and cost failure. In an effort to avoid such failures and make their engagement with digital tools more interactive, architects and designers use digital simulation tools among others to analyze real-time physical and material performances of design solutions. Though the fact that these solutions can be evaluated only through physical testing in real time casts doubts about their contribution and reliability as design tools.

In the field of paper folding, even though there are various softwares developed mostly by mathematicians and computer scientists to design, optimize, and simulate curved crease paper folding, the way they function is not understandable to architects and designers, enhancing thus the creative gap between the human mind and the digital tools. The pre-compiled libraries and black-boxed components and functions embedded in these softwares automate the behavior outcome of an arbitrary curved crease when folded in the three-dimensional space. Pre-defined automated functions such as bending, folding, and twisting and an integrated level of interactivity give the designer some freedom as to how large and where the transformation they are implementing is.

However, by leaving out the tactile aspects of simulating and testing, the designer's bodily engagement and therefore understanding of their design is suppressed. At the same time, imagination is restricted to the geometric description constructed by the softwares. What is more, the mathematically underexplored nature of this geometric problem and the fact that architects and designers lack advanced geometric knowledge render them unable to follow and predict such behavior. Thus, they are unable to either understand how the existing digital design tools work or develop their own.

Historically, there have been significant scientific and engineer-

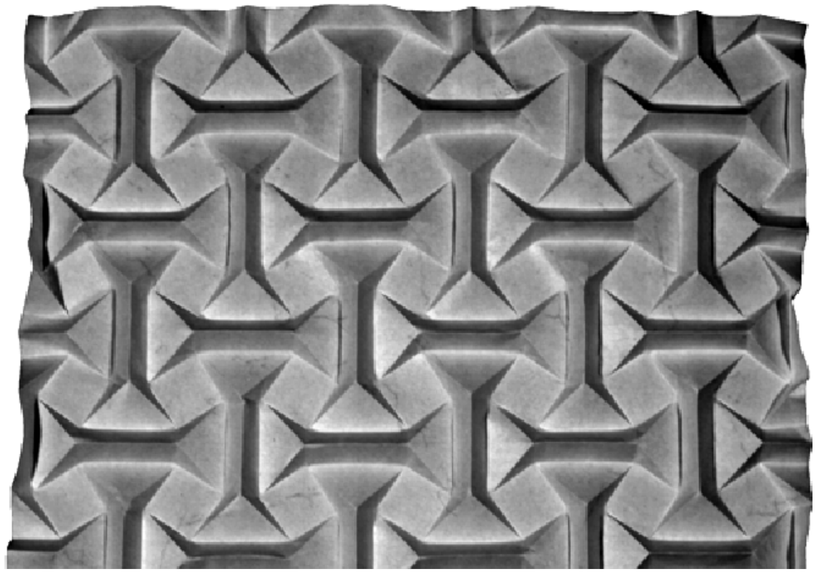


Fig. 10: Reconstruction of David Huffman's "Raised Vanes, Both Vertical and Horizontal" (date unknown) by Eli Davis, Erik D. Demaine, Martin L. Demaine, Jennifer Ramseyer, 2013.

Fig. 11: Curved crease surfaces paper model, Ron Resch, 1960s.

ing contributions to the domain of curved creases with the most fundamental ones, in chronological order, by Richard Riesenfeld, David Huffman (Fig. 10), Ron Resch (Fig. 11) and Ephriam Cohen (1970s), Dmitry Fuchs and Sergei Tabachnikov (1999); Martin Kilian, Simon Flöry, Zhonggui Chen, Niloy Mitra, Alla Sheffer, and Helmut Pottmann (2008); Erik and Martin Demaine and Tomohiro Tachi (2014). However, as there is only limited documentation about how to derive design methods of paper folding and particularly rationalizing curved creases, the promising digital design tools available today and the black-boxed automated solutions they generate suppress the creative aspects of design itself (Demaine & Demaine, 2013).

Yet, Martin Heidegger claims that the problem with the digital tools we use is more our position towards technology and the world rather than the existence of technology per se (Heidegger, 1977, 19). Therefore, I believe that the problematic relationship between what I previously described as instrumental and design knowledge cannot be solved by merely improving technology per se. Instead, there needs to be a paradigm shift moving the emphasis from the type of the problem the designer is asked to define to the way of looking at this problem. To this end, I argue for the development of a new methodology to the way we interact with the digital tools we use while designing today.

On the base of this speculation, there have been efforts to bridge the gap between thinking and making in analog and digital means in the domain of paper folding and advanced computational geometry. Ron Resch's approach to the computation of arbitrary curved crease surfaces in the three-dimensional space incorporates physical simulation and hand-drawing as key elements of the design exploration and computation process (Fig. 12, 13).

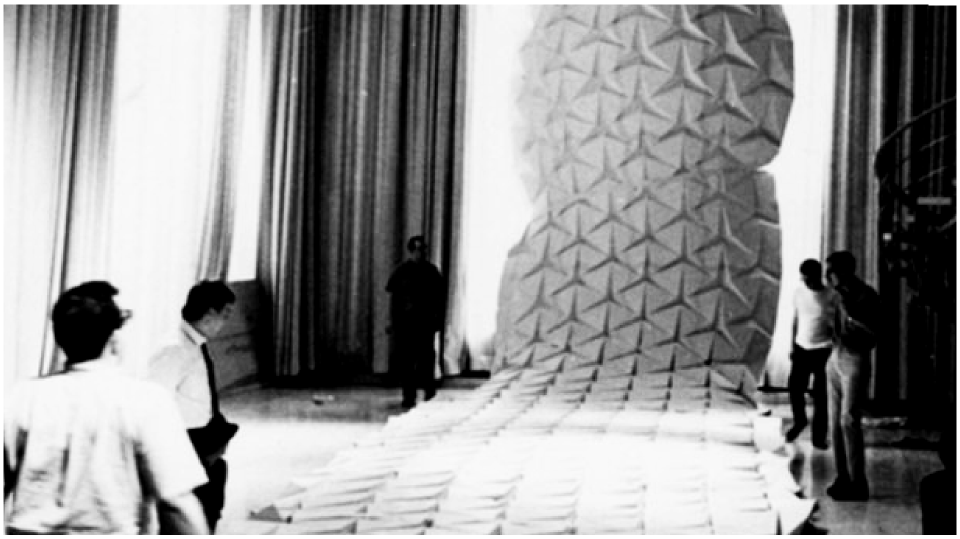


Fig. 12: Curved crease surfaces 1:1 paper prototype, Ron Resch, 1960s.

Fig. 13: Ron Resch at his studio.

Later, Duks Koschitz expands this technique to introduce CAD software in the representational part of the process as the interface translating Ron Resch's visual and physical computing to the digital one.

The contribution of such explorations could impact many fabrication techniques based on the complex geometry hidden behind folding methods, with many economic and energy advantages. Building materials, for instance, fabricated as flat sheets and designed to have a foldable behavior can replace stamping processes with molds (Fig. 14), a technique developed among others by Gregory Epps and Robofold (Epps, n.d.).

Fig. 14: Zaha Hadid Architects' Arum sculpture for the Venice Biennale by Robofold, 2012.

PART III
From Designing to Making to Learning
3.i

Theoretical Foundations: Rethinking Drawing

What is Drawing?

Drawing – one form of designing - is a way of making sense of things.

It is dependent on visual perception and subject to an open-ended understanding and interpretation of visual meanings. As Stiny states, there are many ways in which a drawing can be seen and perceived and one needs to relate drawing to more than one descriptions attributed to it (Stiny, 2006). In this sense, drawing is making meaning out of things.

As meaning is a product of both the perception and intention of the designer, it is closely linked to the way creativity emerges from this exact open-endedness of the perception over the intention. The outcome of drawing is, therefore, not a pre-shaped idea but a visual exploration of the designer's mental aptitude emerging in the course of drawing. It is the vehicle through which ideas are discovered, explored, and transformed or else the visual implementation of the act of ideation.

In art and design literature, drawing is described in ambiguous terms as an embodied and enactive thinking process driven by the triptych eye-mind-hand without geometric precision. In this section, I depart from the theoretical reflections of artists and designers on drawing as the system of the eye, the mind, and the hand to further meditate on designing as a creative act.

PART III

From Designing to Making to Learning

3.ii

Drawing as Thinking

Drawing makes some parts of the designer's thinking apparatus visually tangible and readable in multiple ways. It unfolds as an externalization of the thinking process that lies codified in the form of ideas, drawings, and artefacts in the act of design. For if the mind stores bits of information received from the external world, drawing stands as the interface between these external stimuli and the mental image inherently embedded in the mind itself.

Yet, in considering thinking one of design's driving forces, we find it lingering between the conscious and unconscious mental sphere, somewhere between what we can perceive and what we can imagine. George Stiny states that drawing is primarily an act of seeing rather than thinking and the opposite statement can only constrain and not expand the designer's capacities when it comes to decision making (Stiny, 2006). In this sense, before thinking comes seeing which is instantly transformed into perceiving. But what is seeing if not an unconscious way of thinking?

Peter Cook describes a similar driving force to the drawing process of an architect (Cook, 2008, 9):

> "Perhaps the ideal way in which an architect can approach the act of drawing is to be unaware that he is actually doing it at all."

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From Designing to Making to Learning
3.iii

Drawing as Seeing

According to Rudolph Arnheim (Arnheim in The idea of design, 1993, 72),

> "drawing is a reflection of the guiding mental image; but it is not, and cannot be, identical with it."

In a similar way, Edward Hill argues that drawing is the projection of mental images onto paper and their translation into lines and adds that our visual perception comes with the purpose of making sense or meaning out of these lines. If we choose to focus only on the part of what lies before our eyes that relates to our needs at a specific moment, then seeing is intentionally perceiving and thinking with the eyes. In this sense, drawing is seeing and critically thinking.

In such syllogism, drawing is not produced after a programmed and computed sequence of design steps as part of a deterministic problem-solving process similar to the ones generated by the computer. To the contrary, it emerges as an abstract representation of a shapeless idea sheltered in the mind, aiming to respond to our momentary needs. Stiny extends this claim to add that there is some computational capacity in the act of drawing through seeing which implies that calculating is primarily done by using our eyes (Stiny, 2006).

PART III
From Designing to Making to Learning
3.iv

Drawing as Making

Drawing is a practice of making abstract, mental ideas tangible not only visually but also physically. There is a tactile relationship between the designer and the drawing tool - be it the pencil and the surface – that implies that drawing is making and touching. Making is not only a way to come closer to the material properties of an idea but it also provides a better understanding of the physical implementation and the very nature of this idea in real time.

Donald Schön claims that designing per se is a kind of making defined by the description of things made; the conditions under which they are made; and the manners of making (Schön in Design & Systems, 1995). We build and revise what we design by trial and error until it satisfies our intentions, whether they be aesthetic, perceptual or functional.

There has been a lot of skepticism among artists and designers about the contribution of the computer to the tactile side of the design process. The visual representations on a computer screen ignore the tactile properties of the materials involved in the drawing process. This is probably an explanation about why a lot of interest has been placed on computer interfaces with haptic feedback since the computers first appeared.

As mentioned previously, the SKETCHPAD and HUNCH can be considered two early applications with tactile features. Yet, they both had a questionable contribution to drawing when thought of as touching and making due to the restricted interaction that their pre-defined representational logic implied. Arne Collen claims that it is essential today to “consider and develop more carefully and humanely the design-making/doing interface and their implications regarding the resultant material, technological, and informational products” (Collen in Design and Systems, 1995, 302).

In the 1960s, Ron Resch explored the complex geometric problem of curved creases through an analog methodology that combines the tactile properties of paper folding and drawing (Fig. 15). He first crumples a sheet of paper to reach the particular folding pattern aimed at. Next, he flattens this sheet of paper and draws a notational system on top of it composed of lines and curves indicating where the creases should be. In his film titled *The Ron Resch Paper and Stick Film* he emphasizes on the importance of material exploration and the emergence of a design solution out of paper’s constraints and physical properties by means of folding.

Duks Koschitz further develops this approach among others by exploring a methodology that combines both analog and digital means with regards to the sculpting and post-rationalizing of curved crease surfaces (Fig. 16). In the course of his design exploration, representation unfolds as a pedagogical tool for designing with curved creases, aiming to understand the constraints set by the geometric and material aspects of this mathematically ill-defined problem. His methodology is studied as a creative thinking, designing, and making exercise in which the designer needs to have no prior knowledge of geometry and generates solutions quite quickly controlling the crease patterns at either

Fig. 15: Physical simulation and hand-drawn notational system on paper, The Ron Resch Paper Stick Film, Ron Resch, 1970.

the beginning or the end of the process.

The designer first sculpts a sheet of paper and defines a notational system to keep track of the iterations they undergo in the course of the post-rationalization process. The system is composed of curves signifying ridges and valleys, as well as motion finger tracking as a guide for the following iterations to be made. This hand-drawn notational system is then translated into a digital image by use of vector-based CAD software. The iterations cycle ends when the designer reaches an accurate enough state of the folded model.

Koschitz's approach (Koschitz, 2014) is structured around the following fundamental parameters used to define a heuristic:

1. the top-down compared to or combined with the bottom-up approach to problem solving in which a clear design goal is set at the beginning of the process and becomes less relevant in the course of design;
2. the a priori knowledge of geometry as opposed to that acquired from observation and previous physical or perceptual engagement with this geometry;
3. the material properties of paper as a guiding tool in the course of decision making while designing;
4. the use of digital tools followed by the operational knowledge the designer needs to have before the design process starts.

In the context of the question that I pose with this thesis, I aim to further develop Koschitz's approach and propose a new methodology to design practice and pedagogy that gives architects and designers more control over problems of advanced geometric complexity and the digital design tools used to solve them.

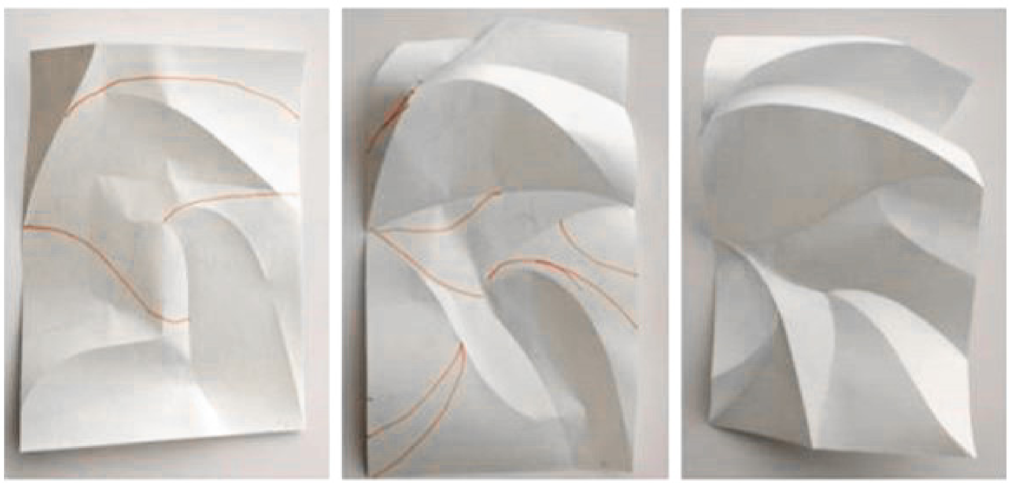

Fig. 16: Duks Koshitz's workshop outcomes on the reconstruction of Ron Resch's curved crease foldings, student work.

This proposal favors tacit knowledge over both a priori geometric knowledge and operational familiarity with the digital tools. It is conceived as an interface that enhances design as thinking, seeing, making, and learning keeping intuition, creativity, ambiguity, and exploration as key elements of the act of the problem solving process.

PART III
From Designing to Making to Learning
3.v

Designing as Learning

> "The creation of an idea or a design or an invention is really a learning process" (Coons, 1975, 28).

If we think of design as the externalization of an abstract mental image to respond to a particular problem by trial and error, it unfolds as a learning process that is interactive in nature. For it is a communication interface between the designer's inner and outer environment aiming to make a change in both. As Collen describes (Collen in Design and Systems, 1995, 299):

> "The change is the result of act and interact, of interaction."

Christopher Frayling and his theory Research through Design point at the pedagogical value of making as a prototyping activity in the course of design and a way of enhancing creative thinking, problem solving, iterating, and eventually learning (Frayling, 1993). Design transitions consciously or unconsciously from problem formulation to ideation, constructive problem solving, and trial-and-error experimentation in a non-linear, iterative order (Collen in Design and Systems, 1995). To utilize its potential as a tool for learning and reach better solutions for a broad range of problems, it is essential to understand both the conscious and unconscious processes underlying in design per se.

PART IV

From Designing to Computing and vice versa

A proposal

William A. Mitchell contends that a design workflow's intelligence is dependent on the balance between the actors of the system itself meaning the designer and their assistant or critic, or else the technological tools used (Mitchell, 1990). In this context, a smart critic can be paired up with a smart or dumb designer or a dumb designer can be paired up with a dumb critic. The role each of them plays in the design process as well as the ways they interact with each other is something that can generate different design methodologies and, therefore, different levels of design intelligence. What is important to note here is that any design methodology must allow for the involvement of human values and decision making at certain points, for the production of original ideas at others, and for moments of symbiosis with the digital tools in-between.

As I noted previously, in the context of this thesis I aim to propose a new design methodology to address the problem of open-ended creative design practices which remain poorly-understood and undermined by the computational tools widely integrated in the design process today. To this end, I use the problem of the advanced geometry of paper folding as a point of departure and in particular that of curved creases and origami tessellations explored by Ron Resch and David Huffman in the 1960s and 1970s, respectively. This workflow unfolds for me as a pedagogical tool teaching architects and designers something about highly complicated computational geometric problems as well as alternative ways of retaining and expanding their intuition in creative think-ing processes like design.

In the context of the workflow, the design effort is divided into two parts: one focusing on searching for a suitable solution keeping human creativity and intuition as the main mechanisms of the design process and the other controlling and evaluating the pattern of search by both physical and digital means (Fig. 17, 18). I develop and run a test to examine how designers of different design backgrounds interact with the digital tools to solve the problem of paper folding. To this end, I give the test user two distinct design prompts: a problem of curved creases surfaces and one of origami tessellations. On the one hand, the clarity and simplicity of the former aims to test the designer's ability to visually compute and produce the design solution in a timely manner (Fig. 19). On the other hand, the latter challenges the way the designer perceives and unpacks a problem of high complexity and ambiguity and tests whether they rely on their own critical thinking and intuition or on the digital tool's capacity for speed and precision (Fig. 20).

Finally, following and further developing Koschitz's approach to curved creases, this proposal favors tacit knowledge and doesn't require a priori geometric knowledge or familiarity with the digital tools. It is conceived as an interface that treats design as thinking, seeing, making, and learning keeping intuition, creativity, ambiguity, and exploration as key elements of the act of the problem solving process.

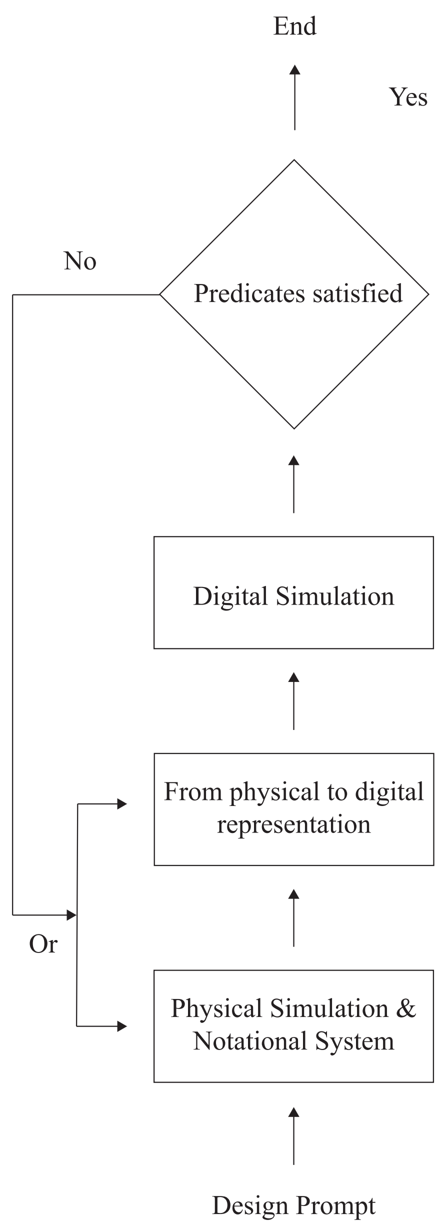

Fig. 17: Proposed workflow.

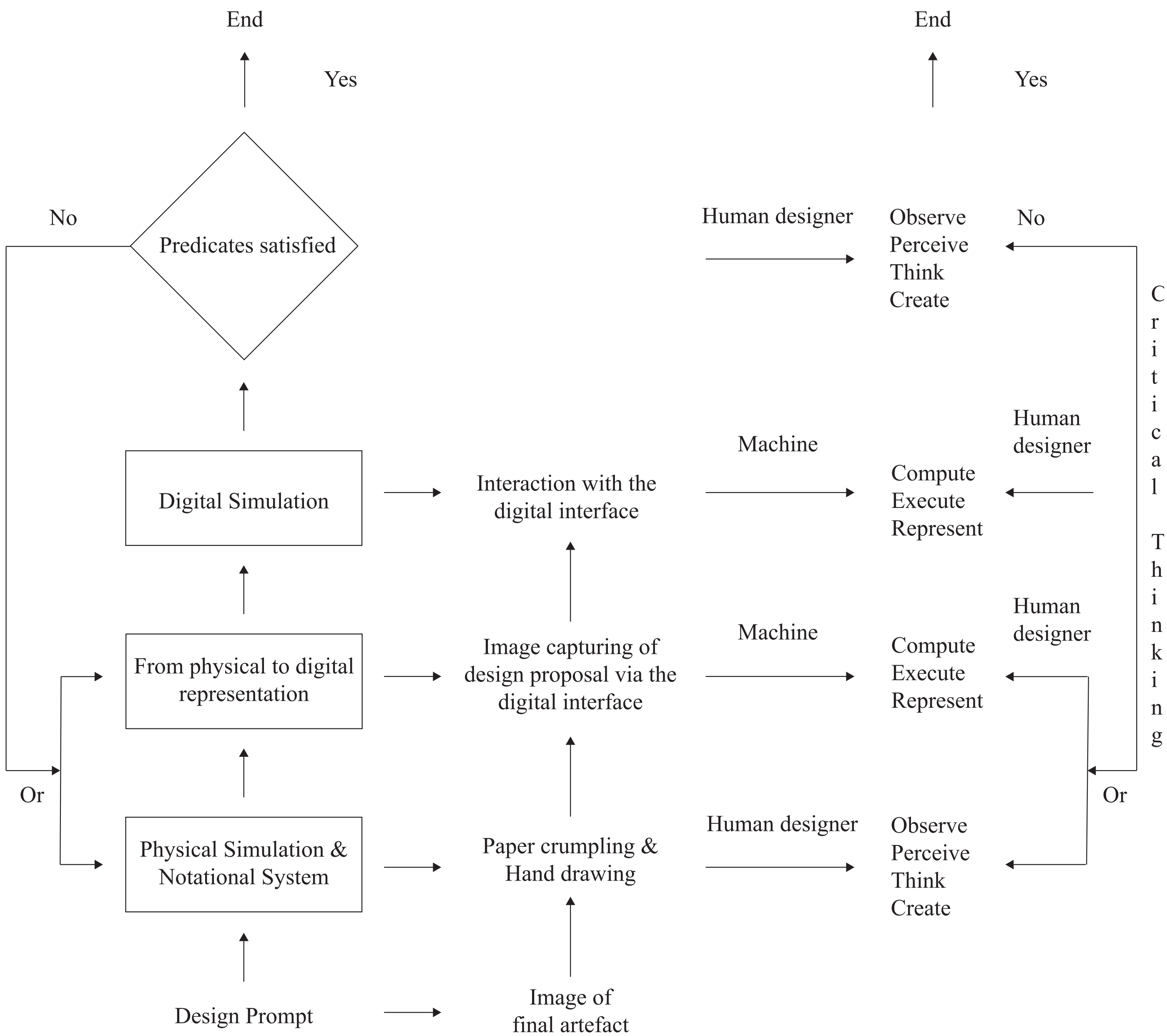

Fig. 18: Proposed workflow: from critical thinking to computing

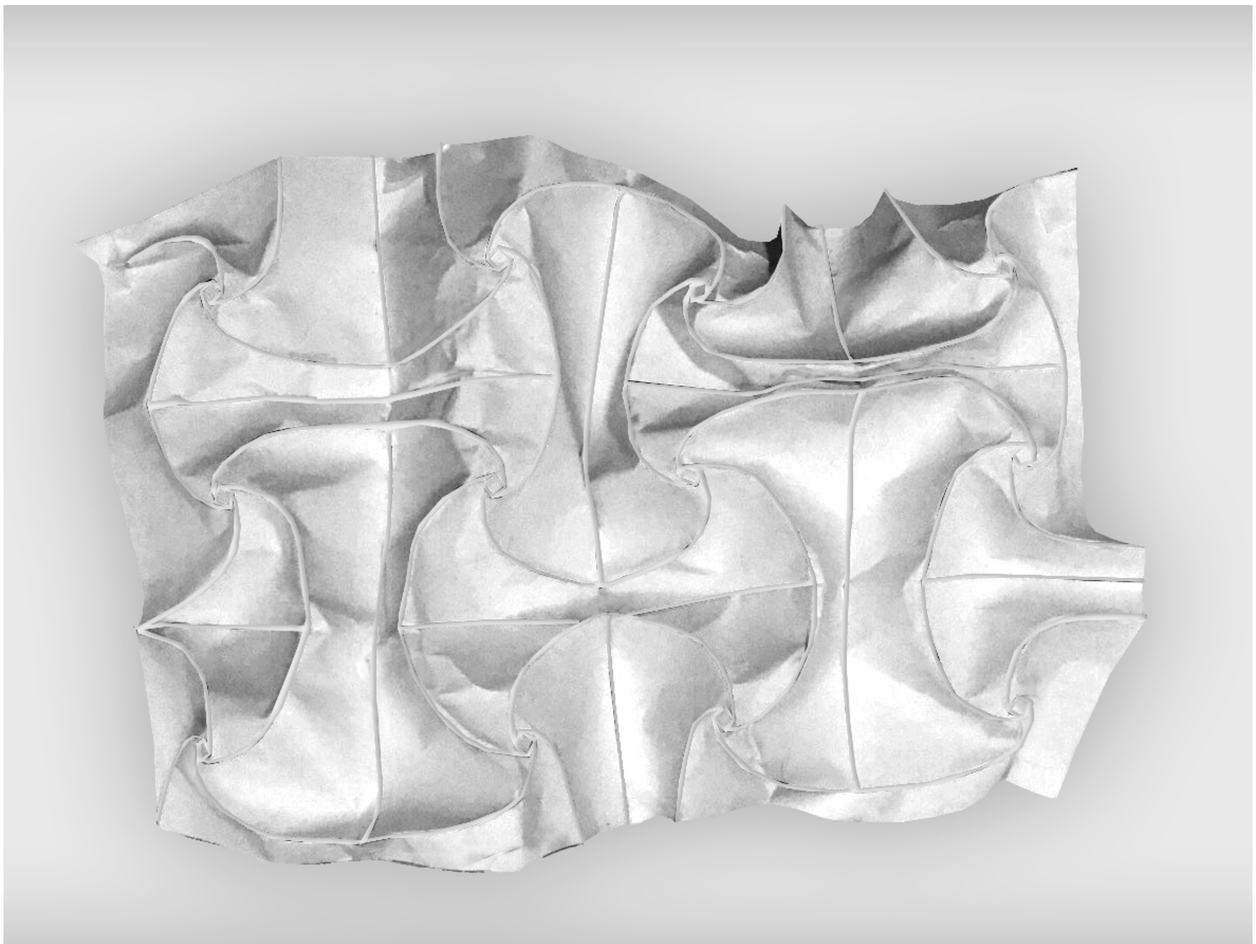

Fig. 19: Reconstruction of Ron Resch's curved crease surfaces model, author's work, 2020.

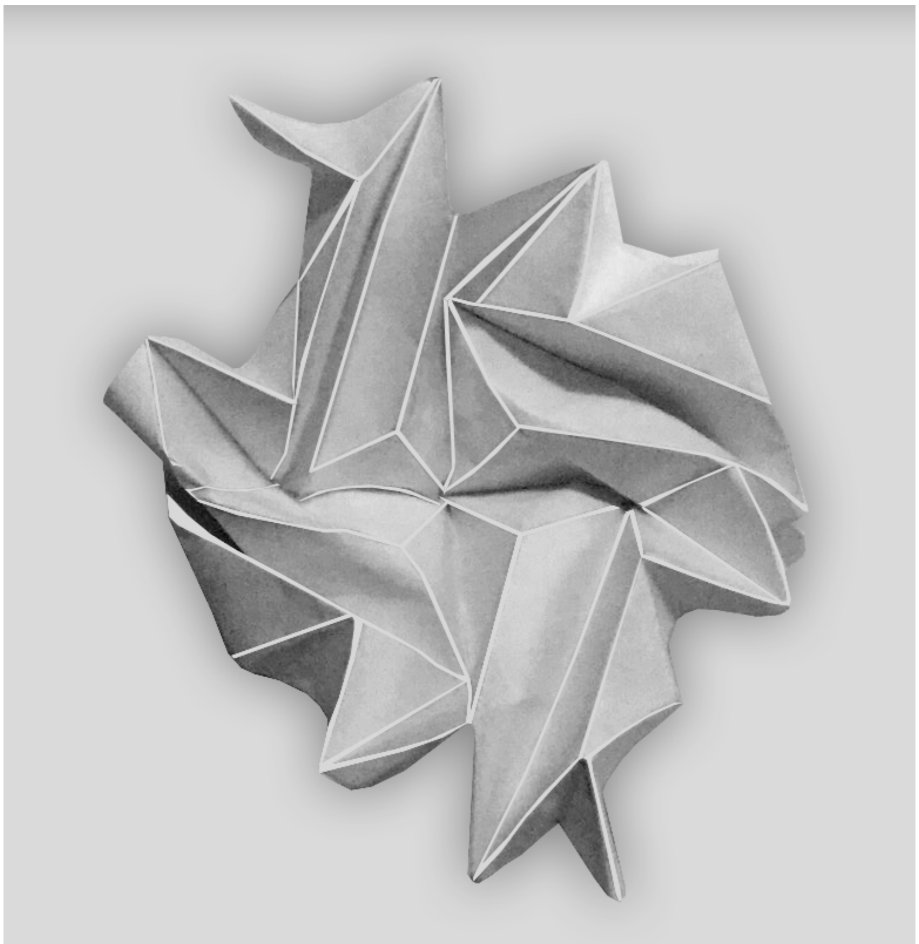

Fig. 20: Reproduction of David Huffman’s Origami tessellations model, author’s work, 2020.

Software and hardware setup

The proposed system is composed of both hardware and software including a sheet of paper, two markers, and a computer on which the digital interface runs (Fig. 21). All parts are complementary to each other, yet have a significant contribution to the act of design as a seeing, thinking, making, and learning process. The givens act at the same time as constraints summing up to form the following three taxonomy logics – an analog, a digital, and a human one – all depicted in the following table.

	constraints	**givens**
analog	paper size	paper size
	paper color	paper color
	photo plane	
	drawing color	drawing color
digital		
		digital image-design prompt
	defined actions in Grasshopper	digital interface (Runway - Grasshopper)
human	architectural background	architectural background
	no advanced geometrical knowledge	no advanced geometrical knowledge
	basic / no prior knowledge of the digital interface (Runway-Grasshopper)	basic or no prior knowledge of the digital interface (Runway-Grasshopper)

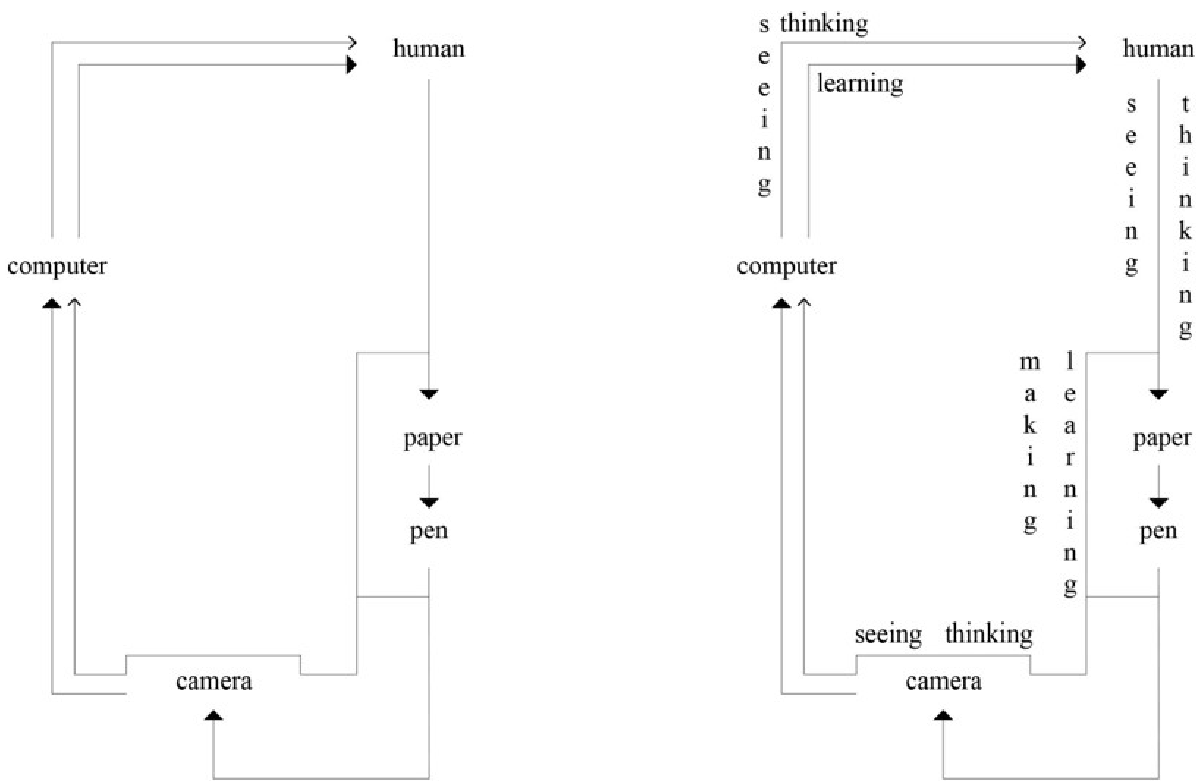

Fig. 21: The workflow as an act of designing.

The workflow is structured around the following axes which also constitute its steps (Fig. 22):

1. the design prompt pertaining to the design domain this thesis focuses on;

2. the physical simulation on paper and the hand-drawn notational system the test user is asked to generate as part of their design proposal trying to solve the design prompt given;

3. the translation of the physical, two-dimensional hand-drawn notational system into its digital representation;

4. the digital simulation of the proposed design solution.

Alternatively, the workflow can be described as a drawing and simulating sequence that involves image capturing, image processing, and simulation in the following order:

step 1_the user is given the design prompt

step 2_ the user observes, crumples and flattens the sheet of paper sequentially and draws the notational system on top of it

step 3_the user projects the drawing on the computer's camera; the digital interface reads and converts the image into a bitmap line drawing

step 4_the digital interface converts the image into a system of vector curves and meshes and starts the simulation

step 5_the user looks, evaluates and decides whether the predicates are satisfied or not following the simu-

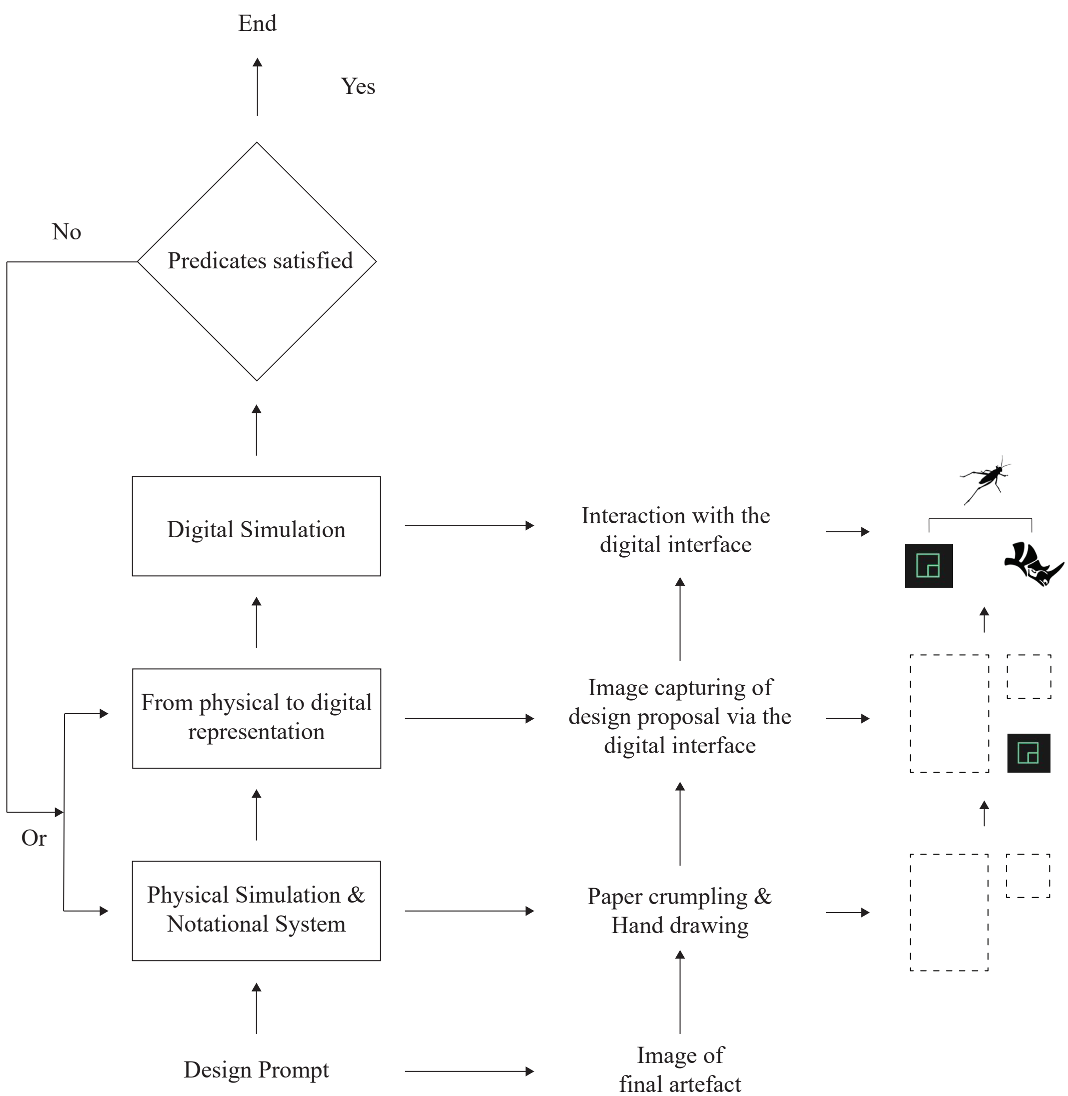

Fig. 22: Proposed workflow and tools.

lation representation as a guideline

step 6_the cycle repeats or ends.

In the course of this workflow, the user may choose the degree to which they will push the physical simulation and develop their notational system before they interact with the digital interface on every round of the cycle. The essence of this design methodology is found in the multi-axial interaction of the designer with ideas, materials, images, and computational tools with the parts where this interaction takes place being flexible and customizable.

The workflow is developed in such way as to examine the following core objectives:

1. In what way does the test user understand, analyze, and approach the problem?

2. How many iterations does each test user go through until they decide they have reached an acceptable solution to the design problem given and how does each iteration cycle inform the following ones?

3. What levels of precision does the test user reachafter running the whole workflow once or multiple times?

4. To what degree does the test user rely on their own creativity and intuition before they transition to the digital interface?

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A Descriptive Example

On the first step, the user is given an image of the design prompt representing a folded three-dimensional physical origami model I produced based on Ron Resch' s and David Huffman's curved crease and tessellations-based designs, respectively.

On the second step, the user observes the image and crumples one sheet of paper to physically simulate where they believe they need to draw the creases in order for the paper to reach the folded state of the origami model they were shown on step 1. Next, they need to flatten the sheet of paper and on top of it draw lines and curves by hand which will represent the notational system of their design proposal. The drawing doesn't need to be accurate on the first try since it only serves as a first approximation of what will next lead to a series of iterations.

On the third step, they need to interact with the first of the two parts of the digital interface meaning a computer vision software (Runway) used to import the two-dimensional physical drawing into the digital space. To do that the user projects first their drawing parallel to the computer's integrated camera to avoid any distorted representations of their drawing in the digital space. The drawing is converted into a bitmap line-drawing image by use of a machine-learning edge-detection module. Next, this image is in real-time imported in the second part of the digital interface meaning a visual programming software (Grasshopper). Any change in the first software changes the data image sent to the second software in real time (Fig. 23-26).

On the fourth step, the user interacts with the visual programming environment to generate the model simulation. Through image processing the bitmap line-drawing is converted into a vector image composed of two different families of lines. The lines are converted into a mesh which is deconstructed into its points. The points are referenced and anchored to curves of the default design and they are used to generate the mean curves of the mesh (Fig. 27). The curves of valleys and ridges are thus produced and the mesh model for the simulation is generated (Fig. 28-33).

If the user finds that their simulation outcome doesn't match with the design prompt's image they were initially shown, they need to repeat the process again by jumping back to any of the previous steps. The experiment is considered complete once the user decides they have reached an acceptable solution to the design prompt given.

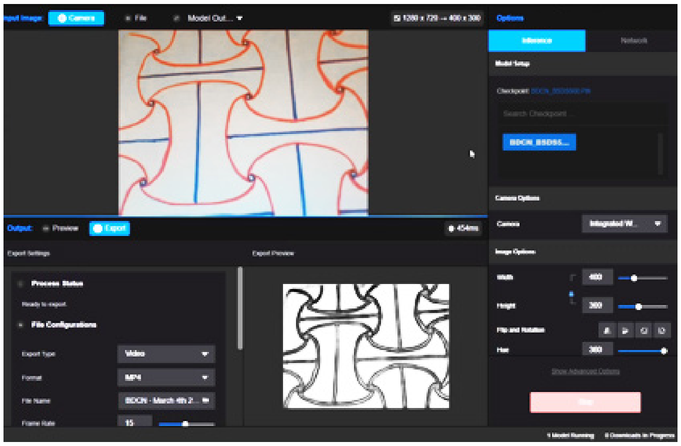

Fig. 23: Edge detection of the hand-drawn notational system in Runway.

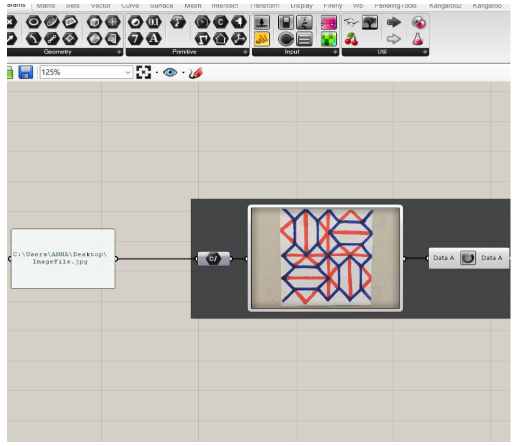

Fig. 24: Importing the line drawing into Grasshopper.

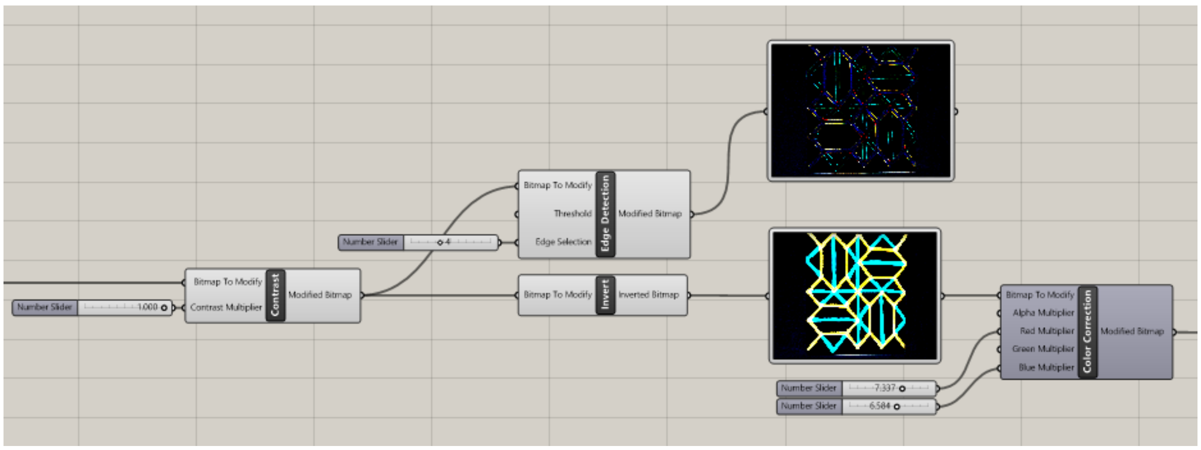

Fig. 25: Color correction of the color-coded line drawing in Grasshopper.

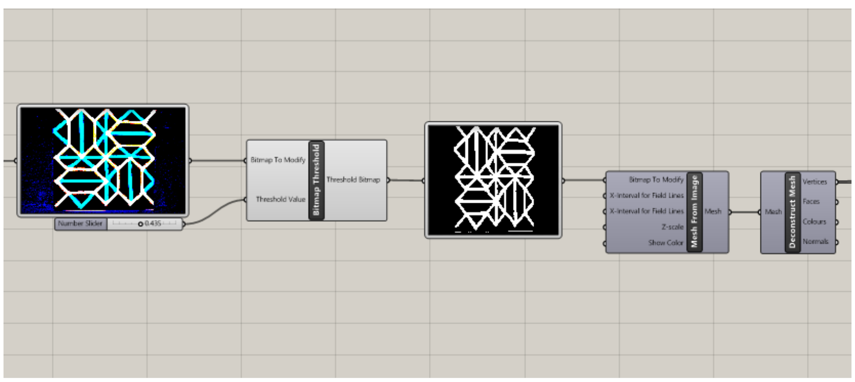

Fig. 26: Mesh generation from the vectorized line drawing in Grasshopper.

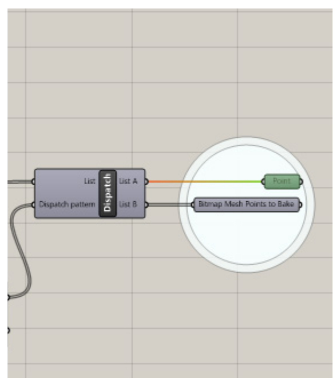

Fig. 27: Mesh points for the mean curves generation.

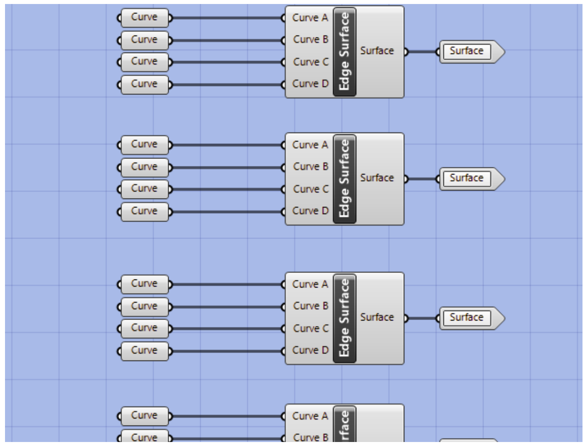

Fig. 28: Surface generation from the hand-drawing's vectorized curves in Grasshopper.

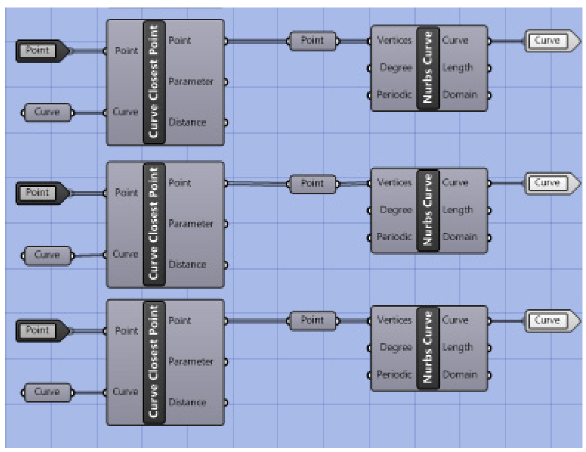

Fig. 29: Generation of the mean ridges curves for the simulation in Grasshopper.

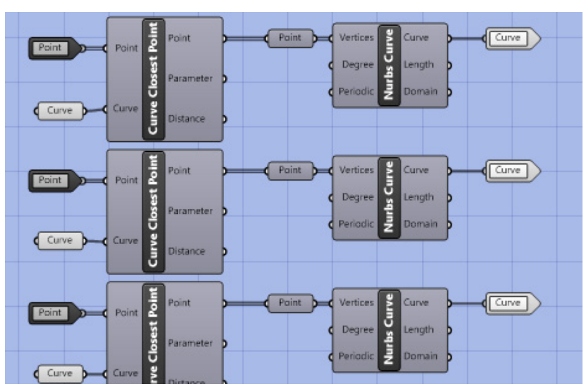

Fig. 30: Generation of the mean valleys curves for the simulation in Grasshopper.

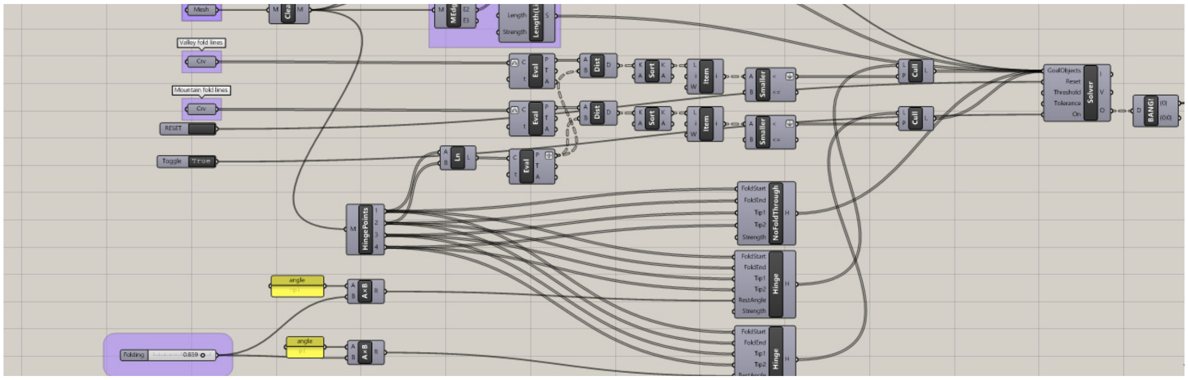

Fig. 31: Importing the valleys, ridges, and the mesh for the simulation in Grasshopper.

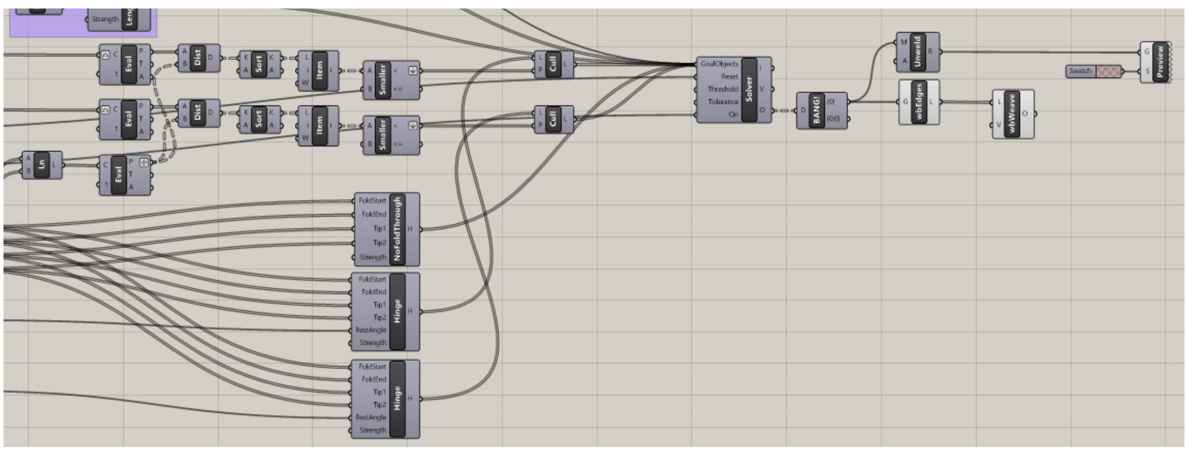

Fig. 32: Triangulation of the imported mesh and calculation of forces (via the Kangaroo plug-in).

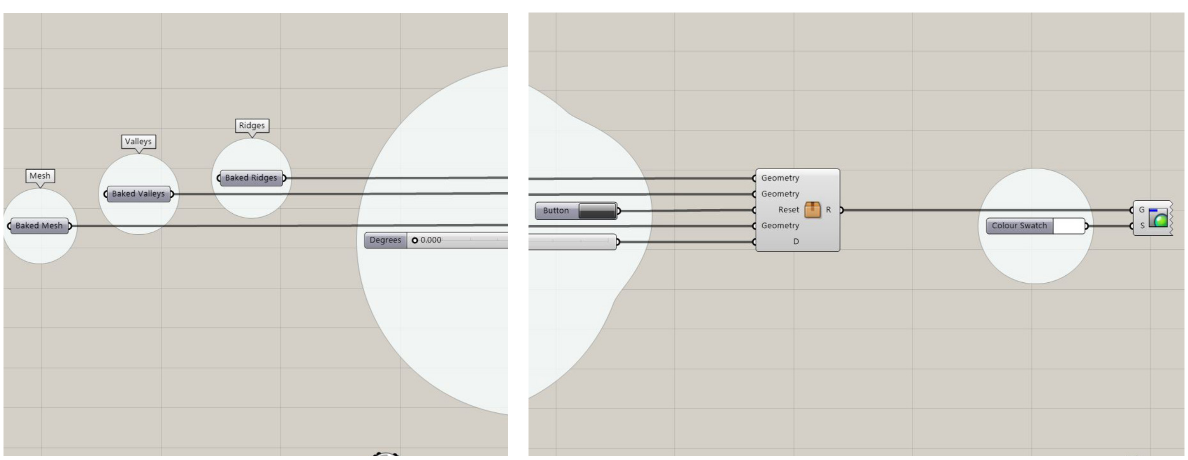

Fig. 33: The simulation button the designer interacts with to start the simulation process.

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Results

The presented workflow shows that designing is a process of aggregated thinking. The designer thinks in lines, shapes, and the relationships between them while drawing their notational system. Hence, the total drawing is the behavior of these sub parts and the relationships between them. By using the Thinking Manual the designer can produce more than mere schematic drawings and folded paper models.

The software doesn't react to any design solution that is considered underexplored in terms of geometric and topological precision, acquiring thus a pedagogical role in the course of the workflow. At the same time, the digital interface narrows down the range of the domain solutions indirectly guiding the designer through how they should structure their way of thinking.

The interaction between the designer and the tools keeps changing from test round to test round, user to user, and problem to problem. With the proposed workflow one thinks, computes, and draws in vague and ambiguous ways reconfiguring shapes and the relationship between them in an attempt to discover the final outcome. Therefore, this process of paper folding within the proposed workflow not only enables the designer to rearticulate the problem and reuse their tools but also to analyze their design process retrospectively.

In another instance, the experiment's results can be described through the outcomes the first and second test users used respectively as follows:

For Curved Creases, the first user (Fig. 34):

1. identified two main creases
2. found the curving of the whole paper sheet all at once to be hard and tried to draw the notational system by crumpling the paper where each of the two curves was previously identified
3. added valleys roughly
4. used the digital interface to realize their notational system was roughly responding
5. ended the process.

For Origami Tessellations the first test user (Fig. 35):

1. identified three main valleys neighbored by two ridges each
2. identified multiple triangles on the edges
3. saw lines, triangles, and polygons blending and identified that the connection between the main three valleys is unclear
4. went on analyzing the top left valley
5. added a valley inside every triangle
6. used the digital interface.

On the first iteration round, he (Fig. 36):

1. maintained the main three valleys
2. added more triangles of a smaller scale to their neighboring connections
3. used the digital interface
4. ended the process.

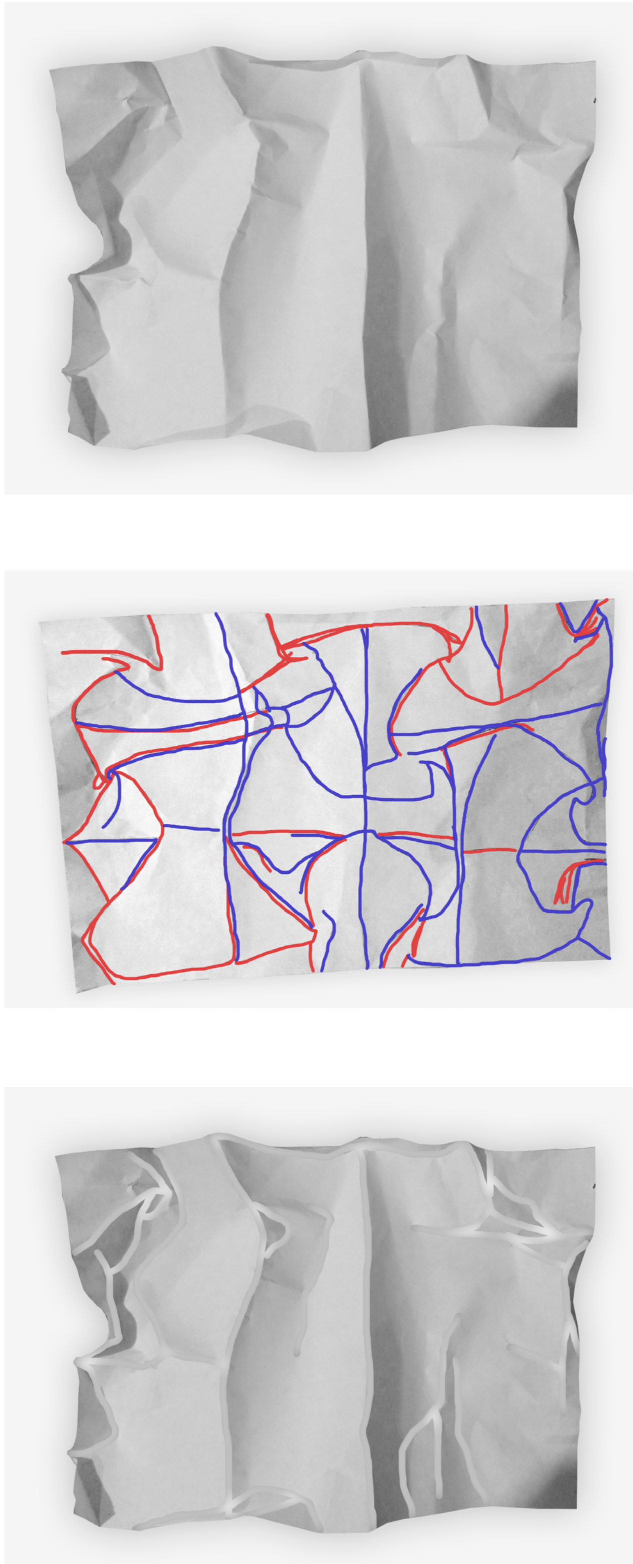

Fig. 34: Curved creases, Prototype 1, Test User 1.

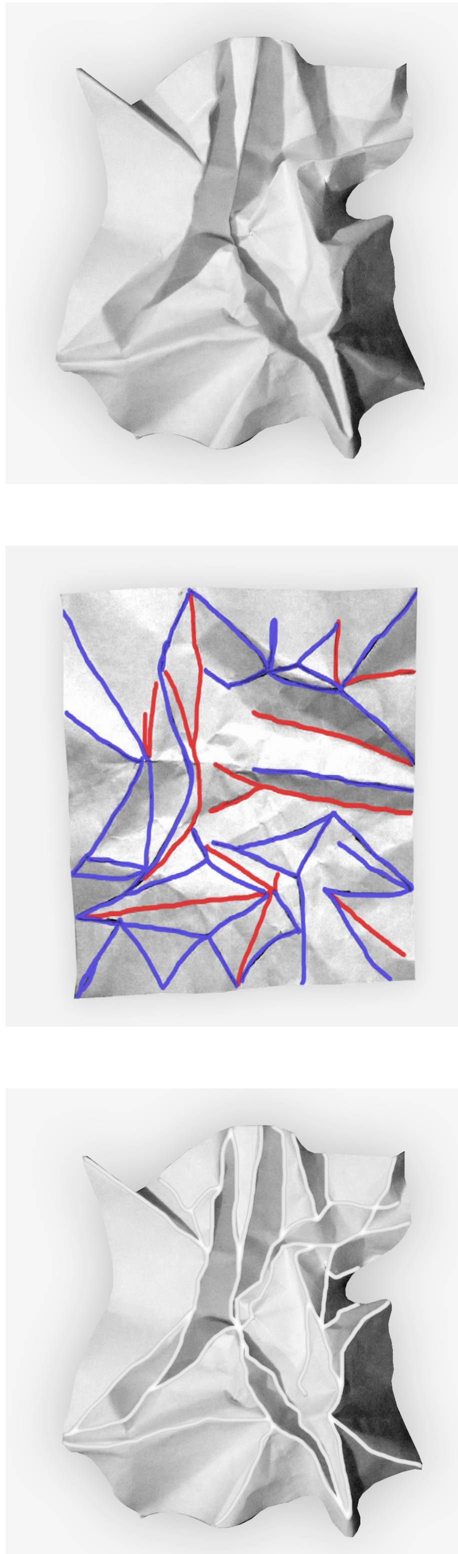

Fig. 35: Origami tessellations, Prototype 1, Test User 1.

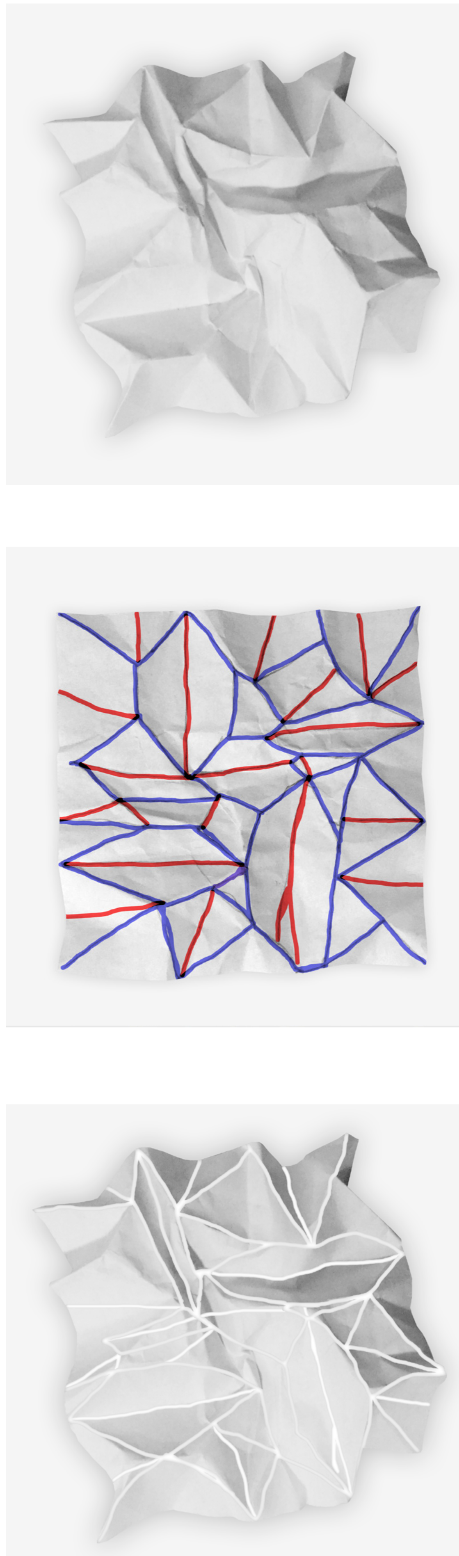

Fig. 36: Origami tessellations, Iteration 1, Test User 1.

For Curved Creases, the second user (Fig. 37):

1. identified five axis of valleys
2. brought creases of a smaller scale on both sides of each valley
3. used the digital interface.

On the second round, he (Fig. 38):

1. identified eight symmetrical axis of valleys
2. brought symmetrical creases of a smaller scale on both sides of each valley
3. left the edges of the paper sheet unfolded
4. ended the process.

For Origami Tessellations, the second user (Fig. 39):

1. identified triangles and polygons composed of three main valleys and their adjacent ridges
2. sculpted the sheet of paper in such way as to create sharp folding lines
3. crumpled the sheet of paper roughly to simulate where the rest of the surrounding creases should be
4. used the digital interface after drawing quickly the no tational system by hand
5. ended the process.

As the user's first proposal was underexplored in terms of precision, the digital interface didin't generate a responsive simulation model. Therefore, on the second round, he (Fig. 40):

1. added triangles of a smaller scale to the parts surround ing the three main valleys he identified on the first round which the digital interface converted into a slightly more responsive simulation model

Fig. 37: Curved creases, Prototype 1, Test User 2.

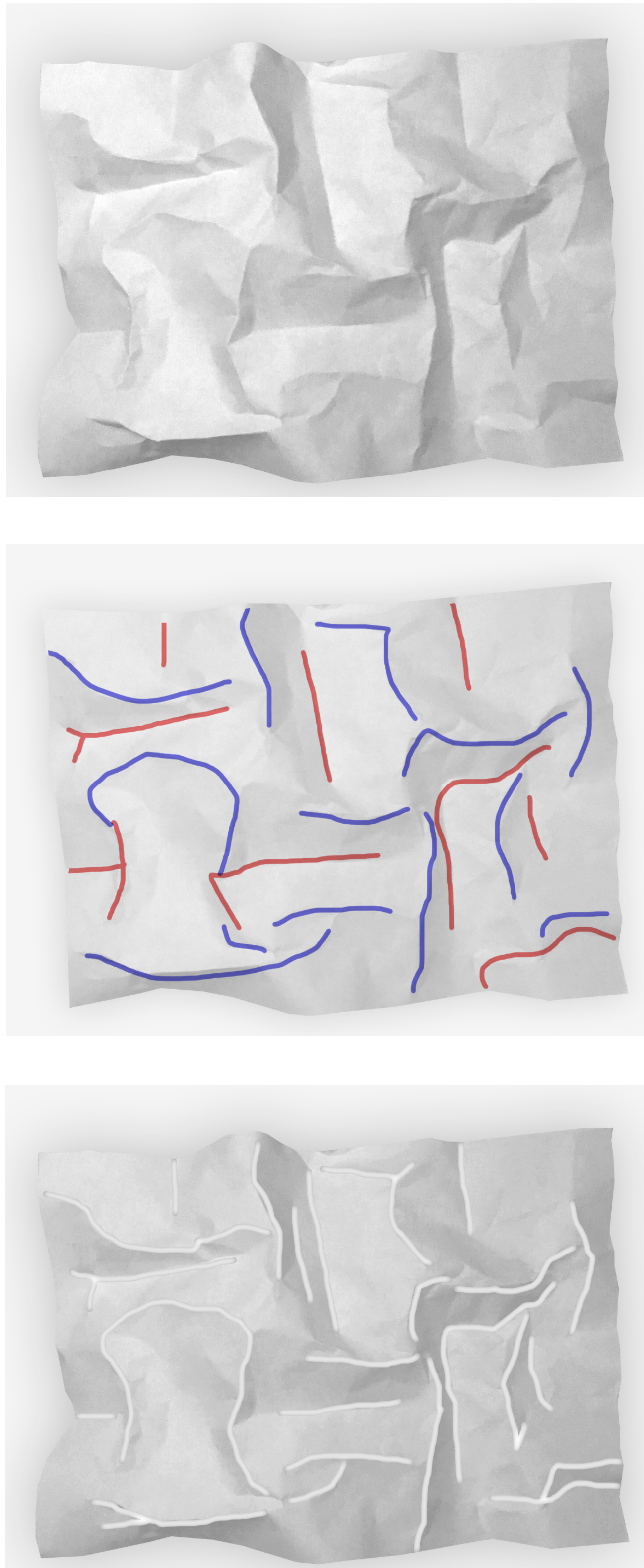

Fig. 38: Curved creases, Iteration 1, Test User 2.

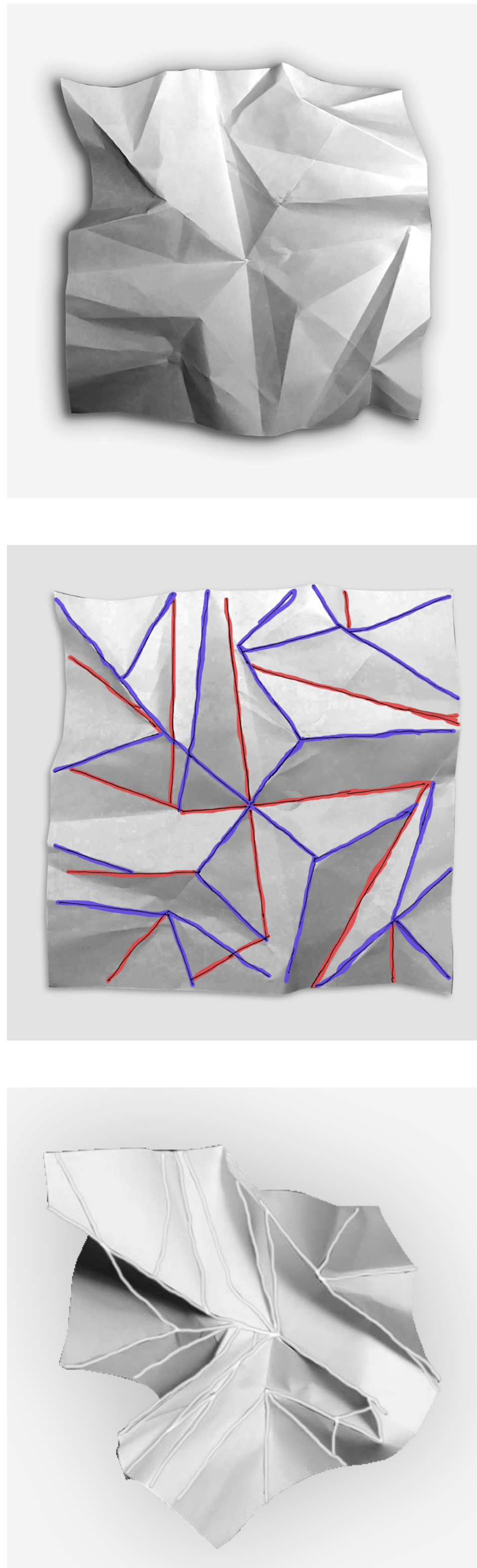

Fig. 39: Origami tessellations, Prototype 1, Test User 2.

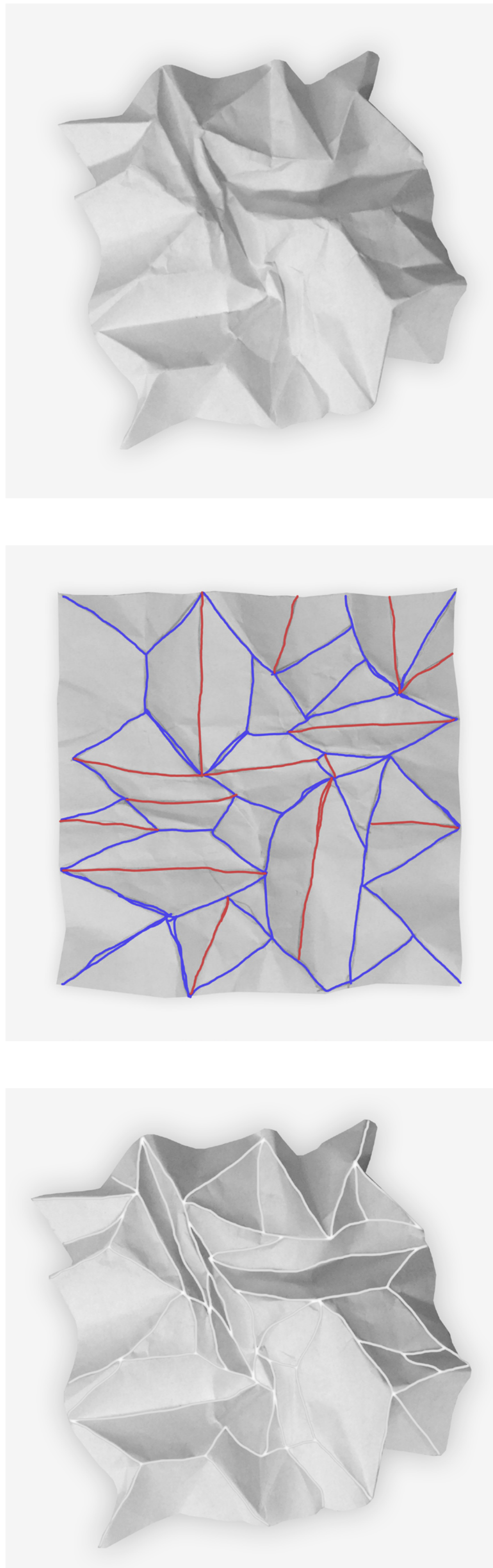

Fig. 40: Origami tessellations, Iteration 1, Test User 2.

2. post-rationalized his overall design system in terms of scale and sculpted the sheet of paper once again
3. moved to the digital interface
4. ended the process.

Similar conclusions can be reached by analyzing the results that the third user produced with a tendency to identifying main axis and symmetry lines as the key elements of the design system and a preference of the digital interface over the analog tools in the case of the Origami Tessellations problem (Fig. 41, 42).

Therefore, the methodology presented in the context of this thesis challenges the designer to trust and retain their intuition and creativity and augments their act of design by adding a computation aid for greater precision and speed.

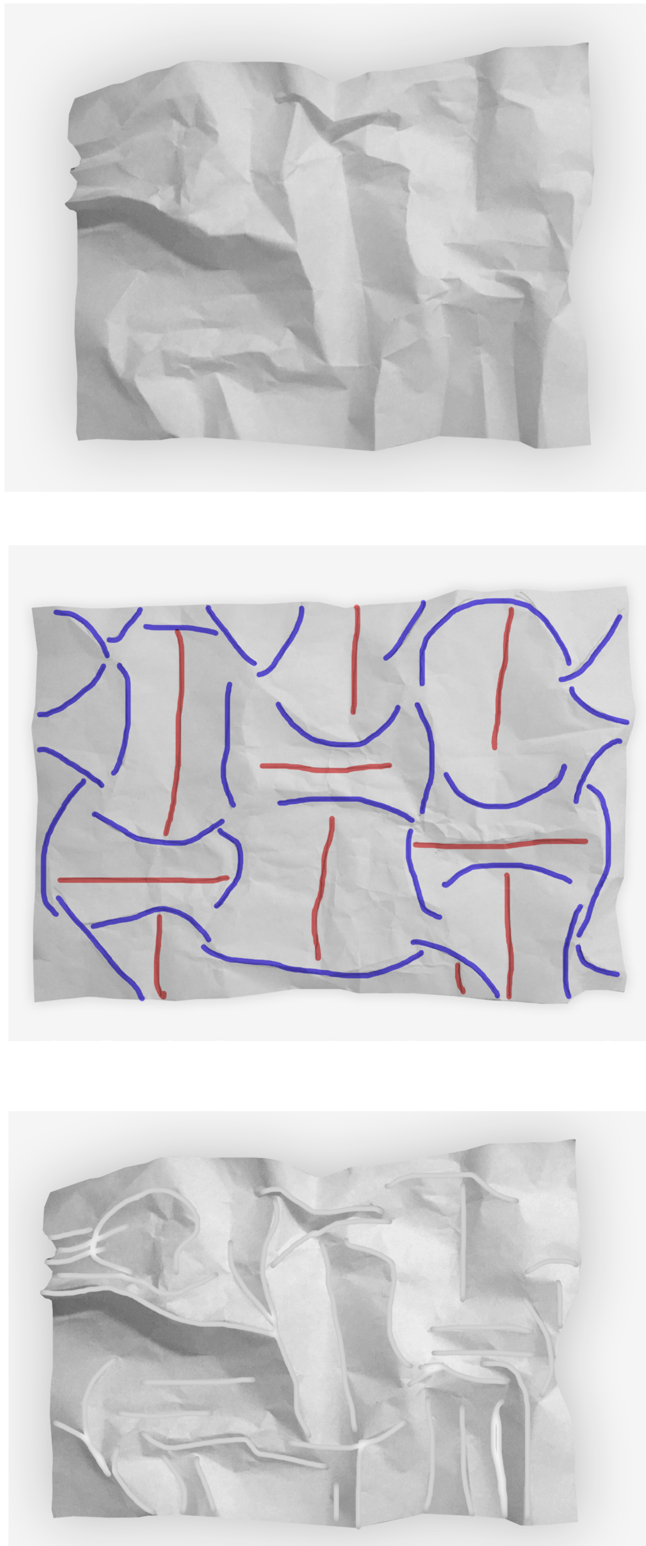

Fig. 41: Curved creases, Prototype 1, Test User 3.

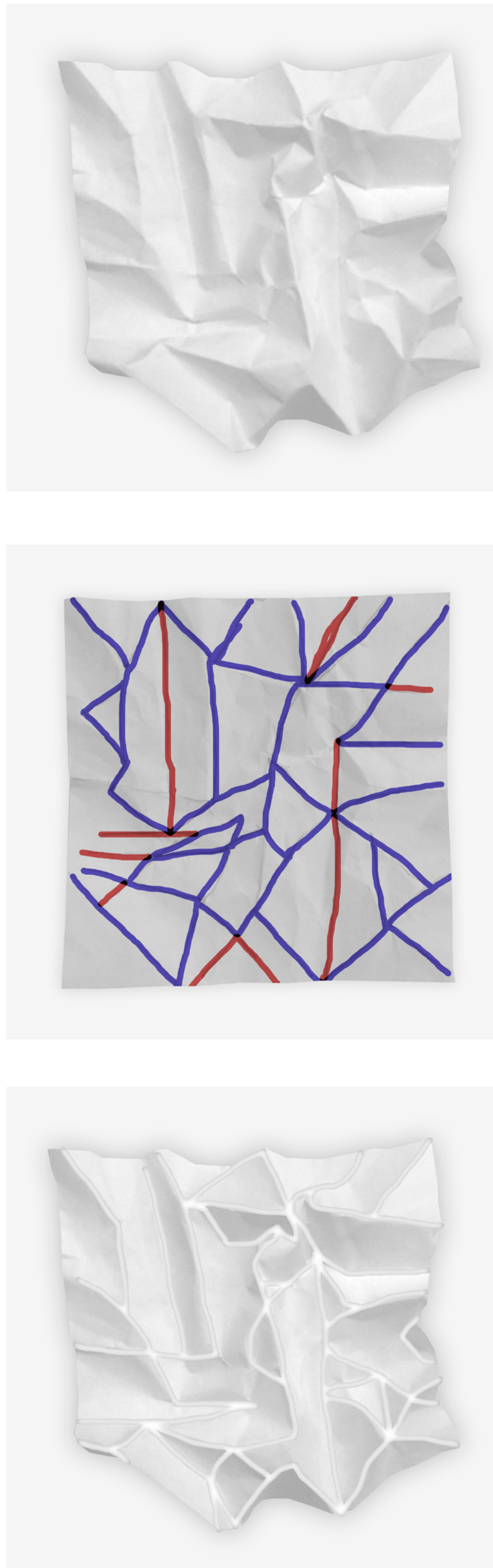

Fig. 42: Origami tessellations, Prototype 1, Test User 3.

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Reflections and Contributions

In this series of studies, I develop a critical outlook about the mechanization and computization of the design process and the marginalization of the designer in creative practices and design problems of high complexity. I introduce a methodology for making visible the otherwise hidden, imaginative, and immaterial bits that are embedded in the thinking, designing, and making act.

The study formulates a critical standpoint to current approaches in design computing and paper folding and is articulated around the following core points, with the first referring to the tool, the second to the designer, and the third to the design process – the tooling- itself:

1. Architectural knowledge is larger than the sum of design and instrumental knowledge with each part having a distinct, yet necessary contribution to design.
2. The problem is more in our position towards technology and the way we utilize and control the digital tools' capabilities rather than in the existence of the tools per se.
3. Design is not an automated information process of digitization. Rather, it is an activity of the mind, a mediating device of seeing, thinking, and making and as such it cannot be directly described or prescribed.
4. Analog and digital modes of designing and making

hardly co-exist in creative practices today.

5. Computational systems are based on a symbolic understanding of lines and thus they cannot use or utilize imprecision and ambiguity, favoring production and efficiency rather than exploration and discovery.

Although there have been prior studies with an aim similar to the one presented here redefining the roles of physical and digital computing in creative design processes, I hold that this thesis offers a different way of addressing the problem. Yet, my goal is not to address a problem and solve it. Rather, I intend to point readers to a different way of thinking about the following core inquiries:

- what computational design systems are used for and how they complement us in the act of design;
- how can we break the boundaries that the precon ceived, goal-directed computational process limits us within;
- how can we utilize computational tools to create an open-ended creative process in which thinking stands as the interface between designing and making.

Finally, I aim to develop and read this thesis as a thinking manual; one utilizing thinking as the mediating device to seeing, perceiving, and making with designing in the role of inventive wandering and critical decision making.

PART V

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References
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Fig. 17: Figure by the author.

Fig. 18: Figure by the author.

Fig. 19: Figure by the author.

Fig. 20: Figure by the author.

Fig. 21: Figure by the author.

Fig. 22: Figure by the author.

Fig. 23: Figure by the author.

Fig. 24: Figure by the author.

Fig. 25: Figure by the author.

Fig. 26: Figure by the author.

Fig. 27: Figure by the author.

Fig. 28: Figure by the author.

Fig. 29: Figure by the author.

Fig. 30: Figure by the author.

Fig. 31: Figure by the author.

Fig. 32: Figure by the author.

Fig. 33: Figure by the author.

Fig. 34: Figure by Test User 1.

Fig. 35: Figure by Test User 1.

Fig. 36: Figure by Test User 1.

Fig. 37: Figure by Test User 2.

Fig. 38: Figure by Test User 2.

Fig. 39: Figure by Test User 2.

Fig. 40: Figure by Test User 2.

Fig. 41: Figure by Test User 3.

Fig. 42: Figure by Test User 3.

Fig. 43: Figure by the author.

Fig. 44: Figure by the author.

Fig. 45: Figure by the author.

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Appendix
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Appendix

Due to the technical problems the transition from the physical to the online learning module at MIT generated as a result of COVID-19's crisis, Runway - the first part of the digital interface - was replaced by an image processing script in Grasshopper. Therefore, an image of the test user's hand-drawing was imported directly in Grasshopper and turned into a mesh and a vector-based line system (Fig. 43). After the second adjustment, the test user executed the analog part of the workflow with me running the digital interface after importing the image of the user's hand-drawing into Grasshopper. The workflow then repeated with no further alterations (Fig. 44).

Figures 45, 46 illustrate the solutions of each of the two design prompts given to the test users in the course of the experiment, that of curved creases and the other of origami tessellations, respectively. These images were shown only in the end of each user's workflow as a point of reference to their own design proposals.

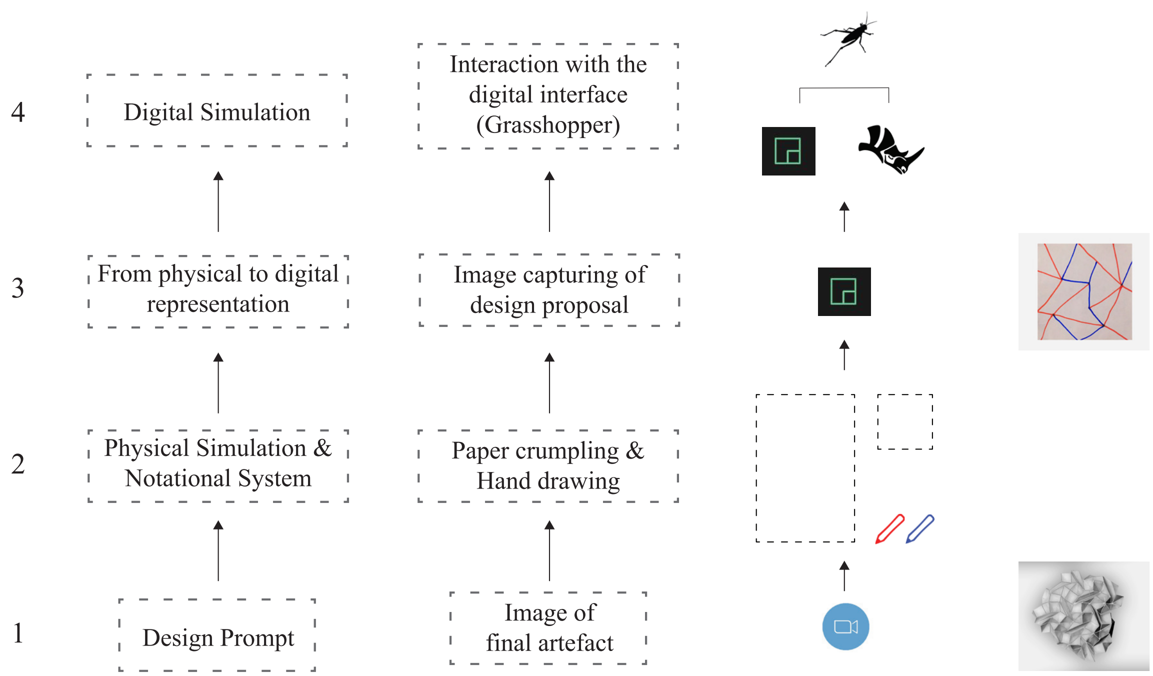

Fig. 43: Workflow adjustment 1.

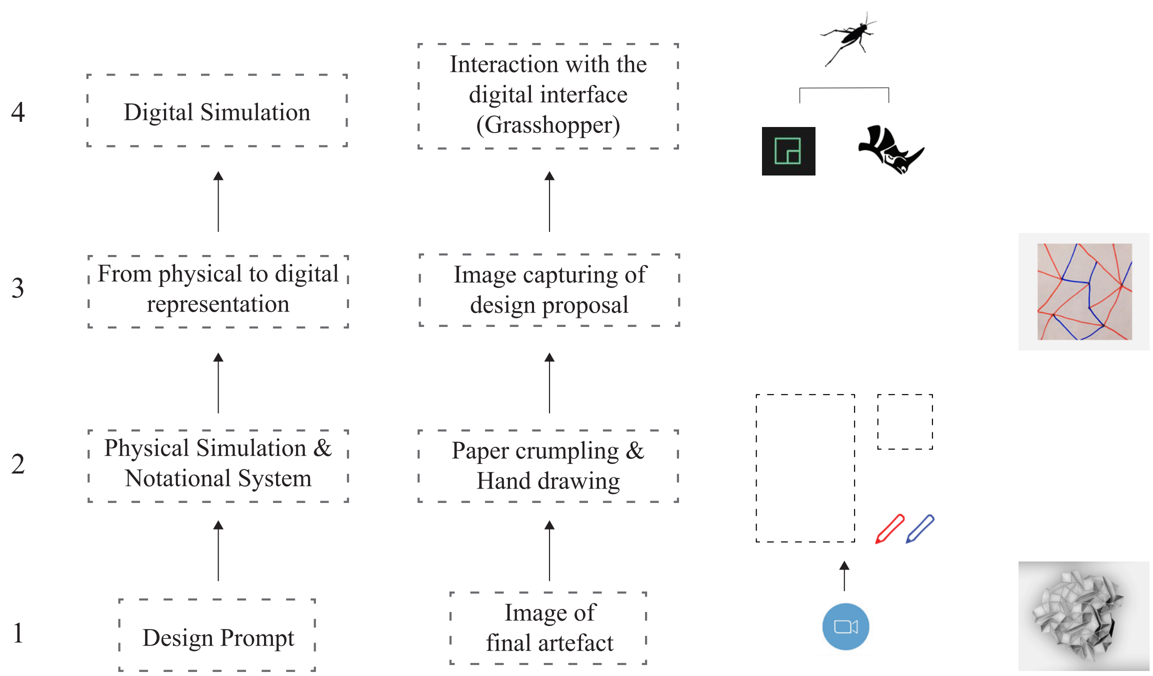

Fig. 44: Workflow adjustment 2.

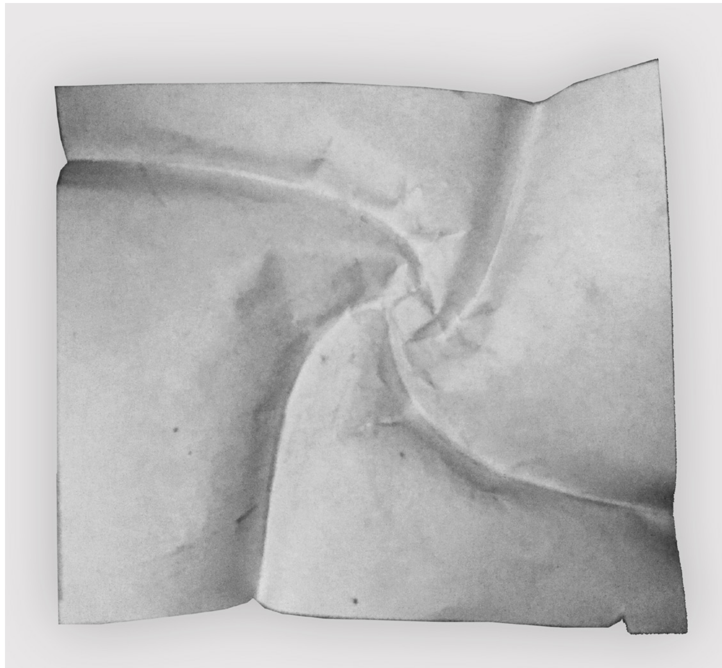

Fig. 45: Reproduction of Ron Resch.'s curved crease model, author's work, 2020.

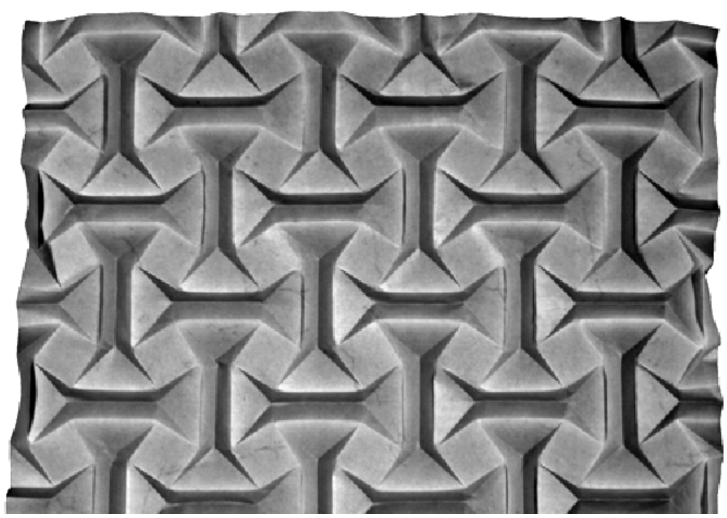

Fig. 46: Reconstruction of David Huffman's "Raised Vanes, Both Vertical and Horizontal" (date unknown) by Eli Davis, Erik D. Demaine, Martin L. Demaine, Jennifer Ramseyer, 2013.