Mass-tailorisation

a digital aid for the decision-making in the designer's design process.

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THANKYOU

To my supervisor Kevin;
For allowing me to explore wildly.
For guiding me to the 'nearest exits' in my wild explorations when needed.

To all my friends whom I've shared my time throughout the five years;
For making these years more memorable.
For making these years more enjoyable.

To mum, dad, and sister;
For supporting me continuously and unconditionally.

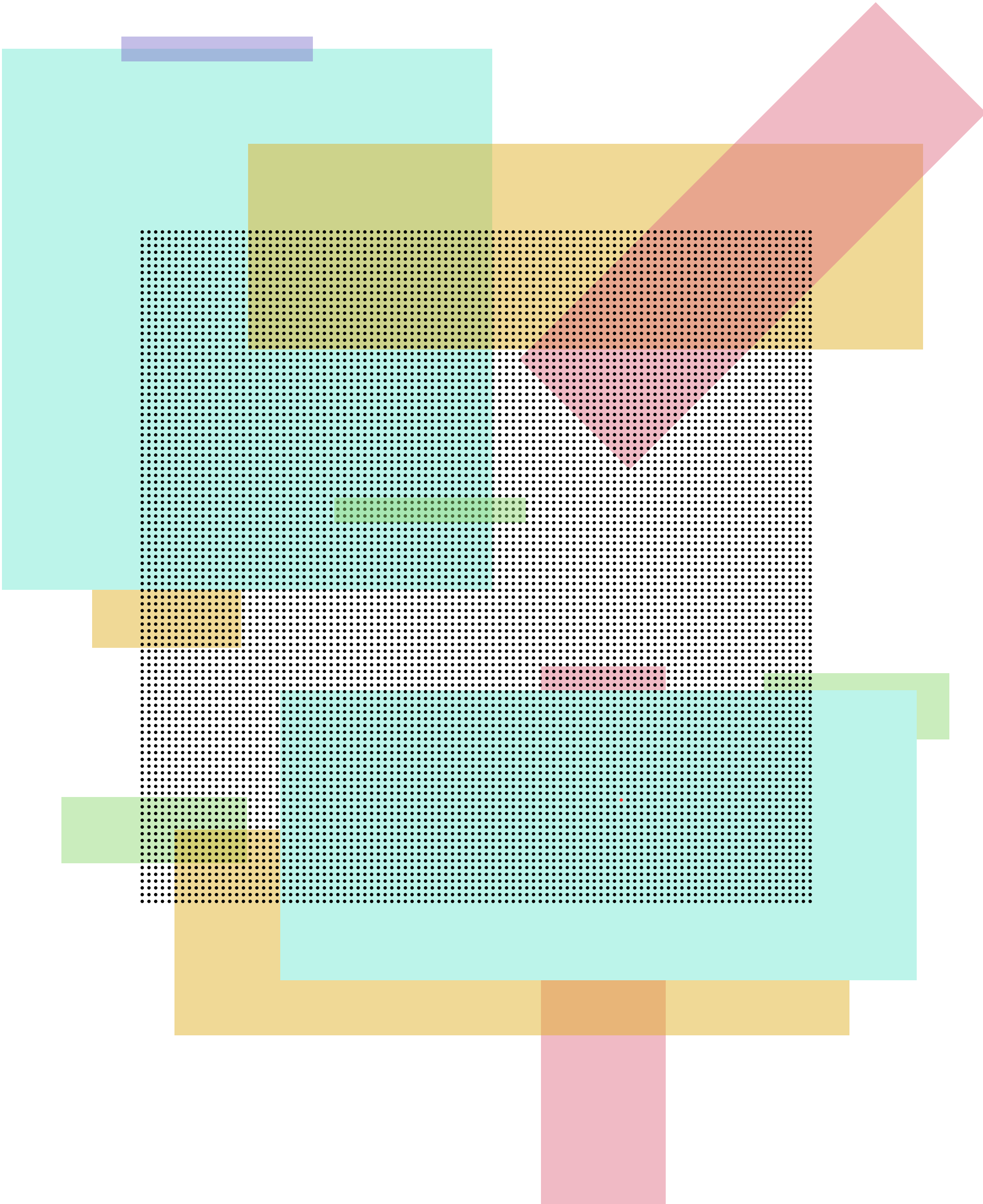
To my father in heaven;
For making good in all things.

PREFACE

"Creativity is just connecting things. When you ask creative people how they did something, they feel a little guilty because they didn't really do it, they just saw something. It seemed obvious to them after a while. That's because they were able to connect experiences they've had and synthesize new things. And the reason they were able to do that was that they've had more experiences or they have thought more about their experiences than other people. Unfortunately, that's too rare a commodity. A lot of people in our industry haven't had very diverse experiences. So they don't have enough dots to connect, and they end up with very linear solutions without a broad perspective on the problem. The broader one's understanding of the human experience, the better design we will have." - Steve Jobs (in Wolf, 1996).

This thesis is a culmination of dots. The dots as products of explorations - sometimes reaching past the boundaries of architecture - in order to accumulate enough dots of diversity to synthesise new things.

Indeed, for myself, this thesis has been an exercise in broadening the borders of architecture and the understanding of the human experience, in order to collect enough dots, in the hopes of having better designs sparked by creativity.



One Red Dot

Figure 1. Deciding on a solution from a solution space.

ABSTRACT

The advent of digital tools and technologies of modern times has provided architectural designers with the ability to create in complexities and volumes of an unprecedented scale. With the myriad of possibilities, the designer has become prone to the Paradox of Choice - the difficulty of making decisions in a field of mass-options.

Mass-tailorisation aims to aid the decision-making process of the designer in a world of unprecedented possibilities, limited only by the practicalities of reality. This research develops a theoretical framework for mass-tailorisation systems that aid the designer in the decision-making process by strategically focusing on four stages of the decision-making process.

The thesis investigates the theoretical framework of mass-tailorisation through several phases of case studies that critically assess the viability and the implications of the components that constitute the mass-tailorisation system. The need for mass-tailorisation, as well as the establishment of the system and the future potential of mass-tailorisation are addressed through these case studies. Thus, leading to an integrative theoretical framework on the validity of mass-tailorisation.

The research also speculates on the possible role of the future designer as they navigate through the near-limitless possibilities of the architectural design process of modern times. Finally, the thesis concludes by discussing the specific importance of the Design-Fabrication-Assembly Digital Continuum and the pursuit for the Move 37 phenomenon in explaining how mass-tailorisation can improve the decision-making process of the designer during the design process.

Findings from this research thesis were prepared as conference papers titled:

"How to design-fabricate-assemble? The pursuit for efficient and effectively bespoke architecture in the age of digital continuum through mass-tailorisation."

for **The 51st Architectural Science Association Conference 2019.**
Pesented at IIT Roorkee, India, on 30th November 2019.

and,
"Mass-tailorisation - through three analogies."

for **The 25th Computer-Aided Architectural Design Research in Asia 2020.**
To be presented at Chulalongkorn University, Thailand, on 5-8th August, 2020.

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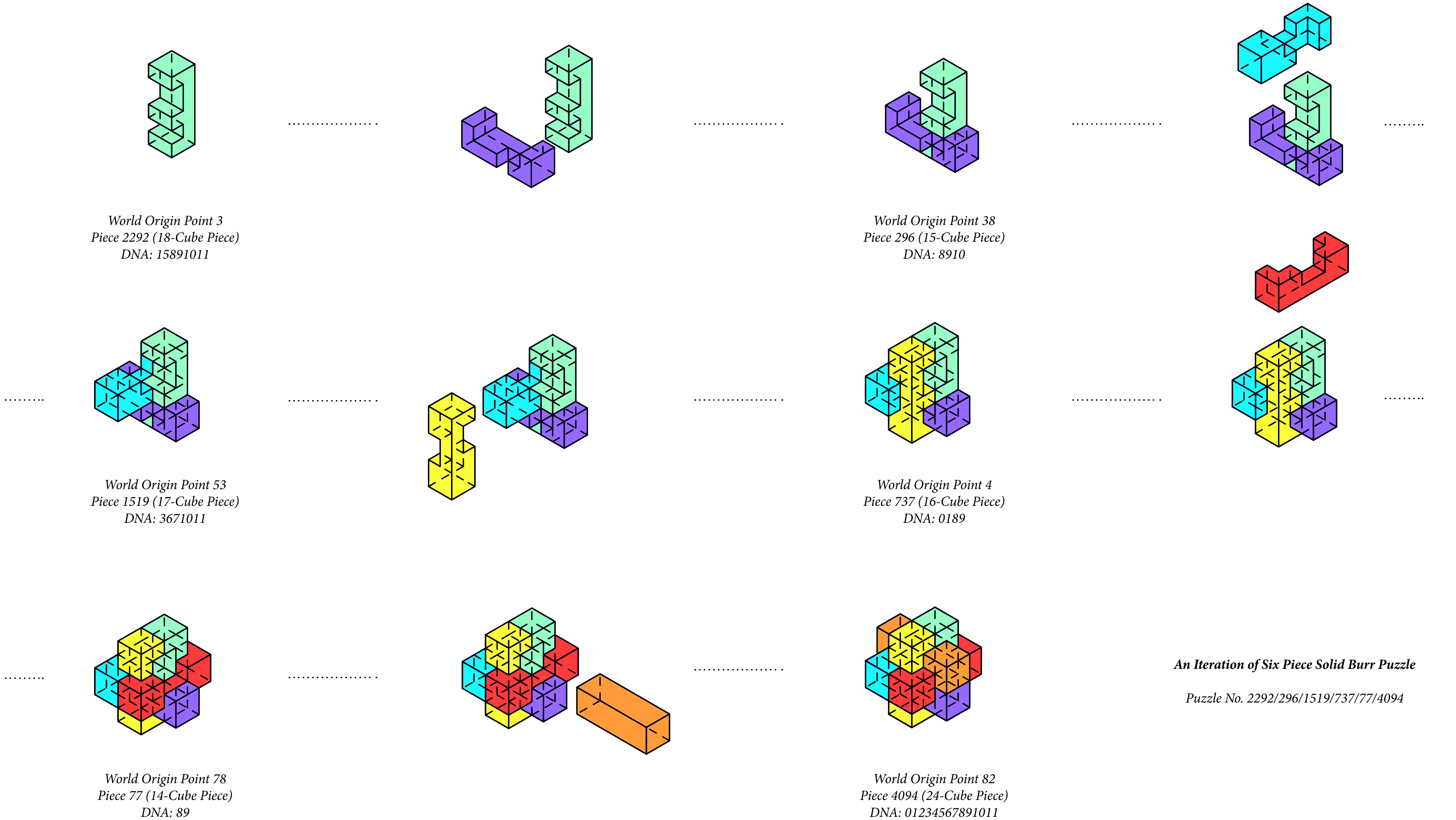

Figure 2. The assembly process for an iteration of a six-piece solid burr puzzle.

BACKGROUND

CHAPTER ONE.

SETTING THE STRUCTURE OF THE THESIS.

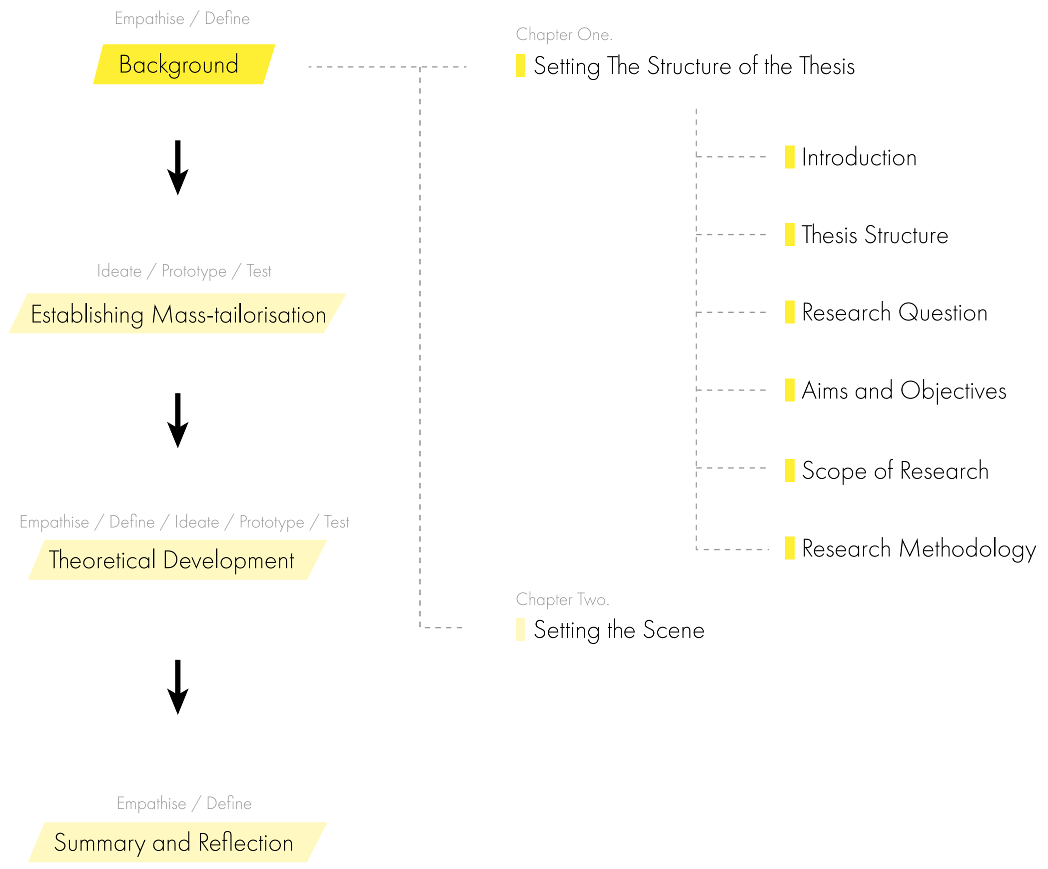

Figure 3. Chapter One Structure.

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Figure 4. Decision-making. Photo by Peter Feghali.

INTRODUCTION

In an episode of the Simpsons, members of the Simpson family visit a large supermarket in Springfield. The store boasts unlimited product choices with limitless shelves and an express checkout with a sign that reads "1000 items or less". Inundated with too many options, the Simpsons later return to Apu's small Kwik-E-Mart.

The supermarket, called Monstromart, is an example of the Paradox of Choice, a state of paralysis in which one cannot make a single decision due to too many options. Unsurprisingly, the supermarket's slogan was "where shopping is a baffling ordeal".

The thesis explores the process of decision-making in an ever-increasing field of choices within the architectural design process caused by the continuous integration of advanced digital tools and technologies - possibly the "Monstromart" of the architectural designer.

The advent of digital tools and technologies has provided the 21st-century society with the ability to create in complexities and volumes of unprecedented scale and efficiency. Today, more can be created with less. The field of architecture is no different. Digital technologies allow the designer to effectively and efficiently create numerous designs with less time and resources.

In 1999, architect and designer Greg Lynn initiated a project titled the Embryological House. The work consisted of a collection of hundreds and thousands of iterative digital and physical responses to Vitruvius' statement that "an ideal house is a house to which no element can be added or subtracted without violating the perfection of the whole" (Lynn, 2019, pg. 71). During the project, Lynn explains that the architecture community challenged the project with the question: "Which Embryological House is best?". Lynn responded: "They are all like my kids, all 50,000 are beautiful; although I have seen all my kids and I have never seen all 50,000 house designs, I can say with absolute confidence that they are all perfect in their own way." (2019, pg. 73).

In most architecture projects, the practicalities of architecture do not allow for numerous designs to be developed through to realisation. While current technologies allow efficiency in iterative design, unfortunately, most architects cannot build 50,000 iterative responses to a design brief, regardless of their level of affection towards each and every one of those designs. It is often the case that only a select few, if not a single solution, is realised at the end of the process. Therefore, the responsibility of the designer as the decision-maker is significant in the decision for a viable solution from the pool of options. The designer needs to make critical decisions at various stages of the design process to limit the number of viable solutions to the brief. However, it is at these stages that the designer is prone to experiencing the Paradox of Choice - the difficulty of making decisions in a field of mass-options. The designer is faced with the risk of losing control over the design process due to the difficulty in making effective decisions. Furthermore, should the designer be able to navigate through the Paradox of Choice, the inherent preconceptions of the designer may potentially limit the effectiveness of the designer's decision-making process.

In this context, the thesis re-examines the question asked to Lynn and attempts to provide a theoretical resolution as to "deciding which is best" from a pool of options – without facing the Paradox of Choice.

The thesis poses the research question of:
How can a mass-tailorised system, founded on a Design-Fabrication-Assembly Digital Continuum, aid in the decision-making typically undertaken in the architectural design process?

The theoretical resolution proposed by the thesis is founded on the idea of mass-tailorisation - the reduction of viable solutions through non-critical biases - in order to strategically focus on four stages of the designer's decision-making process. As such, mass-tailorisation attempts to aid in the decision-making process of the designer in order to avoid the Paradox of Choice and make better-informed decisions. Learning from the shortfalls of mass-customisation and utilising artificial intelligence, the research develops a theoretical framework for a mass-tailorisation system established upon a digital continuum of design, fabrication, and assembly. The thesis explores various case-studies that discuss: the decision-making process, utilising computational capabilities to aid in decision-making, and transforming the mass 'possibilities' to a select, often intentionally biased solution that responds to specific design contexts in question. The research concludes with a discussion of the role of the designer in a mass-tailorised design process.

Finally, while the thesis is built upon an architectural context, the research spans to other fields of academia such as psychology, computer science, economics, and philosophy. The thesis does not claim to be a complete piece of work that encompasses all of these various fields in their full resolution; rather, it emphasises the need for interdisciplinary research in the pursuit of finding the exit in architecture's Monstromart.

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Figure 5. Greg Lynn's Emryological House.

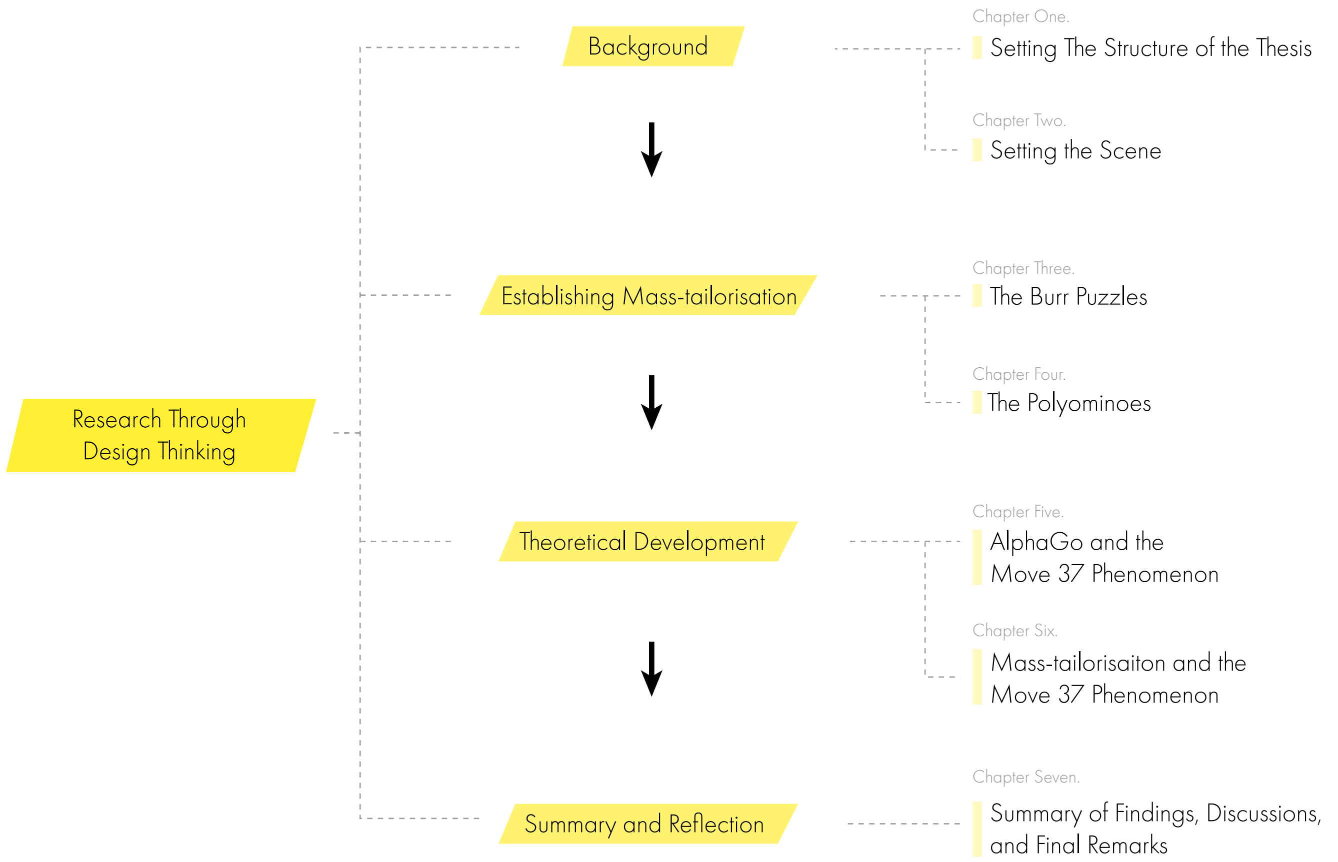

Figure 6. Thesis Structure.

THESIS STRUCTURE

This thesis is divided into seven chapters: the current introduction chapter (Chapter One), two background chapters (Chapter Two & Five) and three case study chapters (Chapter Three, Four & Six), and one concluding chapter (Chapter Seven).

The purpose of this chapter (Chapter One) is to set the structure of the thesis. The chapter introduces the research question, and aims and objectives to introduce the research. This is followed by outlining the scope and the primary research methodology used to conduct the research.

The next chapter (Chapter Two) outlines and elaborates on key frameworks and backgrounds to key terminologies that will be discussed throughout the thesis. First, the chapter defines the terms 'architectural design-process' and 'decision-making' as it pertains to the thesis of this research. This is followed by elaborating on the relationship between architecture and technology. Upon this review, the chapter takes a more in-depth investigation into the ideas of mass-production, mass-customisation, and the Design-Fabrication-Assembly Digital Continuum as it relates to the architectural context. Such a review also reveals the shortfalls of mass-customisation and serves to introduce the framework for the Paradox of Choice and mass-tailorisation. Aggregated together, these frameworks and backgrounds portray the development of the architectural design process and the possible shortfalls/implications that arise with the current environment of digital-aided design.

Chapters Three and Four take the learnings from the background review of the previous chapter to develop the idea of mass-tailorisation through two case studies. The first case study in Chapter Three utilises the Burr puzzle to establish the Design-Fabrication-Assembly Digital Continuum required for the development of mass-tailorisation systems. The case study revealed the difficulty in data management, suggesting the use of artificial intelligence as a means to manage datasets of this size. The second case study in Chapter Four incorporates machine learning techniques to develop a simple mass-tailorisation system using one-dimensional polyominoes. The potential of using artificial intelligence is found through the results. Thus, through the two case studies in these chapters, the requirements for the development of mass-tailorisation systems are identified, and the importance of artificial intelligence speculated.

Upon the findings of the previous chapters, Chapter Five covers additional contextual and literature reviews to clearly identify the potentials of artificial intelligence in the development of mass-tailorisation systems. AlphaGo and Move 37 are studied in-depth as specific case studies which also generate a discussion on the meaning of creativity. Through these additional reviews, the chapter provides the foundation for the refinement of the theoretical framework of mass-tailorisation as proposed by the following chapter.

In Chapter Six, the theoretical framework of mass-tailorisation as a system is refined through a series of case studies and case reviews. Such a refinement sheds new light on the importance of the Digital Continuum and the Move 37 phenomenon in mass-tailorisation systems. Furthermore, the potential implications of mass-tailorisation systems on the role of the designer of the future are speculated.

Finally, Chapter Seven reflects on the development of mass-tailorisation and discusses the implications of mass-tailorisation as a tool to aid in the decision-making of the designer during the architectural design process. The chapter provides concluding remarks to the scope of the research, its strengths and limitations, and possibilities for future additional research.

RESEARCH QUESTION

How can a mass-tailorised system, founded on a Design-Fabrication-Assembly Digital Continuum, aid in the decision-making typically undertaken in the architectural design process?

AIMS & OBJECTIVES

To investigate how an architectural designer might benefit from a mass-tailorised system in the decision-making of their design process, and

To speculate on the future implications of mass-tailorisation systems in the architectural design process.

The objectives of this research are:

1 Undertake research into previous literature and case studies that address decision-making and design.

2. Critically define mass-tailorisation as it pertains to architecture.

3. Undertake research into literature and case studies relevant to establishing a digital continuum or mass-tailorisation.

4. Establish a Design-Fabrication-Assembly Digital Continuum for mass-tailorisation.

5. Establish a mass-tailorisation system.

6. Speculate on future possibilities of mass-tailorisation in the architectural context.

SCOPE OF RESEARCH

The thesis aims to investigate how an architectural designer might benefit from a mass-tailorisation system in the decision-making of the design process - in simple terms, mass-tailorisation defined as the strategic reduction of viable solutions to limit choices. The research aim is left open-ended, and the research is scoped towards a theoretical exercise. As such, the outcome of the research will be achieved through a series of frameworks, developed through design research, that will solidify the theoretical resolution of mass-tailorisation. These frameworks will reduce the epistemological assumptions that might be currently present or arise during the research process.

More specifically, there are three key areas of focus in this research: Firstly, the research involves the development of a Design-Fabrication-Assembly Digital Continuum system. The Digital Continuum is seen as a prerequisite to the development of mass-tailorisation systems. Therefore, without the certainty in the establishment of a digital continuum, mass-tailorisation is not possible.

Secondly, the research involves the development of a simple mass-tailorisation system. As the driver of mass-tailorisation is the advancement of digital tools and technologies, the use of digital tools and technologies is expected during the research. The extent of the use will depend on the level of complexity of the development, which in turn may affect the quality and the time required for research findings. While the extent of the use of digital tools and technologies is not pre-defined, heuristic findings uncovered throughout the research process will inform the appropriate conditions where the inclusion of digital tools is relevant. The goal of this framework is to establish a simple mass-tailorisation system that is of sufficient complexity to validate the theoretical thesis of this research. As a consequence of this flexibility in the scoping of the tools, a robust discussion and reflection will follow at the end of the case studies to fully resolve the scope of digital tools and technologies.

Following the second framework, it is not within the scope of the research to provide a practical example of a mass-tailorisation system within the architectural context. As mass-tailorisation is a proposal for the design methodology of the present and potential future, a robust theoretical foundation is prioritised before its utilisation in a practical context. The time-frame for the research was not sufficient to address both theoretical and practical development. As a result, possible practical research pathways are discussed in place of practical development at the end of the research.

Thirdly, the context at which mass-tailorisation is developed and addressed extend beyond the field of architecture as commonly identified. While due diligence has been done to offer critical research in the fields outside of architecture, some limitations are present in the breadth and depth of knowledge. Therefore, the thesis does not claim to be a complete piece of work that encompasses all fields in their full resolution. However, the research has a sufficient range of primary findings to form an integrative theoretical statement. Therefore, the research has been scoped to invite additional research from architecture and fields outside of architecture alike due to the need for interdisciplinary research in this topic.

RESEARCH METHODOLOGY

"Most important of all, is that the process is iterative and expansive... they first spend time determining what the basic, fundamental (root) issue is that needs to be addressed. They don't try to search for a solution until they have determined the real problem, and even then, instead of solving that problem, they stop to consider a wide range of potential solutions. Only then will they finally converge upon their proposal. This process is called "Design thinking" – Don Norman (2013).

Norman's explanation of Design Thinking is a fitting portrait of this research's methodology.

The term mass-tailorisation appeared as a reactionary concept to the problem of the Paradox of Choice at the beginning of the thesis. Without a well-predefined definition of the term mass-tailorisation, the research question began inherently vague. As such, the research takes a very reflective and dialogical journey between attempting to answer the research question and understanding the research question. Throughout the research, findings from the research question redefined the term mass-tailorisation, which in turn, brought about new findings in light of the new perspectives to the research question. As such, the research naturally followed a "Design Thinking'' approach.

The research is design-led, utilising a cyclical methodology that is adapted from the Design Thinking process proposed by the Hasso-Plattner Institute of Design (d.school) at Stanford. The Design Thinking process is used as the primary research methodology as it allows for robust and iterative development of the thesis that begins with the testing and evaluation of the original 'problem' that ultimately leads to pursuing the correct design output (Hasso-Plattner-Institut, n.d).

The Design Thinking methodology consists of five stages. These stages are cyclical in nature but may also be non-linear (Dam & Teo, 2019).

Empathise: This stage aims to gain an understanding of the problem. It is the clarification of the problem space by identifying and specifying relevant dimensions of the problem. This stage is mainly conducted through an in-depth analysis of key findings in research and bestpractices. Furthermore, the Empathise stage includes the continuous review of the understanding of the problem as the research progresses.

Define: The Define stage aims to construct a conceptual framework for describing the problem as well as the possible solution pathways using the information gathered in the Empathise stage. The formation of the research question is included here; however, the Define stage also acts as a driver for the generation of case studies to be studied upon in the various phases.

Ideate: This stage aims to generate, summarise, and cluster ideas that address the framework developed in the previous stage. It identifies ideas that are most easily and efficiently implementable to allow for the quick and continuous turnaround in the Design Thinking process.

Prototype: The Prototype stage implements the development of ideas. It is the experimental stage of the process, and as such, by the end of the stage, there should be an understanding of the inherent constraints and problems present in the Define stage.

Test: The final stage of the Design Thinking process collects and documents feedback from the Prototype stage to reflect upon, possibly redefining the problems in the process. Furthermore, the newly acquired understanding of the context through the Test stage is utilised at the next Empathise stage.

The research does not follow a single cycle of the Design Thinking process. Instead, multiple cycles of the process occur in various scales and contexts throughout the research. For example, Chapter Two acts as the Empathise and Define stages of the overall research; however, each case study in Chapter Three and Four harbour its own stages of Empathise and Define. In this sense, the research follows a cyclical and dynamic interaction of multiple Design Thinking processes. Therefore, it can be claimed that the thesis is a cumulation of work arising from multiple cycles of the Design Thinking process.

It must be noted, however, that the thesis is represented as a final extended reflection on all prior research. Therefore, the structure of the thesis does not necessarily reflect the overall chronological research process that followed the research methodology. For example, cycles that deviated in a tangent, as well as incomplete cycles, and cycles unsuitable for the overall thesis have been omitted. Instead, the structure of the thesis follows a logical and contextual portrayal of research findings and outputs in order to provide a coherent thesis argument based upon an extended final reflection.

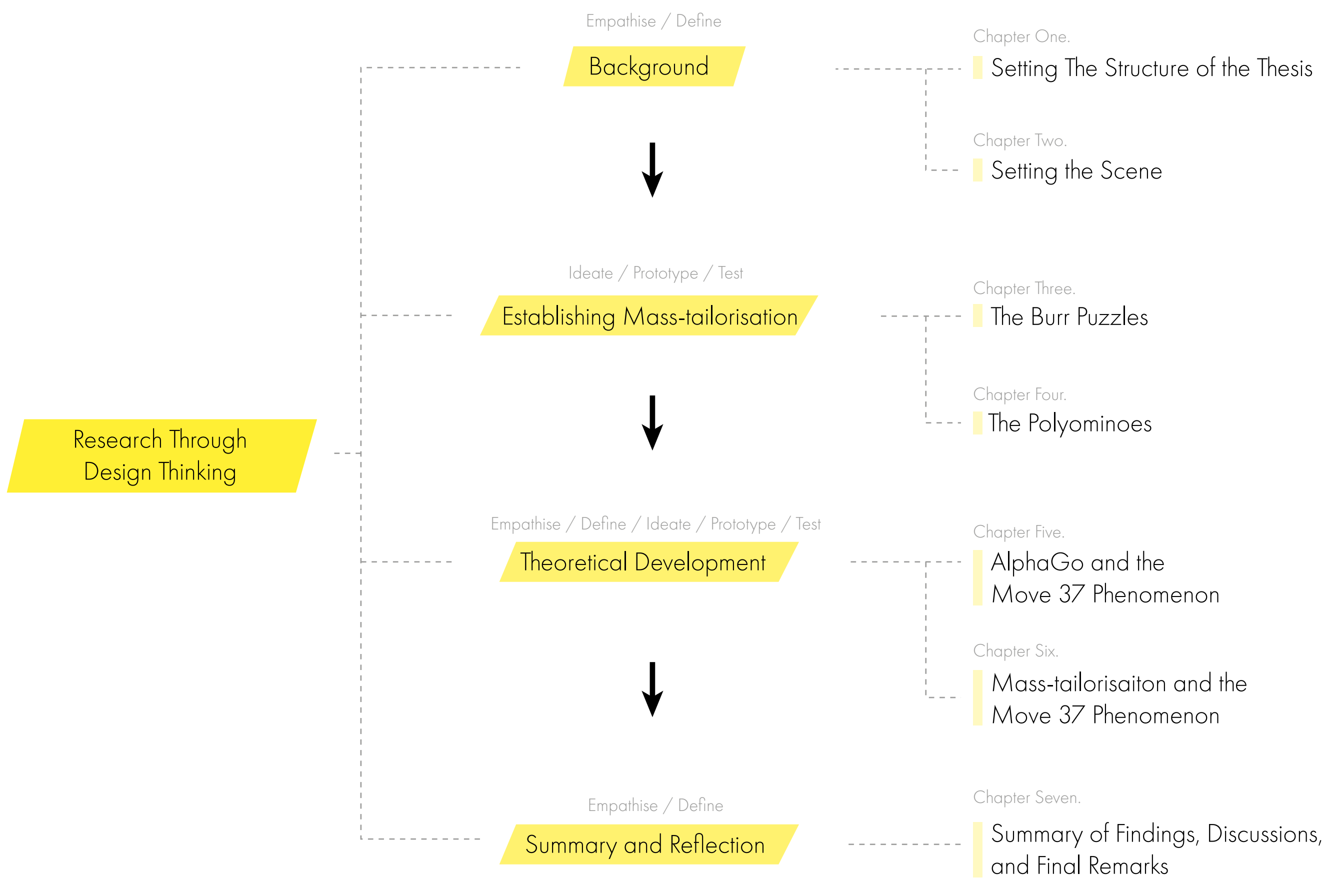

Figure 7. The structure and the research methodology of the thesis.

CHAPTER TWO.
SETTING THE SCENE.

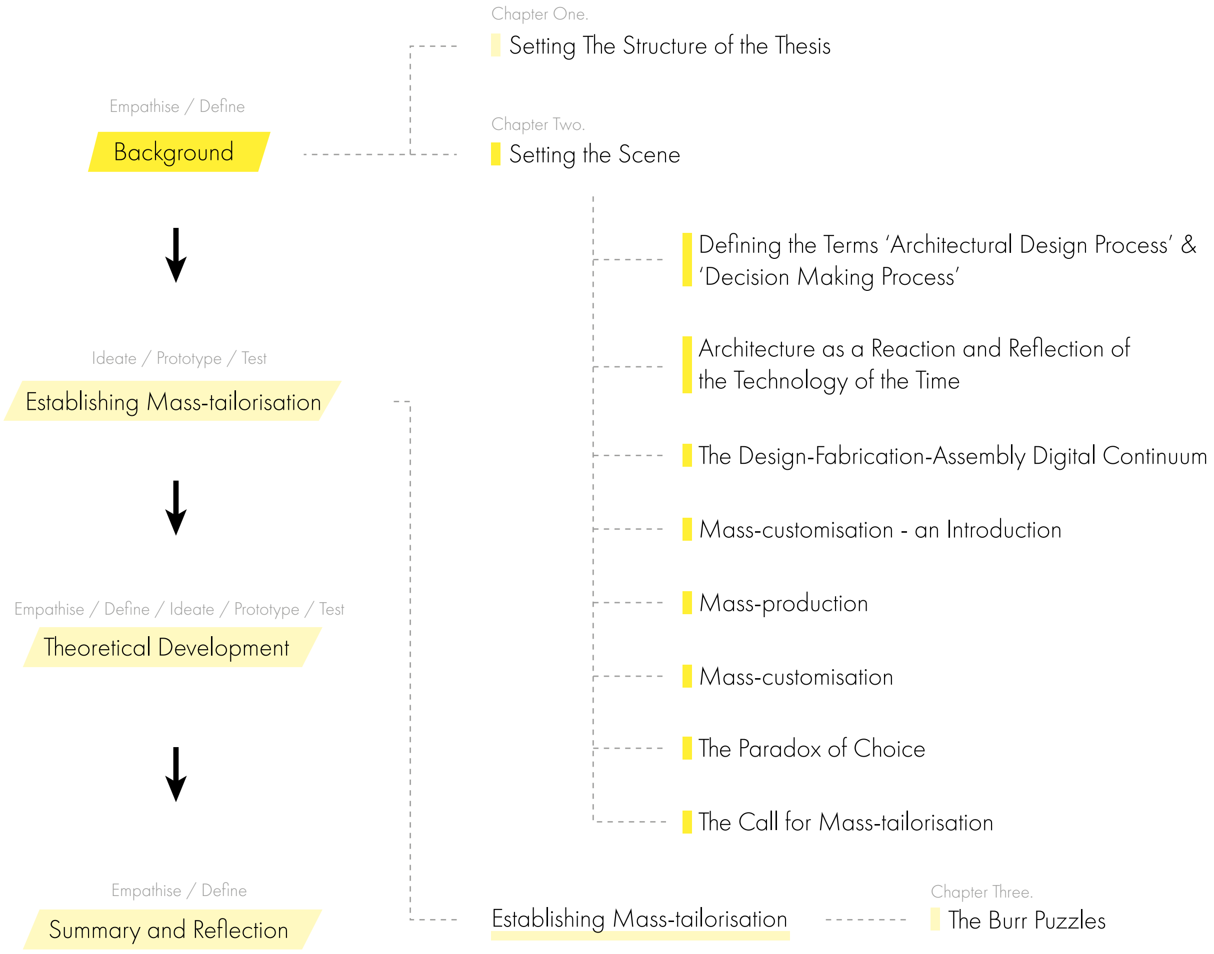

Figure 8. Chapter Two Structure.

"Well, well, I... to me – I... I mean, it's – it's it's all instinctive, you know. I mean, I just try to uh, feel it, you know? I try to get a sense of it and not think about it so much." – Annie Hall (from the screenplay by Woody Allen and Marshall Brickman) (Allen, 1982, p.40)

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Figure 9. Annie Hall and Alvy Singer.

"The decision-making process of the architect becomes ever-important in a world of unlimited possibilities but of limited realities."

Objectives addressed in this chapter:
1/ Undertake research into previous literature and case studies that address decision-making and design.
2/ Critically define mass-tailorisation as it pertains to architecture.

1. Defining the term 'Architectural Design Process' and 'Decision-making Process'

Design (verb) – to conceive and plan out in mind. To have a purpose. To devise for a specific function or end. To create, fashion, execute, or construct according to plan (Merriam-Webster. n.d.)

Decision-making (noun) – the process of making choices, especially important choices. (Cambridge Dictionary. n.d.)

An architectural design process is present in every architectural project. However, unlike the clearly identifiable architectural output, the process has often been portrayed as invisible, mysterious, or even random, being "romantically speculative about the power of vague ideas" (Winston, 1980, p.690).

Perhaps such perception is heavily influenced by architecture's relationship with the arts, and especially with the notion of the genius artist. Immanuel Kant stated that for "judging of beautiful objects as such[,] taste is requisite; but for beautiful art, i.e. for the production of such objects, genius is requisite" (1892, p.193). Under such notions, the idea of the architectural genius "became institutionalized through the legacy of nineteenth-century Romanticism and integrated as an unexamined attitude in architectural Modernism and Postmodernism" (Plowright, 2014, p.34).

However, should the architectural design process depend on the genius, the process of design cannot be taught or learned as it is inherent within the designer. While the instinctive traits of a genius cannot be fully negated from one's architectural design process, the strong characteristic of the master and the apprentice relationship in the field of architecture suggests that architectural design process can be identified, taught, and learned.

As such, in this thesis, the architectural design process does not embrace the genius. Instead, the thesis defines the architectural design process as the means of taking methodological steps to arrive at a conclusion (Plowright, 2014). However, such a definition does not intend to portray a formalised, disciplined, and codified steps for design. The architectural design process has "inherent ambiguity", where "anything is possible. The freedom to create is exhilarating" (Pressman, 2012, p. 19). However, even under such ambiguity, an architectural design process inhabits design methods; methods which are repeatable and recognised in producing results which should be able to be taught, learned, and if applied, has the potential to produce results (Plowright, 2014). Thus, the critical difference to the genius' architectural design process is the interpretability of the design methods amidst the possibility of ambiguity.

Furthermore, if the definition of the architectural design process rejects the notion of the undecipherable genius but embraces the methodological nature of design, the decision-making process of the designer that is conducted during the design process can also be interpreted, evaluated, and developed.

Contrary to the notion of the design process that provokes various definitions within the field of architecture, the term decision-making appears to inhabit a more consensual definition in architecture and other fields alike. The decision-making process in design can be described as constituting of three components that are objectives, alternatives, and evaluation (Kirk & Spreckelmeyer, 1988), or goals, alternatives, consequences (Roozenburg & Eekels, 1995). In a similar context, J. C. Jones, a first-generation researcher of the Design Methods Movement, outlined 'divergence, transformation, and convergence' as key types of thinking related to decision-making (1973). The process of decision-making has also been detailed in terms of actions: defining the problem, understanding possible reasonable solutions, taking action towards the goal, and evaluating the effects of the action (Orasanu & Connolly, 1993). Barry Schwartz, who first coined the term Paradox of Choice, outlines more detailed sequential actions of decision making. A good decision-making process consists of defining goals, the evaluation of the importance of goals, the array of options, the evaluation of options, the identification of the best option, re-evaluation of goals and their importance, and the evaluation of the evaluation methods (2016).

Upon the influences of such definitions, the thesis scopes the term decision-making into four key stages that can be interpreted, evaluated and developed. The four stages suggested by the author from the research above are the Determinant of Success, the Explorations of the Solution Space, the Selection of a Solution(s), and the Critique of Work.

The Determinant of Success: the evaluative criteria to function as a driver for the explorations of the solution-space, as well as the criteria held accountable for the Critique of Work stage.

The Exploration of Solution-Space: the process of generating various possible solutions to the evaluative criteria set in the previous stage.

The Selection of a Solution(s): the process of selecting one or more solutions from the explored options that are deemed to be most suitable to the evaluative criteria set at the beginning of the decision-making process (through The Determinant of Success stage).

The Critique of Work: evaluating the implications of the selected solution/s from the solution-space as a response to the set criteria, as well as the evaluation of the criteria itself.

Another aspect for consideration in the study of the decision-making process is the notion of screening. Most studies and discussions on the decision-making process assume that a selection will always be made from the set of explorable solution-space, thus, always leading to a decision at the end of the decision-making process (Beach 1993). Therefore, in the field of psychology, such assumption emphasises the importance of the notion of screening, "the process that governs admission of options to the choice set" (Beach, 1993, p.215). Studies show that the role of screening is to reduce the number of options in the solution-space in order to reduce the effort required by the decision-maker during the evaluation process (Olshavsky, 1979; Payne, 1976; Payne, Bettman, & Johnson, 1993). While the screening process and the decision-making process may seem similar in definition and process, it is in fact, quite different. The process of screening ensures that the options that will be admitted to the solution-space meet the lowest standard set by the decision-maker, whereas the decision-making process aims to meet the option/s that meets the highest standard set by the decision-maker (Beach 1993).

Upon the findings of the notion of screening as an additional and critical step prior to the decision-making process, the decision-making process that is referred to in the thesis will include the notion of screening. The importance of screening will be revisited later in the thesis.

2. Architecture as a Reaction and Reflection of the Technology of the Time

"... the architecture of modern times is characterised by its capacity to take advantage of the specific achievements of that same modernity: the innovations offered it by present-day science and technology..." - Ignasi de Sola Morales (1997).

For the purpose of this thesis, the context of 'architecture' was scoped to that of a reaction or reflection of the technology of the time.

Architecture has often reacted or reflected the technology of the time. Techne is the Greek root word for technology; meaning "the art of making". Thus, technology encompasses in "one single concept on the one hand the architectural meaning or idea and on the other hand the work or construction needed to realise it as a physical form". (Sánchez Vibæk, 2014, p. 23). Likewise, techne "not only designates tools and fabrication; it primarily signifies their place in the world of values" (Hartoonian, 1994, p.2). Furthermore, Heidegger explains that the term techne is associated with poiesis - a bringing forth, a revealing of something that was concealed. Heidegger explains that "what is decisive in techne does not lie at all in making and manipulating nor in the using of means, but rather in the ... revealing" (1977, p. 13).

This notion of technology that encompasses the craft and the poiesis can be found in its reflection or reaction in the development of architecture: In the Paleolithic age (the Old Stone Age), people were found to have settled in temporary natural shelters in accordance with the seasonal availability of food as nomadic hunter-gatherers. However, with the rise of the Neolithic age (the new Stone Age) that brought the advancement in tools – especially in agriculture – permanent shelters such as mud-brick houses covered in plaster began to develop, signalling the beginnings of permanent human settlements (Shane & Kucuk, 1998). The technological advancement of the Neolithic age brought about an architectural reaction.

This parallel relationship between architecture and technology can be found more recently as well. The Crystal Palace (Figure 10) is an example of the architecture being a reflection of the technology of the time. As the home for the Great Exhibition of 1851 that showcased the latest technologies of the Industrial Revolution, the Crystal Palace was in itself a reflection of the sheet glass technology that was introduced to Britain. At the time, Crystal Palace became the largest glass structure to have ever been constructed.

Redacted due to copyright reasons.

Figure 10. The front entrance of the Crystal Palace.

Today, this thesis argues that one of the most significant technologies of the time is in the vast volume of digital information, also known as data. In 2013, it was reported that 90% of the world's data was generated in the previous two years (SINTEF). More specifically, the technology of the time is in the advancement of the uses of information data in the physical and digital environments. The Fourth Industrial Revolution - also known as Industry 4.0 - is the industrial and technological shift that is currently taking place at this time. The unprecedented generation and application of information data allow for the revelation of new insights – the poiesis of our time. As such, the architecture of our time is expected to react and reflect such technology.

3. The Design-Fabrication-Assembly Digital Continuum

At the beginning of the 21st century, as the digital environment started to develop to a level that was accessible to the mass public, a new notion of architectural methodology was proposed. The notion of "a new digital continuum, a direct link from design through to construction, [that] is established through digital technologies" was implied (Kolarevic, 2003). Kolarevic later coins this idea as the 'Information Master Builder' (2003). In its essence, the Information Master Builder aims to create a direct digital link from design to fabrication and assembly, for the information data of the creation to be transferred and used in the digital environment throughout the process.

The incorporation of such Design-Fabrication-Assembly Digital Continuum proves to be an important factor in the development of architectural systems of modern times. As more of the information of human-made environments transition into the digital, in the field of architecture: "the ultimate goal becomes to construct a four-dimensional model encoded with all qualitative and quantitative dimensional information necessary for design, analysis, fabrication, and construction, plus time-based information necessary for assembly sequencing." (Kolarevic, 2003, pg.8).

Consequently, the act of designing, fabricating, and assembling is becoming more unified. The close relationship between design, fabrication and assembly, and the possibility of complete unification results in every architectural decision becoming more extensive in its influence within the digital continuum. More than ever before, decisions for design will have to consider fabrication and assembly, decisions for fabrication will have to consider design and assembly, and decisions for assembly will have to consider design and fabrication. Furthermore, the capability of the digital continuum to produce unprecedented volumes of design possibilities pose complex implications in the decision-making process of the designer. In this context, mass-tailorisation aims to play an essential role in providing a more focused decision-making process for the designer and the client.

4. The Call for mass-tailorisation.

To understand the motivation behind mass-tailorisation, it is helpful to study its preceding 'mass-manufacturing' systems.

4.1. Mass-Customisation; an introduction

Around the same time that the Design-Fabrication-Assembly Digital Continuum was introduced, the idea of 'mass-customisation' started to develop. Partly influenced by the continuously improving accessibility to the digital environment and a direct reaction to mass-production, mass-customisation aims to increase the variety of produced outputs without losing efficiency in the production process. This idea was first envisioned by Tuffler in his book *'Future Shock'* (1970) and later coined by Davis in his book *'Future Perfect'* (1996).

4.2. Mass-production

The Fordist paradigm of Mass-production is an economic concept birthed by the progressive development of standardisation, mechanisation, and automation that spanned the 19th and the 20th-century industrial revolution (Smith. 2019). The concept revolves around the idea of economies of scale – a cyclical process of greater production of standardised, mechanised, and automated units increasing repetition of manufacture, thus increasing the efficiency of the manufacturing system and reducing the cost per unit, which in turn encourages higher consumption that drives greater production yet again.

Redacted due to copyright reasons.

Figure 11. "You can have it in any colour, as long as it's black" - Henry Ford.

An example of mass-production in its full envisioned potential was the Ford Model T – the first affordable car to be produced. Henry Ford – considered to be a pioneer in mass-production - has explained the car as: "You can have it in any colour, as long as it's black" (1923, p.73) (Figure 11). Ford's explanation is an iconic statement that describes the essence of mass-production. By continually focusing on the repetition of the same output (black paint), the efficiency of the manufacturing system increases, enabling the decrease in the unit prices to an affordable level.

The advantages of mass-production was evident. Approximately 15 million cars were sold between 1908 and 1927, solidifying the automobile as an essential part of the American middle-class life.

However, although mass-production was an innovation that changed economics, it was not without its faults. In mass-production systems, due to the nature of the limited variety of outputs in exchange for low-cost prices, the user essentially has to meet the characteristics of the output to satisfy their design needs. The user can either decide not to acquire the product deeming that its predetermined characteristics do not sufficiently meet their needs or, acquire the output even if it does not fully meet their requirements, potentially compromising some of their needs (eg. "even though I want a red Model T, a black one is good enough"). This notion of compromise – labelled as 'customer sacrifice' – can determine the efficiency and effectiveness of a mass-produced output (Pine, 2019) (Figure 12).

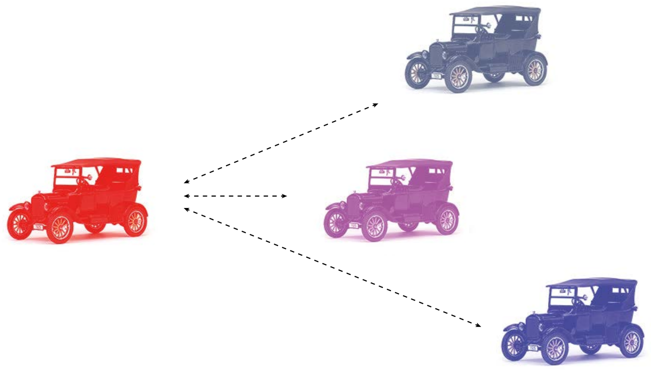

Figure 12. Customer Sacrifice - the gap between the wants of the customer and the products that are acceptable for the customer. Usually, the lesser the gap, the better the customer satisfaction.

4.3. Mass-customisation

Mass-customisation aims to increase the number of viable outputs while maintaining the efficiency established in the mass-production system. First delineated by Tuffler (1970) and coined by Davis (1996), the economic concept of mass-customisation began its emergence in the late 20th century as an advanced technological progression to mass-production. Pine, an economist who wrote extensively on mass-customisation, described mass-customisation as "the new frontier in business competition for both manufacturing and service industries. At its core is a tremendous increase in variety and customisation without a corresponding increase in costs." (1993, pg.xiii). If mass-production is achieved through economies of scale, mass-customisation is achieved through economies of scope – "the application of a single process to produce a greater variety of products or services more cheaply and more quickly" (Pine, 1993, p.48). Thus, the focus shifts from the output in mass-production to the manufacturing process in mass-customisation.

Applying the concept of mass-customisation to the Ford Model T, mass-customisation relieves the condition that Ford has put on the user. Unlike mass-production, mass-customisation explains to the user that "You can have the Ford Model T in any colour" (Figure 13). In mass-customisation, this statement is viable because mass-customisation at its best can increase the variety of outputs while retaining the efficiency of mass-production to keep unit costs down.

Figure 13. "You can have it in any colour".

4.4. The Paradox of Choice

While mass-customisation allows the increase in options for the output, the very concept of mass-customisation can also bring about a duality of opportunity and a problem. In the example of the Ford Model T, due to the potentially infinite possibilities of colour combinations, the user can be faced with the 'Paradox of Choice' - too many options leading to the difficulty of making a single choice (Schwartz, 2016) (Figure 14). Schwartz explains this phenomenon as:
"learning to choose is hard. Learning to choose well is harder. And learning to choose well in a world of unlimited possibilities is harder still, perhaps too hard" (Schwartz, 2016, p.148).

In his book, Schwartz contextualises the term Paradox of Choice in the context of consumer behaviour and wellbeing, stating that numerous options that lead to the Paradox of Choice cause consumer anxiety and diminish the happiness of the consumer. Schwartz maintains the view that by reducing the available options and setting good consumer strategies will lead to better consumer decisions, thus reducing consumer anxiety and increasing consumer happiness and wellbeing (2016).

In this thesis, while maintaining relevance to the original definition as defined by Schwarts, the term Paradox of Choice is modified to fit the architectural context. The thesis defines the Paradox of Choice as the difficulty of deciding due to too many possible options which contribute to poor decision-making. In the book, the term Paradox of Choice is mainly interested in its emotional effect on consumers. In this thesis, the term Paradox of Choice is interested in its effect on the decision-making process of the designer during the architectural design process.

The idea of the Paradox of Choice as a possible risk to mass-customisation has been identified previously. Notably, it has been identified that the advantages of having many options can be easily outweighed by the cost of evaluating those options (Piller, 2019 & Kolarevic, 2019).

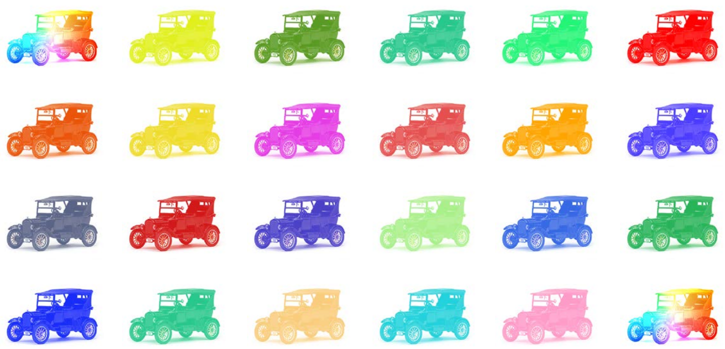

Figure 14. The Paradox of Choice.

4.5. Why the Paradox of Choice resembles a poor Decision-making Process

Experiencing the Paradox of Choice leads to, and reflects, a poor decision-making process.
In the four stages of the decision-making process identified in the previous chapter, the Paradox of Choice phenomenon is most likely to be experienced in the Selection of a Solution(s) stage when the possible solutions generated in the Exploration of Solution-Space stage needs to be narrowed down.

Schwartz explains that one cannot assess an option in isolation from the alternatives (2016). Therefore, the Selection of a Solution(s) stage requires the designer to select the option/s from the solution-space that is deemed to be most suitable to the evaluative criteria set at the Determinant of Success stage at the beginning of the decision-making process. The clearer the evaluative criteria are, the more differentiated the various possible solutions become. Likewise, if the evaluative criteria have not been set with sufficient clarity, the differences between the possible solutions become unclear or insignificant. When there is not a significant difference between two possibilities, the two lose their characteristics as alternatives to each other. As such, experiencing the Paradox of Choice reflects unclear evaluative criteria, thus *reflecting* a poor decision-making process.

Furthermore, once the Paradox of Choice has been experienced during the selection stage, it is more likely for one to select a solution/s irrationally or even randomly as their ability to differentiate between two or more options are diminished. Therefore, experiencing the Paradox of Choice also *leads to* a poor decision-making process.

4.6. The Call for Mass-tailorisation

The vision of mass-tailorisation is to resolve this Paradox of Choice. If mass-customisation increased the outputs of a mass-produced system to allow numerous varieties, mass-tailorisation narrows the output of the mass-customised system to a select few that best represent the user's needs or desires. In the context of the Ford Model T, mass-tailorisation explains to the user that "You can have it in any colour – but as you are after a family car, a blue, green, or red car will be the best. So which one would you like to choose?" (Figure 15). Like mass-customisation, mass-tailorisation can create a potentially near-infinite number of outputs, however, by incorporating a specific contextual context – a family car for example – mass-tailorisation narrows the outputs to a select few that best meets the specified design context. The user is still able to make a choice, even outside the tailorised outputs. However, through the incorporation of specific contextual criteria, mass-tailorisation allows the user to have more control over their own decisions while ensuring that those decisions are beneficial to the design context in question.

Architecturally, the need for mass-tailorisation is evident. The advancement of tools and technologies available to architects has increased the capacity of the designer to create more with fewer resources – such as with the case of Greg Lynn's Embryological House (Refer to pg. 5). Such developments provide excellent variety; however, more often than not, the practicalities of architecture only allow for a select few to be realised to completion. Thus, the decision-making process of the architect becomes ever-important in a world of unlimited possibilities but of limited realities.

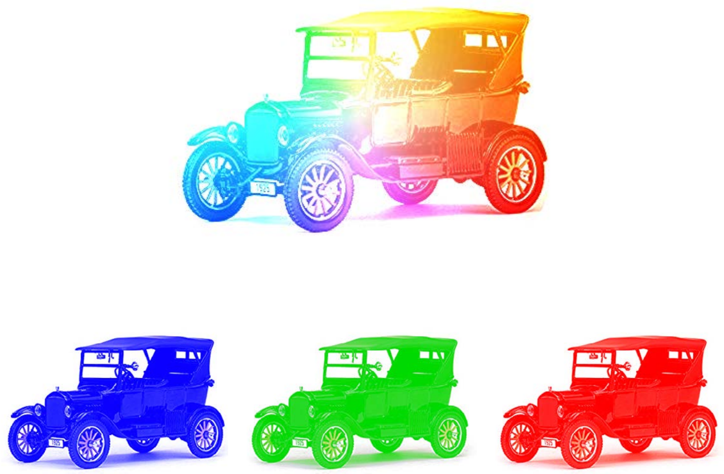

Figure 15. "You can have it in any colour – but as you are after a family car, a blue, green, or red car will be the best. So which one would you like to choose?".

5. Shape Grammar

Finally, the idea of Shape Grammar is worth noting. It was first introduced by Stiny and Gips through the means of offering a "generative specification of a class of paintings or sculptures" (Stiny & Gips, 1971, pp.1460). Since then, Shape Grammar has been studied extensively in the field of architecture. Generally, Shape Grammar in architecture is considered as a method of design that uses a set of rules to create a combinatorial design language that enables designers to generate few to endless design variations in less time than a more traditional method of design (Eloy & Duarte, 2014).

Lynn's Embryological House (1999) is, in essence, an exercise in Shape Grammar. Each of the 50,000 iterations generated by Lynn constitutes seven spline curves that were defined in combinations to define the exterior envelope of a house (Lynn, 2019). As a method of generating several design possibilities for the same design problem, Shape Grammar harbours the characteristics of mass-customisation (Eloy & Duarte, 2014).

More recently, as the limitations of having numerous design variations were highlighted through means such as the Paradox of Choice, the need for a methodological approach to navigating the design variations has been identified. In such a context, the role of 'evaluation' has been emphasised in the Shape Grammar design systems as a means of navigating through the numerous design variations (Duarte, 2019). A clear means to evaluate the performance of the design is needed to manage the numerous design variations that can be generated by Shape Grammar.

6. Conclusion

Identifying the architectural design process as a methodological process allows the potential for the use of tools external to the designer to enhance the design process. As such, identifying architecture as a reaction and reflection of the technology of the time provides the opportunity to use digital tools and information data as drivers for the architectural design process of modern times. However, the use of digital tools has brought about opportunities and problems alike. In the design process, the generation of design iterations has become more efficient and accessible through various digital means such as mass-customisation and Shape Grammar, but it has also posed the risk of the designer experiencing difficulties in the decision-making process - notably through the Paradox of Choice. The aim of mass-tailorisation is to aid the designer in such an ordeal.

ESTABLISHING MASS-TAILORISATION

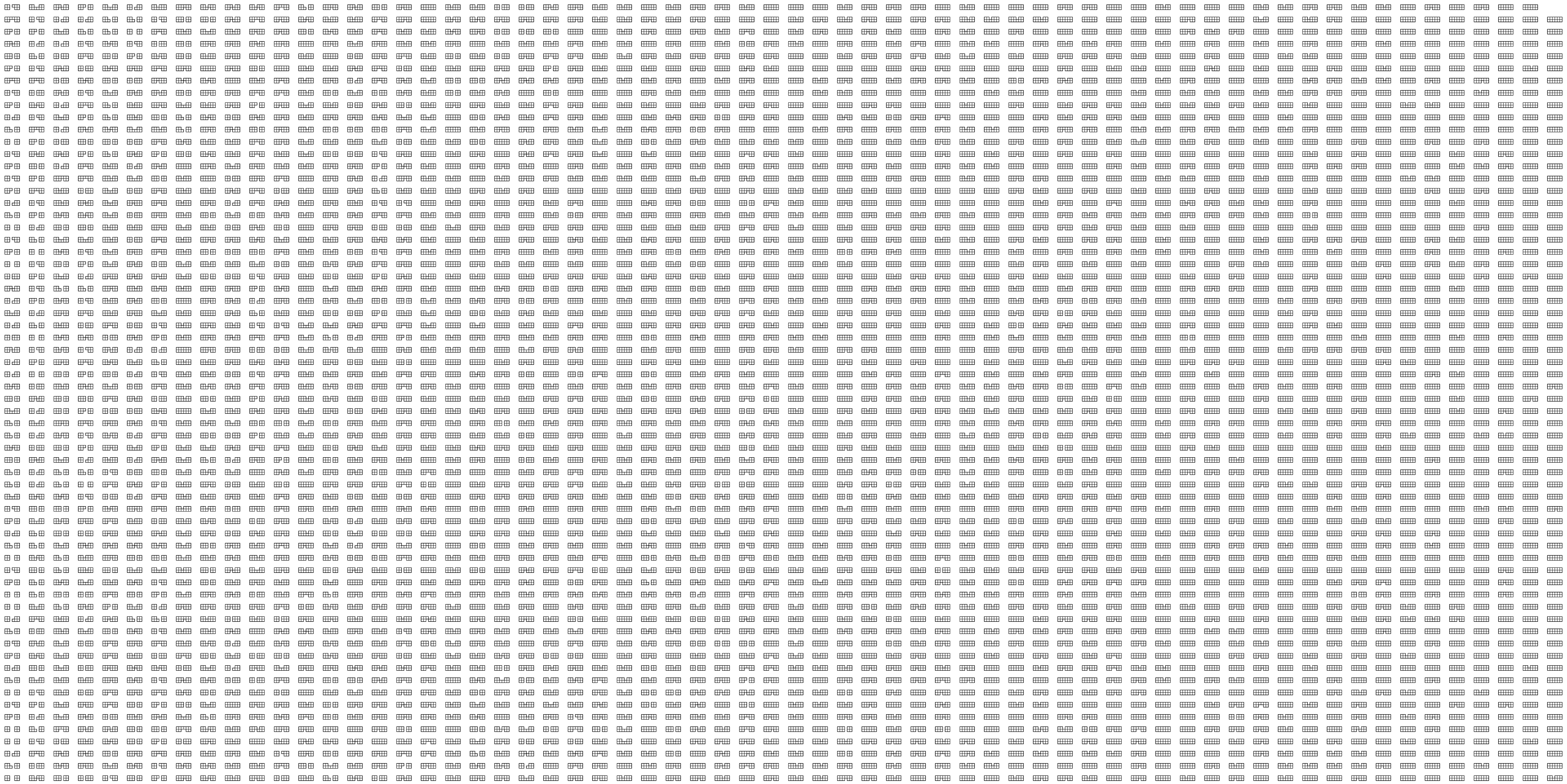

Figure 16. 4096 Pieces.

CHAPTER THREE.

THE BURR PUZZLE.

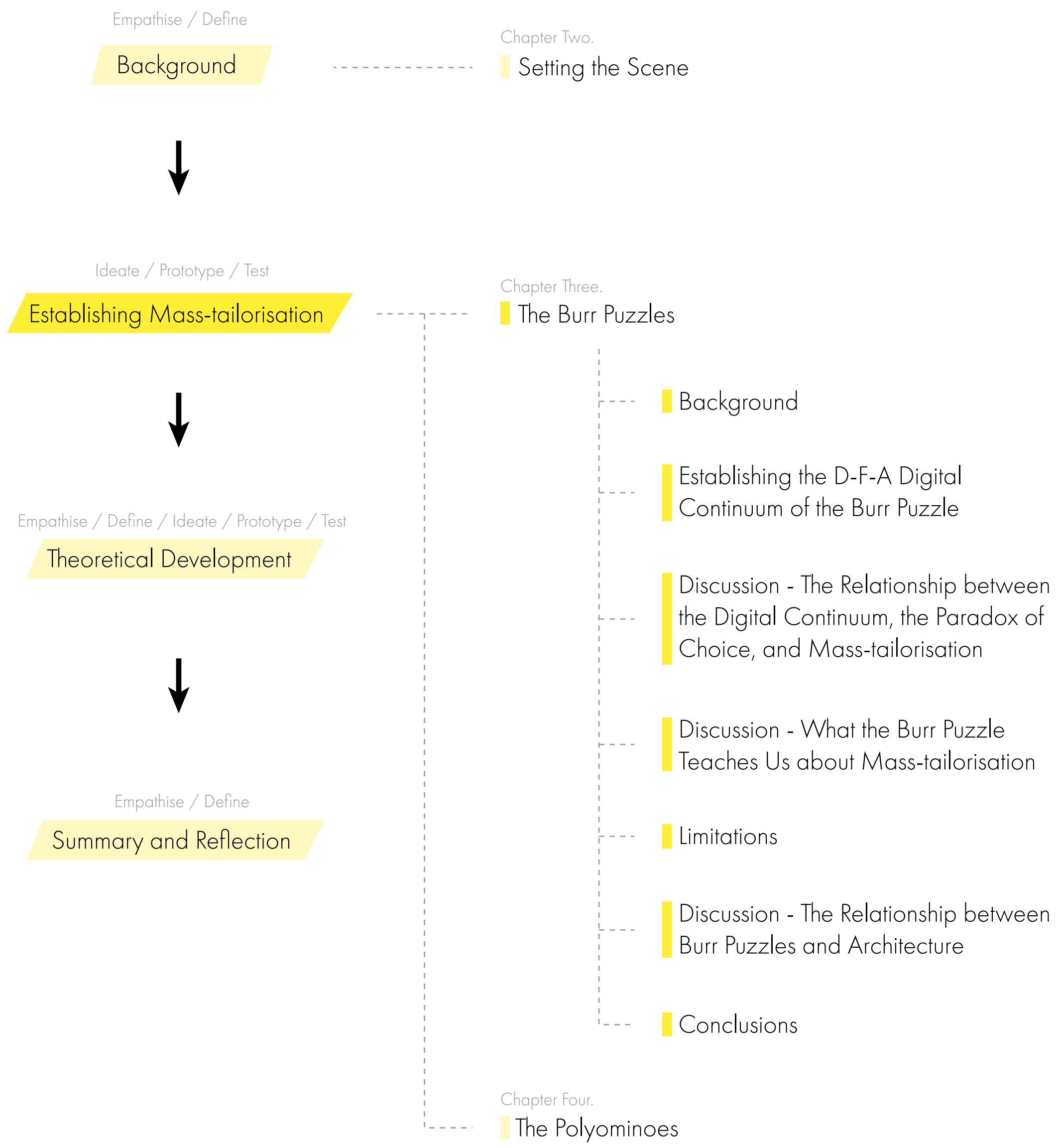

Figure 17. Chapter Three Structure.

"Ironically, while the Paradox of Choice is not welcomed, an increased solution space is appreciated."

Objectives addressed in this chapter:

2/ Critically define mass-tailorisation as it pertains to architecture
3/ Undertake research into literature and case studies relevant to establishing a digital continuum of mass-tailorisation
4/ Establish a Design-Fabrication-Assembly Digital Continuum for mass-tailorisation.

1. Background

Due to the complexity of the near-infinite possibilities in architecture, the research of the potential for mass-tailorisation within the Digital Continuum of architecture needs to begin at a smaller, definable scale. In order to test these ideas, the Burr puzzle was chosen as the first case study. More specifically, the six-piece Burr puzzle was chosen as a case study for developing the basis for a mass-tailorised system through a Design-Fabrication-Assembly digital continuum. The puzzle provides complexity in all three stages of its own Design-Fabrication-Assembly to warrant as an analogy to the complexities of buildings that is within a manageable scope for the research. The analogy of the Burr puzzle is discussed further towards the end of this chapter.

The six-piece Burr puzzle is regarded as the most common three-dimensional puzzle. It consists of six interlocking assemblies of notched pieces arranged symmetrically in three mutually perpendicular intersecting pairs (Coffin, 1991) (Figure 18). Each piece of the puzzle must be of equal length and must not be less than three times its width. The complexity of the Burr puzzle gained significant interest among

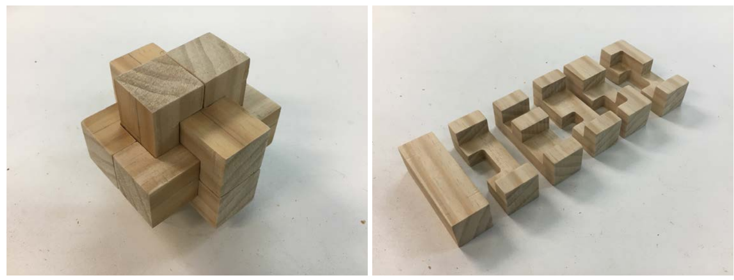

Figure 18. An iteration of a Six-piece Burr Puzzle (assembled & disassembled).

mathematicians and computer scientists in the late 20th century, resulting in significant findings in regards to the puzzle (Coffin, 1991).

In the six-piece Burr puzzle, every piece of the puzzle can consist of up to 24 cuboids in a 6(L)x2x2 proportion. Of the 24 cuboids, every piece will always consist of 12 cuboids, six on each end of the piece forming an 'L' shape. The remaining central 12 cuboids become the variables; each piece may have none to all of the 12 cuboids, or any permutation in between. As such, these iterative permutations define the characteristics of each piece (Figure 19).

Using Grasshopper – a visual scripting software based in the 3D modelling software Rhinoceros 3D – the permutation logic was applied and resulted in 4096 various pieces (Figure 16). However, to ensure that the puzzle consists of only six pieces, any piece that was split into two or more parts was eliminated to reduce the number of valid pieces to 2225 (Figure 20). Eliminating symmetrical pieces further reduces the pool to 837 (Coffin, 1991). In theory, various combinations within this pool are able to create various versions of the puzzle. However, only a select few iterations of the complete and successful versions have been preserved and labelled as the 'Burr puzzle' overtime.

2. Establishing the design-fabrication-assembly digital continuum of the six-piece Burr puzzle through rapid, agile prototyping for proof of concept.

This case study aimed to establish the design-fabrication-assembly digital continuum for the six-piece Burr puzzle. As discussed in the previous chapter, the digital continuum plays a critical role in the idea of mass-tailorisation (Refer to pg.25-26). Therefore, the possibility, as well as the validity, of establishing a digital continuum for a six-piece Burr puzzle was required and tested before the idea of mass-tailorisation could be explored for the Burr puzzle.

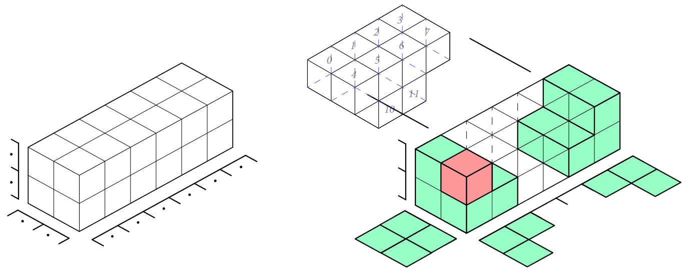

Figure 19. Breakdown of a single Burr puzzle piece.

Figure 20. 2225 Pieces after eliminating invalid pieces.

2.1. The Design-Fabrication-Assembly Digital Continuum

2.1.1. Design

To design the Burr puzzle within a digital continuum, an algorithm selects six pieces to determine whether the selected pieces in their defined sequential order and placement can form a constructible Burr puzzle. Once the algorithm has found six pieces in a specific order and placement that can form the Burr, it has designed an iteration of the Burr puzzle (Figure 21). Many studies have been conducted to calculate how many iterations of the Burr puzzle are possible. While the exact number of solutions is yet to be calculated, it has been estimated that there are up to 71.3 billion iterations of Burr Puzzles (35.65 billion if mirrored puzzles are disregarded) (Cutler, 1994). The aim of this case study is not to design all the possible iterations of the puzzle, instead establish a continuous digital continuum that can be used as the foundation of developing a mass-tailorisation system.

For rapid and agile prototyping in Phase 1, the digital information of the most common version of the Burr puzzle was used instead of a complete algorithm that searches through the pool of puzzles to find an iteration of a single puzzle. The main reason behind this decision was to allow for the quick establishment of a digital continuum as a minimum viable product following the research methodology of Design Thinking. (Refer to pg.16)

The complexity and the implications of the Design stage is discussed later in this chapter.

2.1.2. Fabrication

Once the algorithm has designed an iteration of the Burr puzzle, this digital information can be used for digital fabrication using digital tools such as Computer Numerical Controlled milling machines or industrial robots. Digital fabrication allows for greater freedom in the fabrication of Burr puzzles. Traditionally, only a pool of 59 pieces labelled as 'notched pieces' was preferred as these were the only pieces that could be easily notched using a saw or a dado blade. Other pieces that included blind corners and edges required additional labour such as chiselling or joining several sections together to form a single piece (Coffin, 1991). This process required greater intricacy in the craft as functional and aesthetical deficiencies were more likely; hence these pieces were less preferred. However, with the advent of digital fabrication technologies, these limitations are no longer the case. Digital fabrication technologies provide more control and capabilities than traditional hand tools. Its flexibility, adaptability, and intricacy provide new ways of fabrication that is different from human fabrication. Therefore through the use of digital fabrication, the human fabrication limitations are removed, allowing

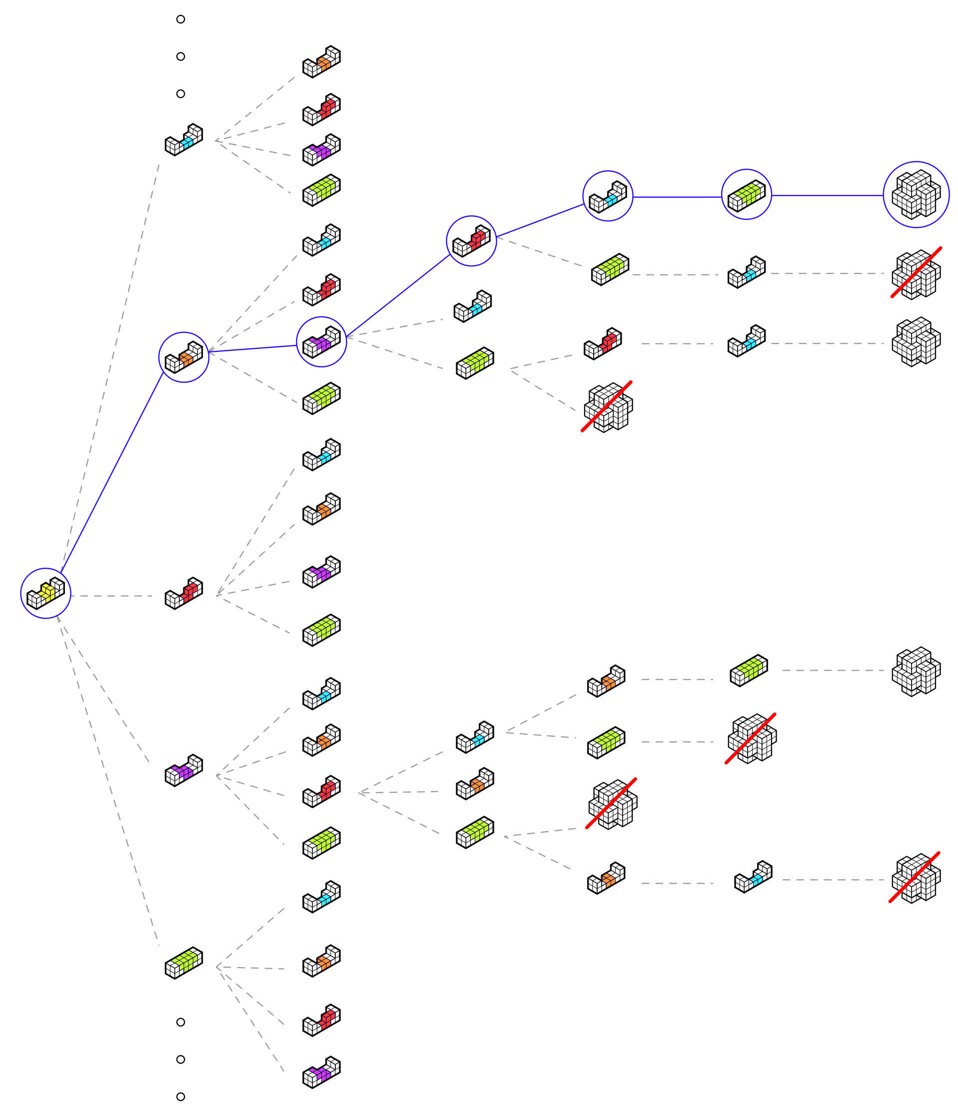

Figure 21. A diagrammatic representation of an algorithmic design process.

Figure 22. The digital fabrication process of a six-piece Burr puzzle using a CNC machine.

all the pieces to be considered of equal preference and produced with more efficiency (Figure 22). The preferred pieces are no longer unwillingly limited to 59 pieces but expand to 2225, consequently unlocking the potential to fabricate all of the estimated 71.3 billion possible puzzle iterations.

2.1.3. Assembly

Once the Burr puzzle pieces have been digitally fabricated, the same digital information that fabricated the pieces can be used for digital assembly (Figure 23). While the purpose of puzzles is to challenge the users in the assembly of the pieces, the goal in this case study was to allow for quick and easy assembly, simulating the complexities of architectural assembly and construction on a small scale, and testing whether digital assembly is able to efficiently and effectively aid in its process. The Microsoft Hololens, an augmented reality headset, along with Fologram, an augmented reality plugin for Grasshopper, is used for the assembly section of the digital continuum. Using the Hololens, the user is able to see a step-by-step interactive holographic demonstration alongside the physical puzzle pieces in real-time (Figure 24). Without the aid of digital assembly, the assembly of an unfamiliar iteration of the Burr puzzle could take several hours or even longer. However, through the use of augmented reality, the assembly time for any iteration of the puzzle reduces to under ten minutes.

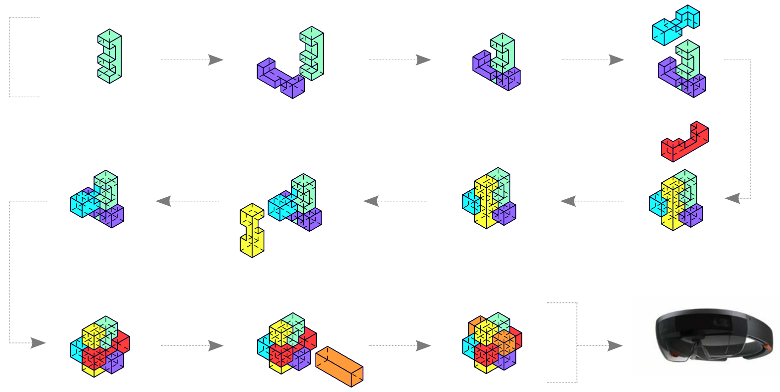

Figure 23. A step by step assembly process can be transferred to an augmented reality headset.

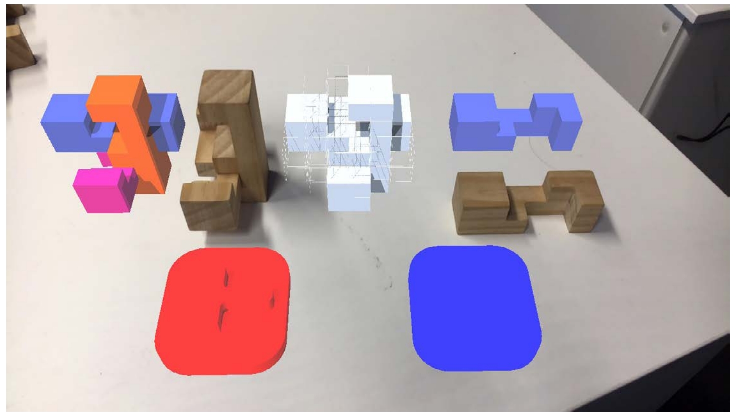

Figure 24. Augmented reality view of the step by step assembly process.

3. Discussion - The relationship between the Digital Continuum, Paradox of Choice, and Mass-tailorisation

The testing of a Design-Fabrication-Assembly Digital Continuum is now complete and successful as a proof of concept. However, the establishment of the Digital Continuum does not necessarily result in a mass-tailorisation system. In fact, it was discovered that it has the potential to further complicate the Paradox of Choice.

3.1. Mass-production, Mass-customisation, and Mass-tailorisation of the six-piece Burr puzzle

When the Digital Continuum is able to generate one iteration of the Burr puzzle repeatedly, a mass-production system is established. Likewise, when the continuum is able to generate variations of the Burr puzzle using the pool of pieces, a mass-customisation system is established. One can design, fabricate, and assemble different variations of the Burr puzzle without compromising the efficiency and effectiveness of the process because every variation satisfies the requirements for the Burr puzzle in the Digital Continuum. However, it is at this point that the shortfall of mass-customisation can be seen within this context, explained through an illustration below:

Should the digital continuum be able to create all of the estimated 71.3 billion iterations, there is no clear and logical method for the user to select one output over another. This is because each of the puzzle pieces did not have specific design contexts beyond its role as a burr puzzle piece. Due to the context-less nature of the pieces, the designed puzzles become context-less beyond its Burr design. Thus, **no puzzle can become more 'valuable' than the other as all designed puzzles are now 'only' Burr puzzles**. This leaves the selection of a single Burr puzzle to a near-random selection based on inefficient, ineffective reasoning. The user has experienced the paradox of choice and has lost control of the decision-making process.

To help address this problem, mass-tailorisation aims to add additional layers of specific design context to the Burr puzzles to essentially 'cull' the numerous designed outputs based on weighted criteria. Through this process, the outputs are able to be ranked in their 'value' against its response to the given design context. For example, a mass-tailorised algorithm will be able to apply specific design contexts such as 'the easiest to assemble', 'the easiest to fabricate', or even 'the most aesthetically pleasing' if those criteria can be quantified by the designer. Through these additional layers, the outputs can be evaluated in its relative degree of response to the specified design contexts. The designer and the client become more engaged and gain an added understanding of the properties of each output, aiding in their decision-making through a quantified evaluation of the specific context criteria.

Therefore, the establishment of the Digital Continuum has theoretically allowed access to all 71.3 billion variations. In this sense, as things stand, the Digital Continuum has brought a greater Paradox of Choice upon the Burr puzzle. More specifically, the Digital Continuum has created a mass-customisation system which results in a greater Paradox of Choice upon the Burr Puzzle. While this may seem like a counter-intuitive step towards mass-tailorisation, the need for a mass-customisation system within mass-tailorisation is evident. The ironical relationship between mass-customisation and mass-tailorisation is explained below:

3.2. The more solution space there is, the more specific the tailorisation can occur.

An interesting relationship exists between mass-customisation and mass-tailorisation. As mass-tailorisation is a reaction to mass-customisation, the more comprehensive the mass-customisation system is, the more comprehensive the reacting mass-tailorisation must be.

The shortfall of mass-production was customer sacrifice - limited outputs to serve a variety of needs. Mass-customisation addressed this by providing a variety of outputs to serve a variety of needs - customer sacrifice is reduced, but the risk of experiencing the Paradox of Choice increased. Mass-tailorisation addresses the Paradox of Choice by tailorising the variety of outputs to a select number that meets specific needs. Because the user is presented with limited outputs, it may bear similar characteristics to that of mass-production. Consequently, customer sacrifice might re-present itself in the process. Hence, to reduce the amount of customer sacrifice in the tailorised outputs, the total number of mass-tailorisable outputs needs to increase. Therefore, the more mass-customised outputs there are, the less risk of customer sacrifice in mass-tailorisation.

Simply put, the larger the variety of outputs created by mass-customisation - otherwise known as solution space - the better the select number of outputs can be tailorised in mass-tailorisation, reducing customer sacrifice. Hence, ironically, while the paradox of choice is not welcomed, an increased solution space is appreciated.

4. Discussions - What the Burr puzzle teaches us about mass-tailorisation.

If mass-tailorisation is the filtering of numerous outputs through a biased specific design context, it can be claimed that the grouping of the 59

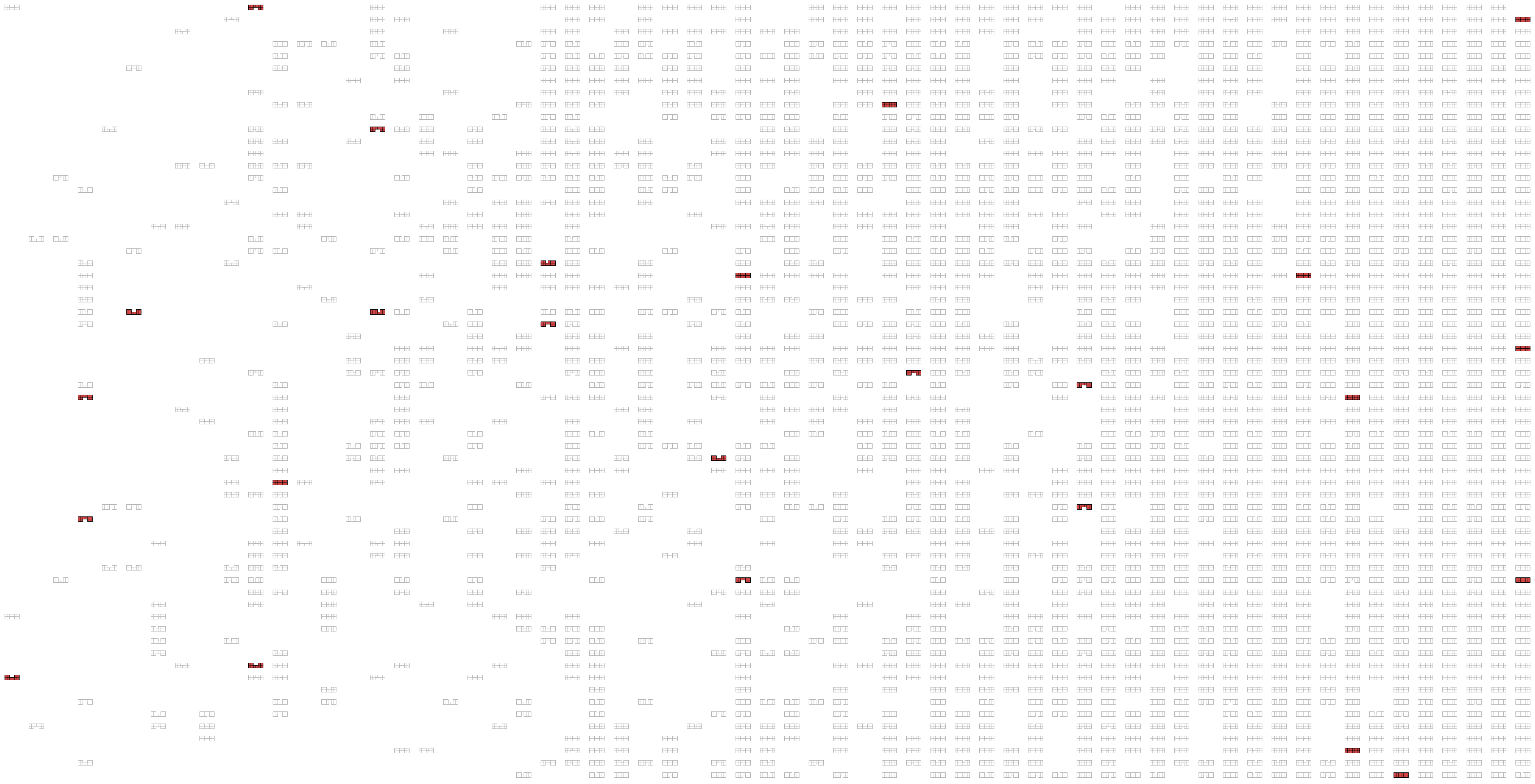

Figure 25. The 25 Notchable Pieces.

notchable pieces was an unintended beginning of mass-tailorisation for the Burr puzzle. This is because culling the pool of pieces due to limitations in fabrication significantly reduced the number of possible variations of the puzzle. Perhaps it could be speculated that this is an early version of mass-tailorisation where the ranking/filtering occurs in its most primitive form - as a binary condition to the fabrication limitation of the time. The specific contextual criteria being "a burr puzzle that can be made from the 59 notchable pieces because those pieces are the only pieces that can be fabricated".

In this context, the research aims to generate controlled and purposeful mass-tailorisation systems that are not formed by the limitations of technologies but aided by the technologies of the time.

Interestingly, the traditional Burr puzzle has another group of pieces that has the characteristics of mass-tailorisation. Traditionally it was customary for a Burr puzzle to be only solid - having no internal voids. Therefore, if only solid Burr puzzles are considered, there are only 25 notchable pieces out of the 59 notchable pieces that can satisfy this specific design context; these are known as the '25 Notchable Pieces' (Figure 25). Using these 25 notchable pieces, there are 314 solid Burr puzzle variations that can be formed. In this example, the purposeful decision for a specific aesthetic has culled the number of variations for the Burr puzzle, which in turn, culled the number of pieces in the pool. A critical difference between this example and the 59 notchable pieces is that the '25 Notchable Pieces' begin to mass-tailorise due to design intentions rather than design limitations. Furthermore, and perhaps more importantly, a critical holistic difference between the two groups of pieces is that the '25 Notchable Pieces' mass-tailorised the Burr puzzle through the design output (the burr puzzle has to be solid), whereas the 59 notchable pieces mass-tailorised the Burr puzzle through the design inputs (the puzzle pieces need to be able to be fabricated using hand tools).

In this sense, it can be speculated that mass-tailorisation could be achieved at both ends of the 'creating process'. Like the 59 notchable pieces, a mass-tailorised burr puzzle system could work at the design input stage by grouping a select few pieces that respond to specific design contexts (eg. pieces that are easiest to fabricate, pieces that are most aesthetically pleasing). Alternatively, the mass-tailorised system could also work at the design output end of the process (the variations of the Burr puzzle) that respond to the specific design context in its entirety. For example, **the six most aesthetically pleasing pieces (design input) that form a single version of the Burr puzzle might be well different from the most aesthetically pleasing version of the Burr puzzle (design output). Therefore, it can be speculated that the idea of mass-tailorisation can be applied to various stages of the 'creating process' spanning from the design input stage to the final output stage.**

5. Limitations

While researching the Burr puzzle, it was soon apparent that the scope of the information needed to establish a mass-tailorisation system was much broader than the initial investigations suggested. More specifically, the management of large volumes of data has been identified to be a critical factor that needs to be addressed and carefully maintained throughout the research process. The Burr puzzle is essentially a complex permutation of several layers that can quickly populate to exponential volumes of data.

Currently, for the algorithm to solve the puzzle using a pool of pieces, 'cuboid0' (red cuboid in Figure 19) of each piece is assigned as the origin, and all other cuboids of the piece – referred to as the piece cuboids - are referenced on their vector relationship to the origin. This reference system creates a unique relationship identifier for each piece.

The assembled Burr puzzle consists of 104 cuboids – these are referred to as the puzzle cuboids. As the assembled Burr puzzle has a pre-defined form, each puzzle cuboid is also location-specific. This means that while each of the six pieces may consist of up to 24 cuboids, the sum of the six pieces' cuboids must equal to 104 and each piece cuboid must only match with one puzzle cuboid.

The algorithm aims to place each piece within the boundaries of the assembled puzzle. Through an iterative process, the origin of the puzzle pieces is matched to each of the puzzle cuboids to identify whether the piece will fit within the boundaries of the puzzle. Depending on whether the rest of the piece fits, the algorithm either retains (does fit) or discards (does not fit) the specific iteration. This exercise is conducted for each piece on every puzzle cuboid available in order to determine all the possible locations that the piece can fit within the puzzle. For example, the first piece – regardless of what piece it may be – will be tested 104 times; each of the 104 puzzle cuboids assigned to host the origin of the piece.

Once this exercise has been done for the first piece, the same process is repeated for the next piece, albeit the puzzle cuboids occupied by the first piece and each subsequent piece will be removed from the list of possible puzzle cuboids to test. This results in high volumes of data that each contains unique positions for each puzzle piece. Combining this logic, with the permutation logic for the selection and assembly order of the six pieces quickly results in an exponential increase in data that has to be carefully managed.

This exponential growth of data can be explained through a permutation factorial logic that is:
n! / (n - r)!
Where: n = the total number of puzzle cuboids; r = the total number of pieces.

Applying this equation to the Burr puzzle algorithm that only uses six pieces as its pool, there is a minimum of 1.09 x 10^12 various origin locations from which the pieces can be tested.

If only a pool of six pieces were used, there are 720 various sequential combinations that the puzzles can be calculated from. Each and every one of these combinations has 1.09x10^12 testing possibilities if it were to be tested using brute force calculations.

Therefore, with a pool of 2225 pieces, there are approximately 120,517,426,290,000,000,000 various sequential combinations with 1.09x10^12 testing possibilities for each combination. Theoretically, this leads to 71.3 billion variations of the Burr puzzle and an even larger number of invalid variations that have to be calculated. As is evident by the magnitude of the possible Burr puzzle combinations, careful attention needs to be paid to ensuring the manipulation of the data is controlled. At the time of the research, maintaining control of the data required significant technical investment and as such further development of the Burr puzzle was beyond the scope of this thesis.

Due to the magnitude described above, the sheer volume of data that has to be processed was hindering the performance of the visual scripting software Grasshopper and has proven to be a significant barrier to the progression of the research. Therefore, the possibilities of incorporating artificial intelligence – specifically, machine learning through evolutionary computation was suggested at this stage of the research. As evolutionary computation deals with the processes of selection (pieces) and reproduction (variations on piece combinations and positions) based on the performances defined by a specific environment (an assembled Burr puzzle), this method of computation may be able to calculate the designs more efficiently (Spears et al., 1993).

An interesting point to note is the concept of 'fitness' in evolutionary computation. Each evolutionary algorithm is based upon performance criteria defined by a specific environment. Therefore, the better an individual data point 'fits' within the performance criteria of the environment, the higher its 'fitness' becomes. This process holds very similar characteristics to that of the 'specific design context' that is applied in mass-tailorisation. **The 'specific design context' that is being applied in mass-tailorisation is essentially a performance criterion given to the environment that is the Burr puzzle. In this sense, it could be speculated that the development of mass-tailorisation is highly dependent on artificial intelligence. Furthermore, it may be that the transition towards artificial intelligence has already initiated the continual development of mass-tailorisation.**

6. Discussion - the relationship between Burr puzzles and architecture; looking at the bigger picture

Architecture creates complex fields of possibilities and variations to any given design context upon which every decision-making process occurs. In this context, the Burr puzzle played an important role in the pursuit of an efficient and effective decision-making process through both the Digital Continuum and in turn, mass-tailorisation. The puzzle provides a balance between the need for the fair representation of the complexities in architecture and the need for a manageable research scope. Unlike the possibly infinite variations in the design, fabrication, and assembly (D-F-A) of buildings, the Burr puzzle has finite solutions. However, the scope of the solutions is too large to allow for an effective and efficient decision-making process. Hence, the finite 'solutions' are in-fact only 'possibilities' to the user. The development of mass-tailorisation allows for an effective and efficient decision-making process that will transform the mass 'possibilities' of the puzzle to a set of intentionally bias 'solutions' that consequently become the responsive outputs to specific design contexts. Therefore, through the investigation of mass-tailorisation of Burr puzzles, the ideas of mass-tailorisation can be tested within a controlled environment while maintaining its connection to the original intent that is the Design-Fabrication-Assembly Digital Continuum of architectural design and processes.

7. Conclusion

The case study identified the six-piece Burr puzzle as a research analogy to the complexity of architectural design through its complex but finite scope. Through the case study, it was revealed that the establishment of a Design-Fabrication-Assembly Digital Continuum was possible and could remove existing limitations that limit the number of possibilities of Burr puzzles.

Perhaps most importantly, the case study revealed that while the Paradox of Choice is unwanted, a large solution-space is appreciated for its ability to provide a finer mass-tailorisation system. Furthermore, it was found that mass-tailorisation can occur at various stages of the creating process ranging from design inputs to design outputs.

Finally, the case study revealed that efficient data computation and management is integral to the development of mass-tailorisation. Consequently, an off-the-shelf visual scripting software did not provide an efficient and effective development environment for the mass-tailorisation of Burr puzzles. Therefore, the need to create a tailored development environment through programming and the possible use of artificial intelligence has been identified by the research. This shift to a more flexible development environment provides greater potential for adaptability in subsequent research, allowing for easier transitions to architectural contexts in future.

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Figure 26. All possible arrangements for a Monomino.

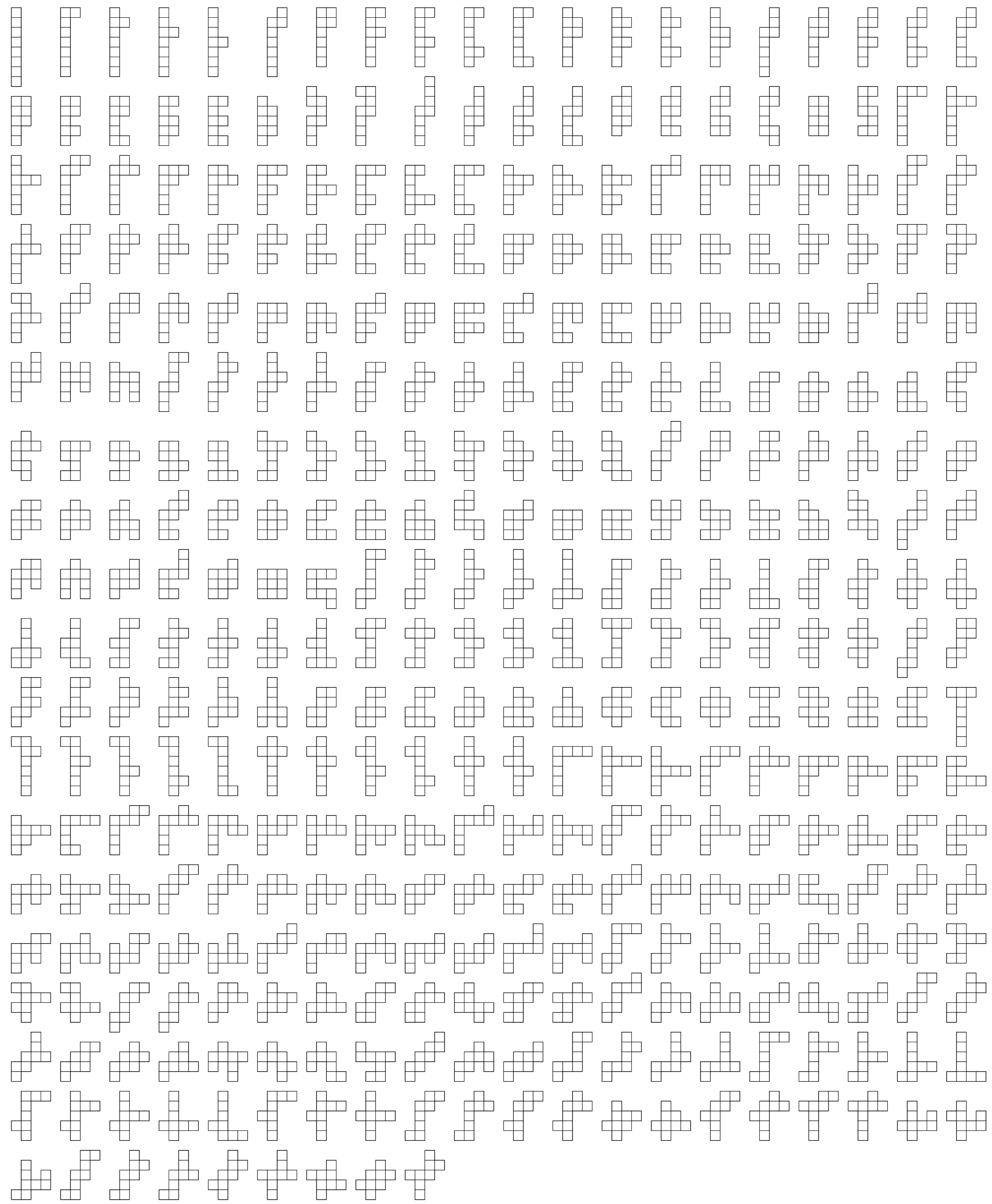

Figure 27. All possible arrangements for an Octomino.

CHAPTER FOUR.

THE POLYOMINOES.

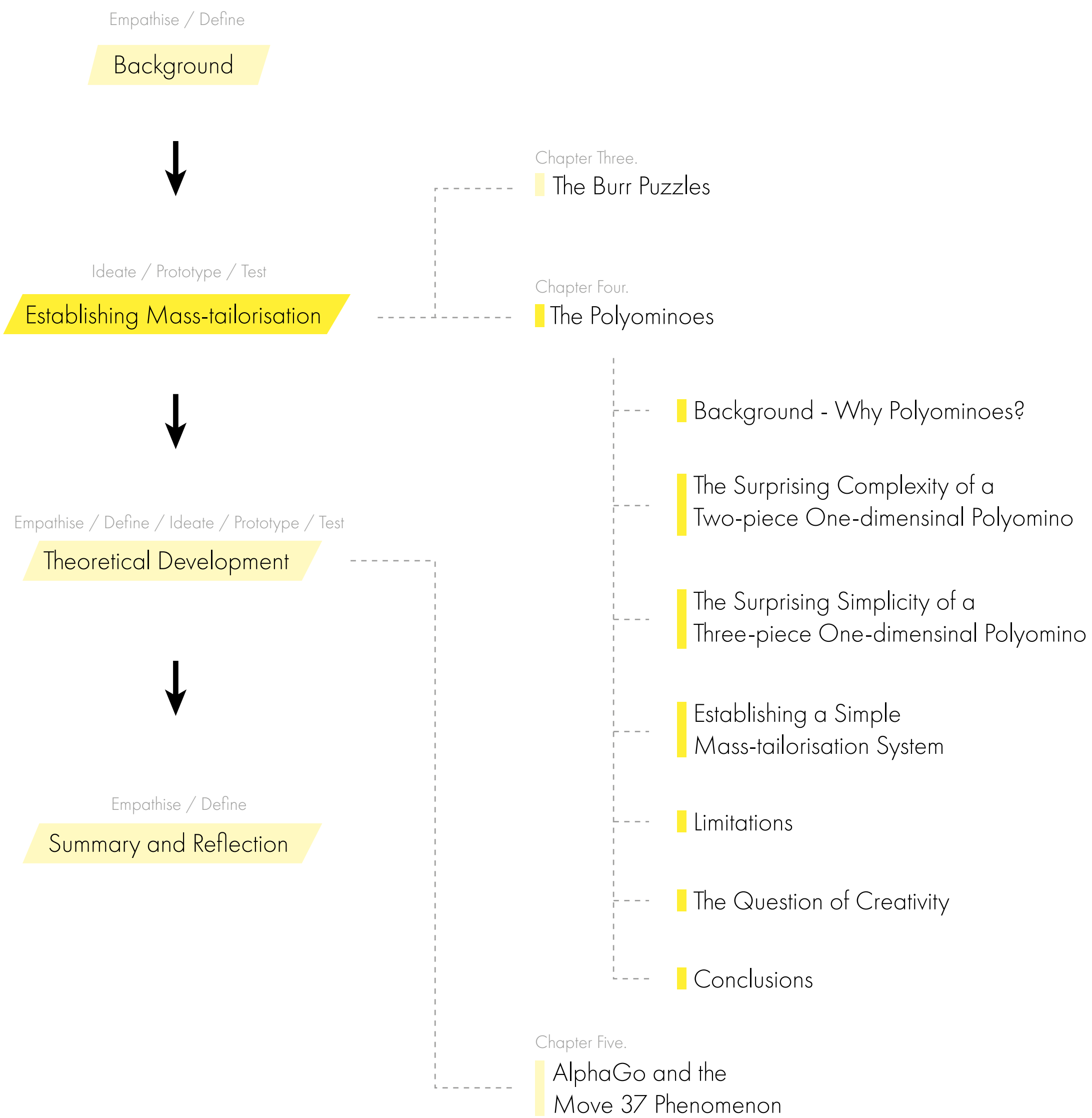

Figure 28. Chapter Four Structure.

"The context that determines whether 'Piece O above Piece P' is the same as 'Piece P above Piece O' is the reason that there can be a various number of solutions to the two-piece, one-dimensional polyomino."

Objectives addressed in this chapter:

2/ Critically define mass-tailorisation as it pertains to architecture
3/ Undertake research into literature and case studies relevant to establishing a digital continuum of mass-tailorisation
5/ Establish a Mass-tailorisation system.

1. Background – Why Polyominoes?

The focus of this chapter shifts from establishing the Digital Continuum to investigating the potential relationship between mass-tailorisation and artificial intelligence. In the previous chapter, the validity of a Design-Fabrication-Assembly Digital Continuum has been established in relation to the feasibility of mass-tailorisation for the Burr puzzle. The most significant limitation of the previous case study was the data management of burr puzzle pieces which in turn led to the revelation that artificial intelligence might be necessary for mass-tailorisation systems. Therefore, this case study is interested in attempting to establish a simple mass-tailorisation system through the adoption of artificial intelligence in the form of machine learning. Also, continuing on from the findings of the previous chapter in regards to the importance of specific design contexts, this chapter further illustrates the importance of specific design contexts and its implications to the final design output. The case study that will be investigated in this chapter is polyominoes.

The Encyclopedia Britannica defines polyomino as "equal-sized squares, joined to at least one other along an edge" (n.d.). Furthermore, polyominoes can be classified according to how many squares they have (Figure 26, 27, 28, 29, 30). For example:

1 - monomino	2 - domino
3 - tromino	4 - tetromino
5 - pentomino	6 - hexomino
7 - heptomino	8 - octomino
9 - nonomino	10 - decomino

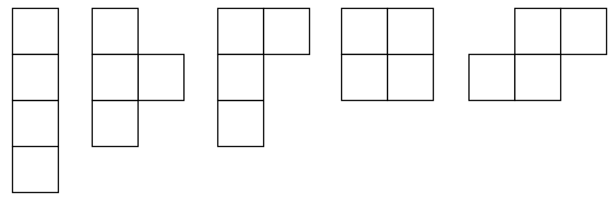

Figure 29. All possible arrangements for a Tetromino, also used in the game of Tetris.

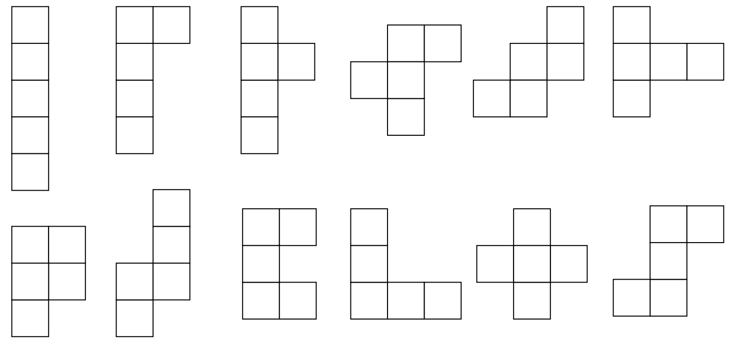

Figure 30. All possible arrangements for a Pentomino.

The classic game of Tetris is an example of a simple polyomino system (Figure 29). Players are required to move and rotate five distinct tetrominoes (4 squares) in order to fill the puzzle space without creating and voids. In this sense, the Burr puzzle is essentially a three-dimensional polyomino defined within a specific formal property that is the shape of the Burr puzzle. Therefore, by reducing the number of dimensions, it was deemed that the same process of developing a mass-tailorisation system can be conducted for polyominoes while ensuring that the volume of data was manageable through limited dimensions. Likewise, once the mass-tailorisation system has been established, it is a matter of adding additional dimensions to the system to create mass-tailorisable three-dimensional polyominoes - the Burr puzzles.

While most polyominoes are regarded as two-dimensional objects that span in two axes, in this case study, one-dimensional polyominoes that only span in one axis were used to ensure the most simplified and therefore the most controlled process (Figure 31). Like the Burr puzzle, the aim of the polyominoes was to successfully fit all the given pieces inside the puzzle space.

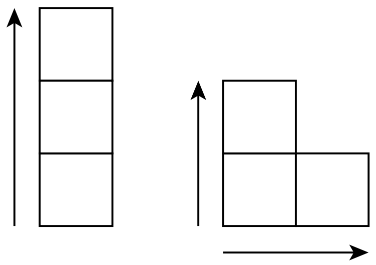

Figure 31. A one-dimensional polyomino (left) and a two-dimensional polyomino (right) as defined by the thesis.

2. The surprising complexities of a two-piece, one-dimensional polyomino

The first design iteration began with a two-piece, one-dimensional polyomino; a single monomino (Piece O - O for Orange), and a single domino (Piece P - P for Purple) (Figure 32). Therefore, the puzzle space for this polyomino iteration is three units long - equivalent to a linear tromino.

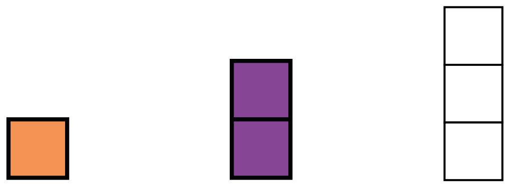

Figure 32. Piece O (monomino), Piece P (domino), and the puzzle space.

It was determined at the beginning of the exercise that every piece except for the monomino was to be given an orientation. While this was not a necessity in a one-dimensional polyomino, orientation grows in its significance as additional dimensions are added. Therefore, orientation was considered from the single-dimension space to understand its implications fully (Figure 33). The significance and implications of orientation will be further explained later in this chapter.

Figure 33. Piece O (monomino) and Piece P (domino) with orientation.

To fit all the pieces within the puzzle space, the first task was to find all the possible locations that each piece could fit within the puzzle space. This is because a fully assembled puzzle is essentially a combination of the individual pieces that fit in various positions within the puzzle space without colliding with each other. Therefore, if each piece in the two-piece, one-dimensional polyomino is configured to every possible position and orientation within the puzzle space, Piece O and Piece P have three and four possible configurations respectively (Figure 34). Note that Piece O, a monomino, has no orientation.

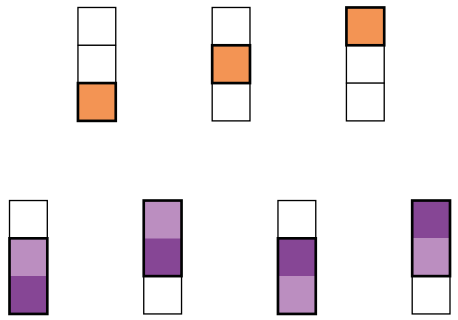

Figure 34. Every possible configuration of Piece O (monomino) and Piece P (domino) in the puzzle space - note the orientation of Piece P and the lack of orientation on Piece O.

Now that all possible locations for the pieces are known, the sequential assembly of the pieces needs to be tested. Similarly to the orientation of the pieces, while the sequence of the pieces is not a necessity in a one-dimensional and two-dimensional polyomino, it is a significant factor for Burr puzzles (three-dimensions). In one and two-dimensional polyominoes, if one has the correct set of pieces and the right location for each piece, the sequence at which the pieces assemble does not matter. However, in a three-dimensional polyomino (the Burr puzzle), the correct sequence of assembly is required along with the correct set of pieces and locations. Due to this reason, the sequence of the pieces was considered from the beginning to understand its implications fully.

To test the sequential assembly of the pieces, all possible locations & orientations were iterated for the designated first piece from which the second piece was tested to determine whether it will fit in the remaining puzzle space for each iteration. Following this logic, when the sequential order was Piece O - Piece P, there are four complete puzzles and one incomplete puzzle (Figure 35). However, if the sequence order was flipped to Piece P - Piece O, there are only the four complete puzzles (Figure 36).

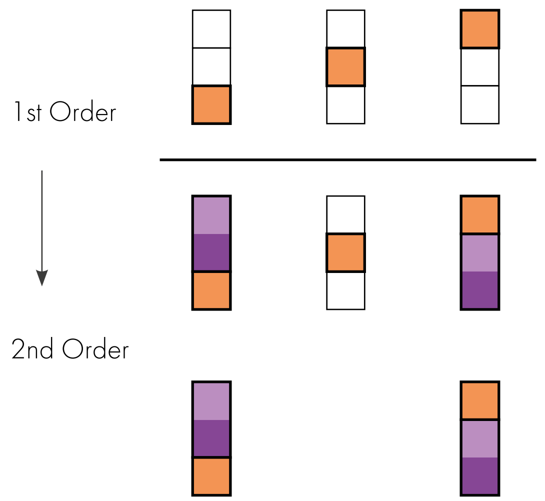

Figure 35. Assembly sequence of Piece O - Piece P.

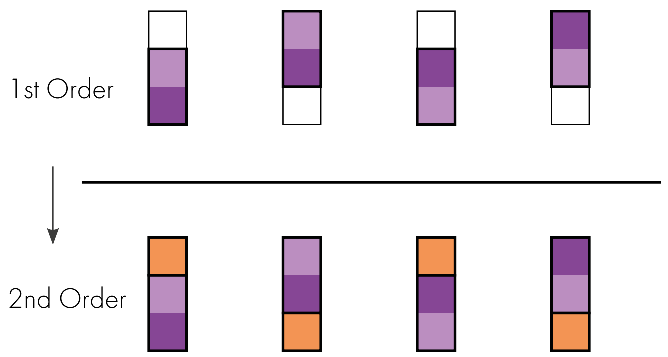

Figure 36. Assembly sequence of Piece P - Piece O.

2.1. How many solutions does a two-piece, one-dimensional polyomino have? - The specific design context of polyominoes.

The number of solutions that a two-piece, one-dimensional polyomino has depends on the context in question. If only the 'form' of the polyomino was concerned, the polyomino has only one solution - Piece O and Piece P adjacent to each other in one single axis (Figure 37). However, if 'form' and 'orientation' is concerned, the number of solutions expands to four (Figure 38). Furthermore, if 'form', 'orientation', and 'sequence' is concerned, the number of solutions expands to eight (Figure 39).

The reason that the number of solutions for a two-piece, one-dimensional polyomino has several answers is because the context at which the polyominoes are evaluated is different each time.

The context that determines whether 'Piece O above Piece P is the same as Piece P above Piece O' is the reason that there can be a various number of solutions to the two-piece, one-dimensional polyomino. Therefore, in the context of polyominoes, 'form', 'orientation', and 'sequence' essentially become the **primary specific design contexts** at which the polyominoes can be designed to; the three criteria become the specific design contexts that determine **whether Piece O above Piece P and Piece P above Piece O** is the same or independently unique polyominoes.

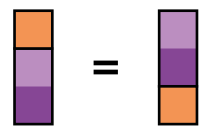

Figure 37. If only 'Form' is considered, there is only one solution.

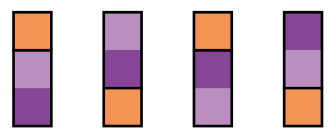

Figure 38. If 'Form' and 'Orientation' are considered, there are four solutions.

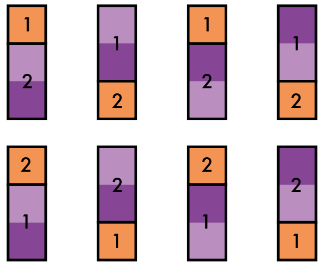

Figure 39. If 'Form', 'Orientation', and 'Sequence' are considered, there are eight solutions.

3. The surprising simplicity of a three-piece, one-dimensional polyomino.

The systematic process that was applied to the two-piece, one-dimensional polyomino can also be applied to a three-piece version that incorporates a tromino as Piece B (B for Blue). As a consequence; the puzzle space expands to six units long - equivalent to a hexomino (Figure 40).

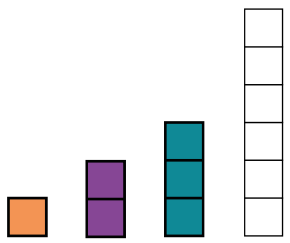

Figure 40. A three piece polyomino consisting of a monomino (Piece O), a domino (Piece P), a tromino (Piece B), and a hexomino puzzle space.

The configuration exercise for 'form', 'orientation', and 'sequence' generate 2880 possible arrangements in total (complete and incomplete combined). However, like the two-piece version, the number of solutions differ significantly in relation to the context in question. If only form is concerned, there are only three solutions - Piece O in the middle, Piece P in the middle, and Piece B in the middle. If form and orientation are concerned, there are 24 solutions, and if form, orientation, and sequence are concerned, there are 144 solutions (Figure 41).

It is clear that the number of solutions increases significantly, especially as more of the specific design contexts are considered and the number of pieces increases. The jump from 1 to 3 (form), 4 to 24 (form + orientation), and 8 to 144 (form + orientation + sequence), and 9 to 2880 (all possible complete and incomplete arrangements) adds perceived complexity to the solution space of polyominoes due to its sheer volume. However, the increase in number also increases the chances of finding possible patterns, relationships, and behaviours that in fact, simplify the perceived complexities.

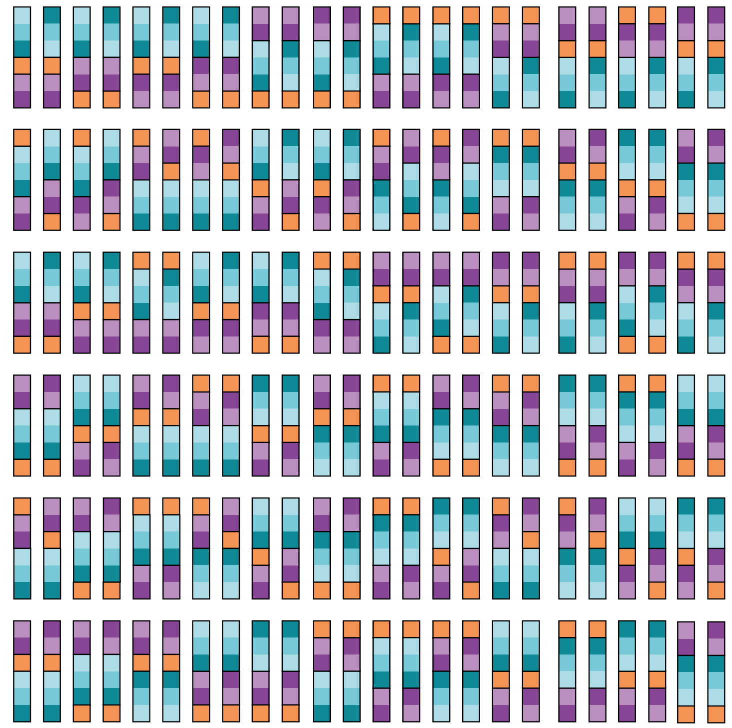

Figure 41. All possible arrangements of the three piece polyomino when 'Form', 'Orientation', and 'Sequence' are considered.

3.1. The Visual Diagrammatic Pattern-finding Process

The 144 solutions can be sorted in an attempt to find specific patterns, relationships, and behaviours. In Figure 42, each sequence solution has been independently sorted in reference to the location of the monomino. While distinguishable patterns begin to emerge already, these can be further simplified by extracting the location and orientation of each piece (Figure 43). Removing the orientation for each piece can further simplify the pattern to purely extract the location of the piece within the puzzle space (Figure 44). Overlaying these on top of each other creates a visual 'heatmap' of the piece within the puzzle space (Figure 45). This heatmap shows the *likelihood of the piece being placed at a specific location within the puzzle space* in relation to *the likelihood of a fully assembled puzzle*. The heatmap for the monomino is a clear example of this. The heatmap shows that the monomino has an equal likelihood of being placed on four of the six puzzle spaces in a fully assembled puzzle. If the monomino was to be placed on the two puzzle spaces represented in white, there will be no chance of the puzzle being fully assembled. In other words, there is no likelihood that the monomino will be placed on those two puzzle spaces, hence, represented in white.

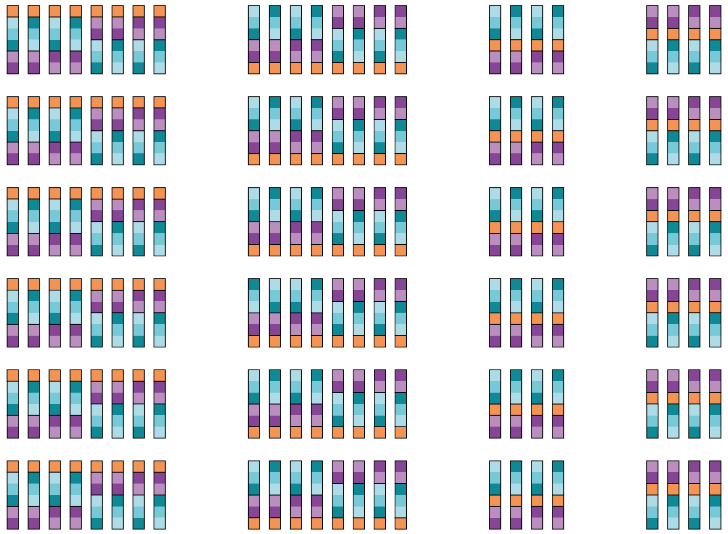

Figure 42. All possible arrangements of the three piece polyomino when 'Form', 'Orientation', and 'Sequence' are considered, sorted in reference to the monomino (Piece O).

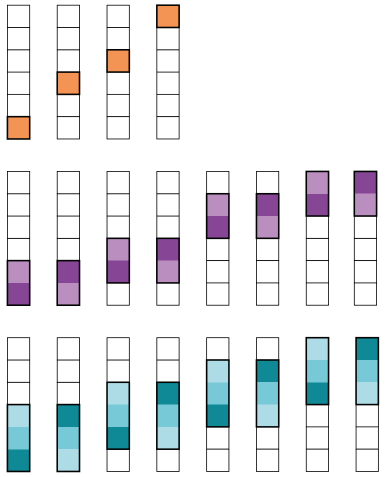

Figure 43. Extracting the location and orientation of each piece.

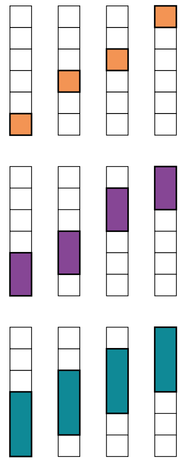

Figure 44. Extracting the location of each piece.

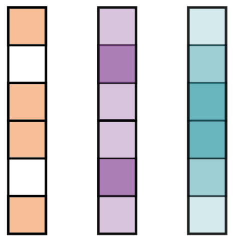

Figure 45. Visual heatmap of the puzzle pieces.

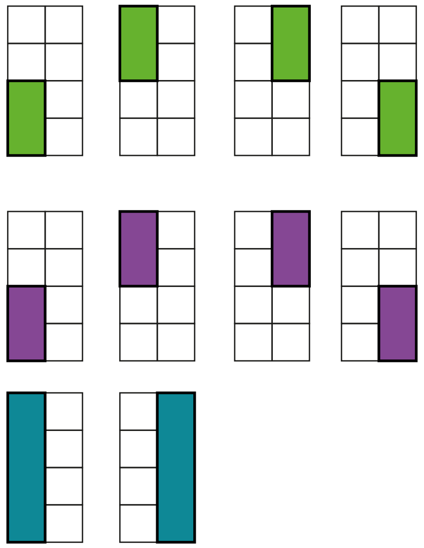

Figure 46. The Location pattern for a three-piece two-dimensional polyomino.

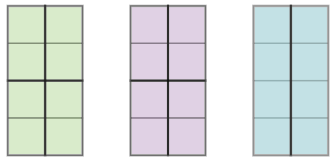

Figure 47. Visual heatmap of the puzzle pieces for the three-piece two-dimensional polyomino. In this instance the dominant border lines show the orientation and location of the available puzzle pieces.

The heatmap can also suggest the possible orientation of each piece in relation to the likelihood of a fully assembled puzzle. While orientation data has been removed during the pattern-finding process, the final heatmap has created pseudo-orientation data. The darker the heatmap is, the more likely the piece be located on the puzzle space. Furthermore, the darker it is, the more likely the piece has several orientations possible from the puzzle space. (most well expressed for the tromino). However, this data should be considered less accurate than the location data that can be derived from the heatmap.

Finally, sequence data cannot be derived at all from the final heatmap visual diagram.

3.2. The digital numeric pattern-finding process, its similarities and differences to a visual pattern-finding process, and the introduction of machine learning.

A pattern-finding process is a simplification process. In the pattern-finding process above, information about sequence and orientation has been deliberately diluted at various stages of the process. Patterns are formed because complex data has been diluted and simplified.
The visual diagrammatic pattern-finding process is a clear example of such simplifications. In the example above, the qualities of form, orientation, and sequence have been simplified to a trio of colours in various opacities. While this provides a quick and easy overview, it is limited in its detail. The finer such visual diagram becomes, the harder it becomes to distinguish specific patterns and differences (Figure 48).

Figure 48. The difference between two adjacent shades on a 4 step gradient vs 25 step gradient.

The same pattern-finding process can be achieved through a numerical representation. Each piece, orientation, sequence, and puzzle space is assigned a specific numerical system that aims to replicate the visual diagrams in a numerical form (Figure 49). Through the numerical representation, the polyominoes are transformed into a set of digital information data - in other words, polyominoes are represented through the technologies of the current time. While this form of representation is not an intuitive mode of representation for the designer, it becomes a powerful mode for the computer. Unlike the need for humans to simplify and dilute complex information to find patterns, due to the strengths of computers in efficient calculations, the computer is able to use the raw data to find patterns. This allows access to the overall pattern, relationships, and behaviours without losing the individual data of each solution

100220330	*140300230*	*250111320*	*250320111*	*300151230*
100220351	*141300250*	*250111341*	*200331110*	*321151230*
110200330	*151300230*	*230140300*	*200331121*	*330121200*
110200351	*100330220*	*230140321*	*250321100*	*351121200*
111220330	*110351200*	*200140310*	*250321111*	*300230140*
111220351	*111330220*	*200140331*	*200351110*	*300230151*
121200330	*121351200*	*230151300*	*200351121*	*310200140*
121200351	*130321250*	*230151321*	*250341100*	*310200151*
140200310	*140310200*	*250130300*	*250341111*	*321230140*
140200331	*141321250*	*250130321*	*300130250*	*321230151*
151200310	*151310200*	*200151310*	*310140200*	*330200110*
151200331	*100341250*	*200151331*	*320100250*	*330200121*
100250320	*111341250*	*250141300*	*321130250*	*331200110*
100250341	*140321230*	*250141331*	*330100220*	*331200121*
111250320	*151321230*	*200310140*	*331140200*	*351200110*
111250341	*100351220*	*200310151*	*341100250*	*351200121*
130250300	*111351220*	*220330100*	*351100220*	*300250130*
130250321	*140331200*	*220330111*	*300140230*	*300250141*
140230300	*151331200*	*230300140*	*310151200*	*320250100*
140230321	*200110330*	*230300151*	*320111250*	*320250111*
141250300	*200110351*	*250300130*	*321140230*	*321250130*
141250321	*220100330*	*250300141*	*330110200*	*321250141*
151230300	*220100351*	*220351100*	*331151200*	*330220100*
151230321	*250100320*	*220351111*	*341111250*	*330220111*
100320250	*250100341*	*230321140*	*351110200*	*341250100*
110330200	*220111330*	*230321151*	*300141250*	*341250111*
111320250	*220111351*	*200330110*	*321141250*	*351220100*
121330200	*200121330*	*200330121*	*330111220*	*351220111*
130300250	*200121351*	*250320100*	*351111220*	

Figure 49. The numerical representation of the 144 solutions that can be used as digital information data.

4. Establishing a simple mass-tailorisation system

The aim of this exercise was to create and test the numerical representation of the pattern-finding process. A Python algorithm was written using Scikit-Learn, a machine learning library consisting of several pre-built functions that allow for various machine learning methods to be quickly implemented in a range of contexts. The aim of the algorithm was to successfully determine the position, orientation, and sequence of a single piece within the polyomino given a set of existing solutions. The success was to be evaluated by aiming to find the missing data using the patterns found through the algorithm's given data.

More specifically, the algorithm was provided with 138 solutions (144 less 6 solutions for testing) to the three-piece polyomino in an attempt to find specific patterns, behaviours, or relationships that the algorithm could find in those data. Once this was complete, the algorithm was enquired about the remaining six solutions using the following queries:

Q1. Can the chosen three pieces (the correct pieces, orientation, and sequence) fit together?

Q2. If the second piece and the third piece is known, what is the first piece that is required?

Q3. If the first piece and the third piece is known, what is the second piece that is required?

Q4. If the first piece and the second piece is known, what is the third piece that is required?

For the 24 'questions' that were asked (4 questions per each of the six removed solutions), the algorithm was able to generate answers for the queries (Figure 50 & Figure 51). In other words, the algorithm used 138 solutions for the puzzle to find patterns, behaviours, and relationships, to then predict the remaining six solutions.

4.1. Results

Out of the 24 'questions', the algorithm only failed to suggest the correct piece for two of the 24. While the correct piece was suggested for the remaining 22, for most of those suggestions, the orientation of the piece was opposite to the actual orientation of the solution. While the exact reason for this could not be specified, it is highly likely that the solutions provided by the algorithm were heavily influenced by the mirror opposite pieces that already existed within the training data.

The nature of the questions posed meant that at least two of the three pieces were always known and correct in their piece, orientation, and sequence. Therefore, when the algorithm was asked to recommend the missing piece, it would be biased towards existing sets of puzzles that shared the same two pieces, and hence likely to suggest the third piece that accompanied them – the mirrored orientation of the actual missing piece.

Perhaps it could have been possible to set the algorithm to only suggest solutions that did not exist in the training data, however, at the time of the research, the researcher's technical knowledge of this field did not suffice.

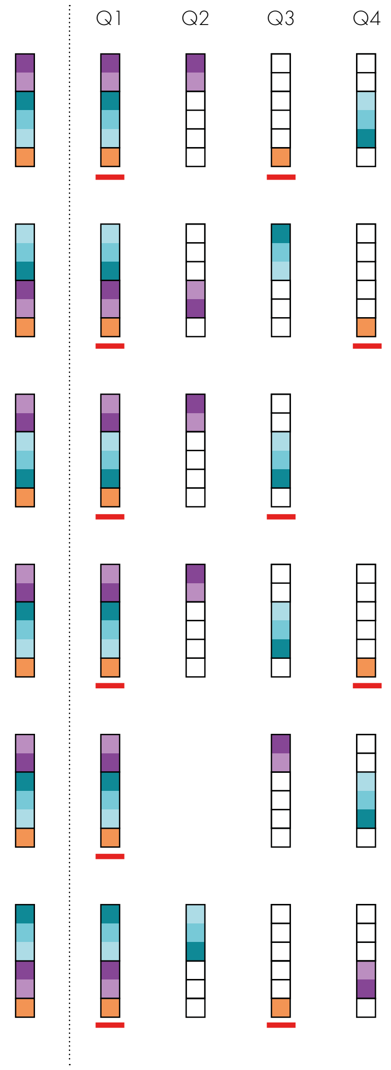

Figure 50. A visual representation of the 24 responses generated by the algorithm. Responses that met all of 'Form', 'Orientation', and 'Sequence' criteria have been underlined with red. Note that in many cases, the algorithm generated the correct piece but wrong orientation. The algorithm failed to generate responses for two of the queries.

	Q1	Q2	Q3	Q4
151200331	151200331	140200331	151200331	151200310
121330200	121330200	110330200	121351200	121330200
140310200	140310200	151310200	140310200	
140331200	140331200	151331200	140310222	140331200
200140331	200140331		200151331	200140310
351200121	351200121	330200121	351200121	351200110

Figure 51. A numerical representation of the 24 responses generated by the algorithm. Responses that met all of 'Form', 'Orientation', and 'Sequence' criteria have been underlined with red. Note that in many cases, the algorithm generated the correct piece but wrong orientation. The algorithm failed to generate responses for two of the queries.

4.2. A Simple Mass-tailorisation System

While the exercises conducted in this phase are of a simple nature, it is argued that it is the very beginnings of a mass-tailorisation system. A three-piece one-dimensional polyomino has 144 solutions. Therefore, the polyomino, as a design context, has 144 possible design outputs that can be chosen from. This leads to the possibility of facing the Paradox of Choice if no additional design contexts are introduced (Figure 52). However, by applying additional layers of contextual information – in this example, through pre-defining two of the three pieces – a mass-tailorised output can be generated through the use of artificial intelligence such as machine learning (Figure 53).

In this phase, the contextual information was just a pre-definition of two pieces, and therefore the so-called 'mass-tailorisation' was only a puzzle-solving calculator. However, with more time and further technical knowledge in the relevant fields, more robust and contextual tailorisation criteria that can aid in the quantitative as well as the qualitative decision-making process would be possible.

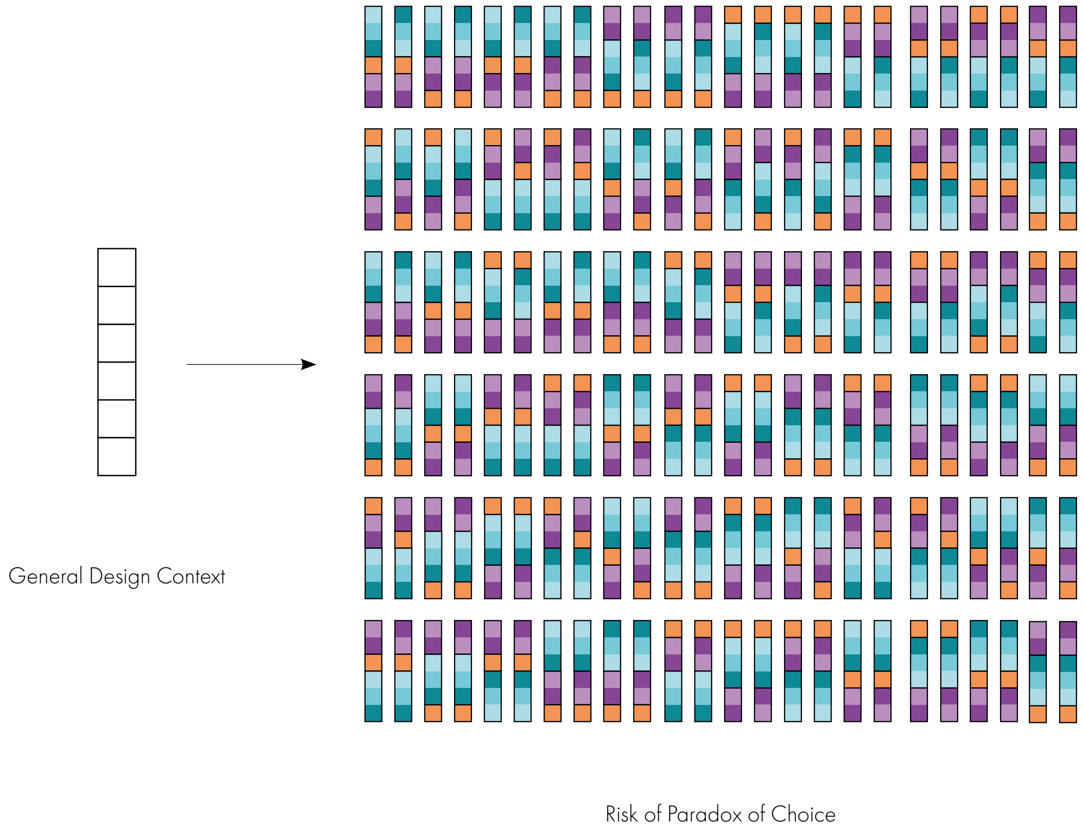

Figure 52. The risk of paradox of choice in a three-piece one-dimensional polyomino.

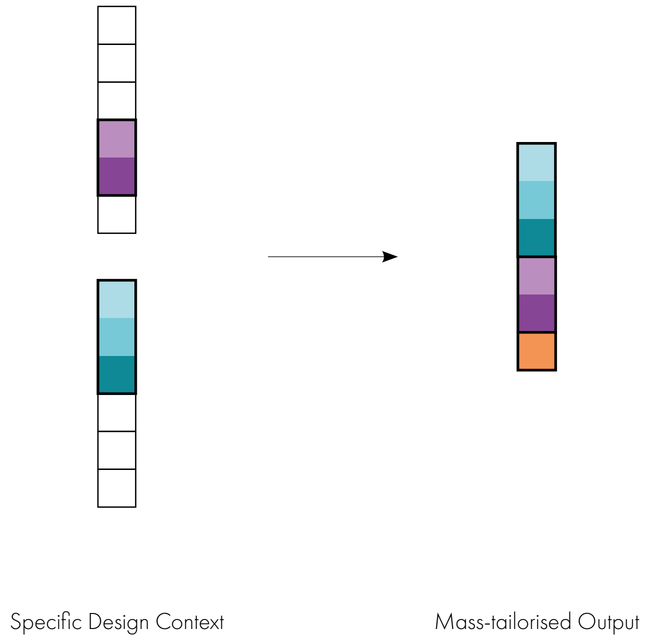

Figure 53. A simple mass-tailorisation of the three-piece one-dimensional polyomino.

5. Limitations

Through the aid of the internet, technology and information have become more democratised and accessible over time. This chapter was a beneficiary of such a phenomenon also. Key components of this chapter were the use of the coding language Python, and Scikit-Learn – an open-source library for simple machine learning algorithms. The open-source availability of machine learning libraries easily allows the implementation of these tools into the workflows and projects of industries not typically associated with computer science. As such, **using the library of functions allowed the research to proceed without much expertise in the field of computer science, data management, and mathematics**. Hence, studies and results such as those demonstrated in this exercise were possible. However, once the research required more in-depth analysis and understanding, the rate of accessibility and learning curve grew exponentially. **This meant that while implementation of standard procedures was possible, customisation of the procedures was slow and difficult. In this sense, perhaps the research conducted in this case study might have benefitted by the input of an expert in the field of computer science.**

5.1. The Appearance of the Black Box

It is ironic that for research that engages with the decision-making process, the work in this phase could not comprehensively specify the 'decision-making' process of the algorithm that was used as part of the study. The algorithm could provide answers, and as such, the study was successful in generating solutions. However, the logic behind the answers could not be comprehensively defined; hence the attempts to influence the answers with complete control of the algorithms was not successful. The limitations that arise from the 'Black Box' will be discussed further subsequently in the thesis.

6. The Question of Creativity

Finally, the investigation in this phase raises a fundamental question that needed to be addressed. The exercise required the algorithm to use 138 solutions to find patterns, behaviours, and relationships in order to find the six remaining solutions. If and when the algorithm successfully suggests the last six solutions for the three-piece one-dimensional polyomino, an interesting question can be asked – Can the six solutions suggested by the algorithm be considered new information? If so, could it be considered as a creative creation?

In light of such curiosity, the next chapter will begin to delve into the theoretical implications of mass-tailorisation and discuss how mass-tailorisation could shape the role of the designer of the future.

7. Conclusion

This chapter studied the polyomino as a case study for establishing a simple mass-tailorisation system. The simplicity of the underlying logic as well as its close relationship to the Burr puzzle (a three-dimensional polyomino) made the polyomino a suitable case study. The study of the polyomino revealed the importance of specific design contexts, even in design elements such as the polyomino that seem very simple in nature. The importance of setting the correct specific design contexts provided significantly different results to the final design outputs.

A simple mass-tailorisation system could be achieved using an open-source machine learning library. However, without the technical knowledge to customise the open-source algorithms further, continuous development was limited.

Finally, the exercises conducted in this chapter posed a fundamental theoretical question of creation and creativity. As a question worthy of investigation due to its implications on the theoretical framework of mass-tailorisation, the following chapters will step back from practical investigations to focus on this theoretical question.

THEORETICAL DEVELOPMENT

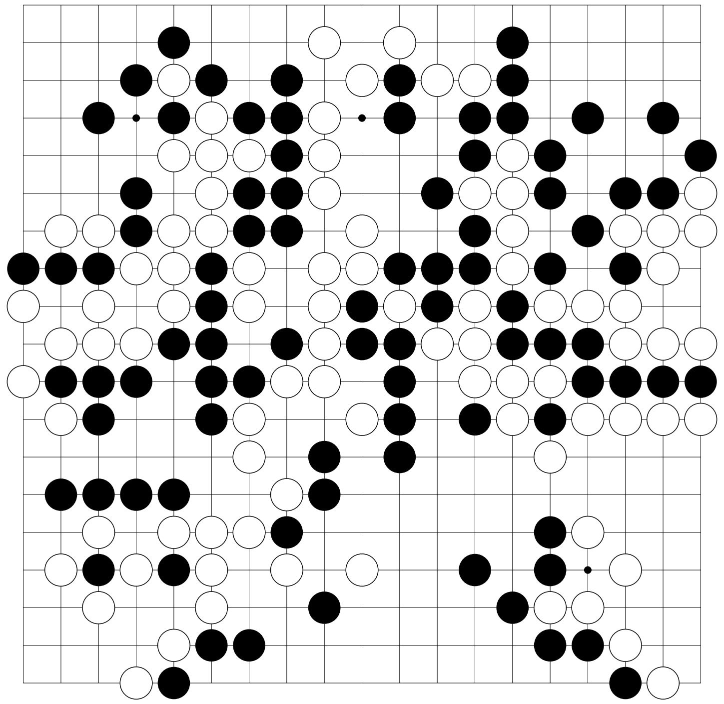

Figure 54. Game Four of the match between AlphaGo (B) and Lee Se-Dol (W).

At the conclusion of the previous chapter, an important question was asked: If the algorithm uses the existing data set to generate additional data, can these additional data be considered new information? If so, could it be considered as a creative creation?

The aim of the following two chapters is to shed some light into this query by critically interrogating the theoretical implications of mass-tailorisation rising from such questions as above. In order to build a robust theoretical framework for mass-tailorisation, the second part of the thesis studies AlphaGo as the primary case study to investigate the possibilities of artificial intelligence as a creative agent and speculate on the role of artificial intelligence in mass-tailorisation systems. Through this study, the thesis covers several interconnected themes that will complete the framework of mass-tailorisation. The themes are:

- Studying the possibility of creativity in artificial intelligence through the case study of AlphaGo and Move 37.

- Providing a resolution to the question of 'artificial creativity' raised in the previous chapter.

- Studying the implications of such 'artificial creativity' on mass-tailorisation. (The relationship between MT and Move37)

- Providing a coherent theoretical framework to mass-tailorisation as it relates to the importance of the D-F-A Continuum and Move 37.

- Speculating on the role of the designer of the future.

Through the progression of the themes stated above, the following two chapters will complete the theoretical framework of mass-tailorisation systems. Its opportunities for future research and explorations, as well as the current limitations, will be discussed in the chapter that follows.

CHAPTER FIVE.

ALPHAGO AND THE MOVE 37 PHENOMENON.

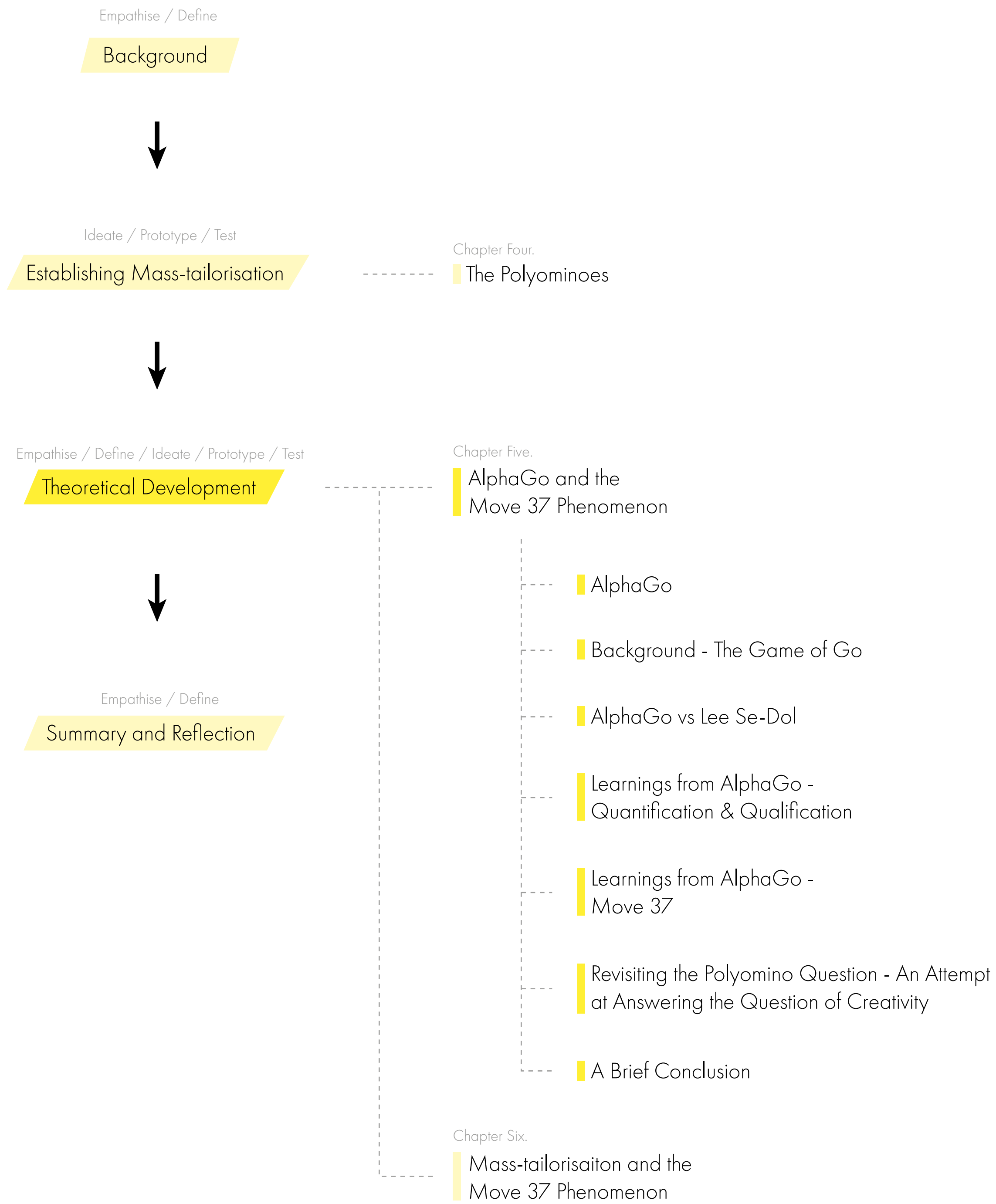

Figure 55. Chapter Five Structure.

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Figure 56. A painting of the Chinese warrior Guan Yu (160AD - 220AD) playing the game of Go.

"Go is often described as 'hypnotic', 'most abstract', 'intuitive', and 'creative'."

Objectives addressed in this chapter:

1/ Undertake research into previous literature and case studies that address decision-making and design.
3/ Undertake research into literature and case studies relevant to establishing a digital continuum or mass-tailorisation

1. Alpha GO

Developed by Google DeepMind, AlphaGo is a computer programme that plays the ancient Chinese board game of Go. In a simplified definition, AlphaGo uses machine learning and Monte Carlo tree searching techniques in deep neural network technology to calculate the possible moves and predict its implications. In 2016, it became the first artificial intelligence machine to beat a human world champion in the game of Go.

2. Background - The Game of Go

Considered to be the oldest board game still played to the present time, the game of Go is an ancient Chinese board game that was invented more than 2500 years ago (Shotwell, 1984). It is an abstract strategy game with the aim to surround more territory than the opponent within the playing board. Though the rules of Go are seemingly simple, the complexities of the game can create endless possibilities in how the game unfolds.

The game of Go is played on a board of 19x19 grid intersections (Figure 57). Two players take turns to place black and whites stones on the intersections of the board, starting with the black stone player. Once a stone has been placed on the board, it cannot be moved; however, the opponent's stones can be removed by 'capture' - surrounding the opponent's stones (Figure 58). The main purpose is to control more of the board using the stones by creating continuous orthogonal lines to claim as much of the board area as possible (Pumperla, & Ferguson, 2019).

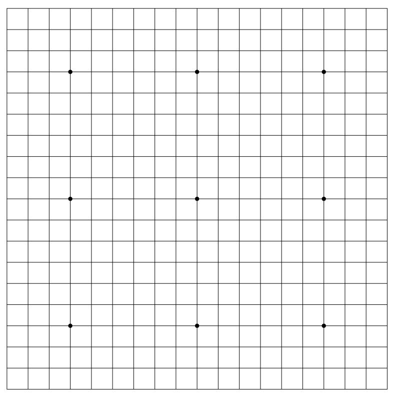

Figure 57. A blank 19x19 intersection Go board.

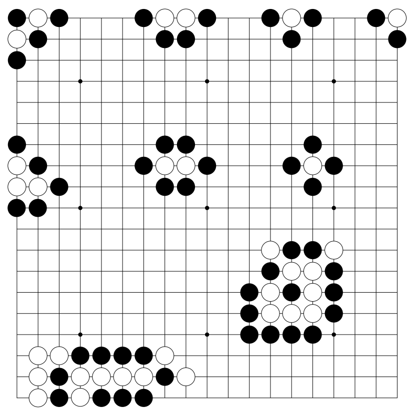

Figure 58. Examples of Black stones capturing white stones.

The complexities in Go mainly arise from its large number of possible moves - the branching factor of the game. In the game of Chess, the average branching factor is considered to be around 30. The game begins with 20 possible moves for the first move. The number of moves increases gradually as the game unfolds to reach an average of 30 possible moves per turn. In contrast, the game of Go has 361 possible first moves. This number slowly decreases as the game unfolds to an average branching factor of 250. In other words, there are 250 new and unique board configurations available per every turn (Figure 59). By the fourth move of the game, the game of Chess will have approximately 810,000 possible board configurations. In the game of Go, the approximate possible board configurations by the fourth move are around 4 billion (Pumperala, & Ferguson, 2019). David Silver, the lead researcher at DeepMind, explains the cause:

If you look at the board, there are hundreds of different places that this [black] stone can be placed down, and hundreds of different ways that white can respond to each one of those moves, hundreds of ways that black can respond in turn to white's moves, and you get this enormous search tree with hundreds times hundreds times hundreds of possibilities. (Nature Video, 2016).

It is estimated that the possible moves in Go outnumber the number of atoms in the observable universe (Figure 60). Due to these complexities, Go is often described as 'hypnotic', 'most abstract', 'intuitive', and 'creative'. (Kohs, 2017).

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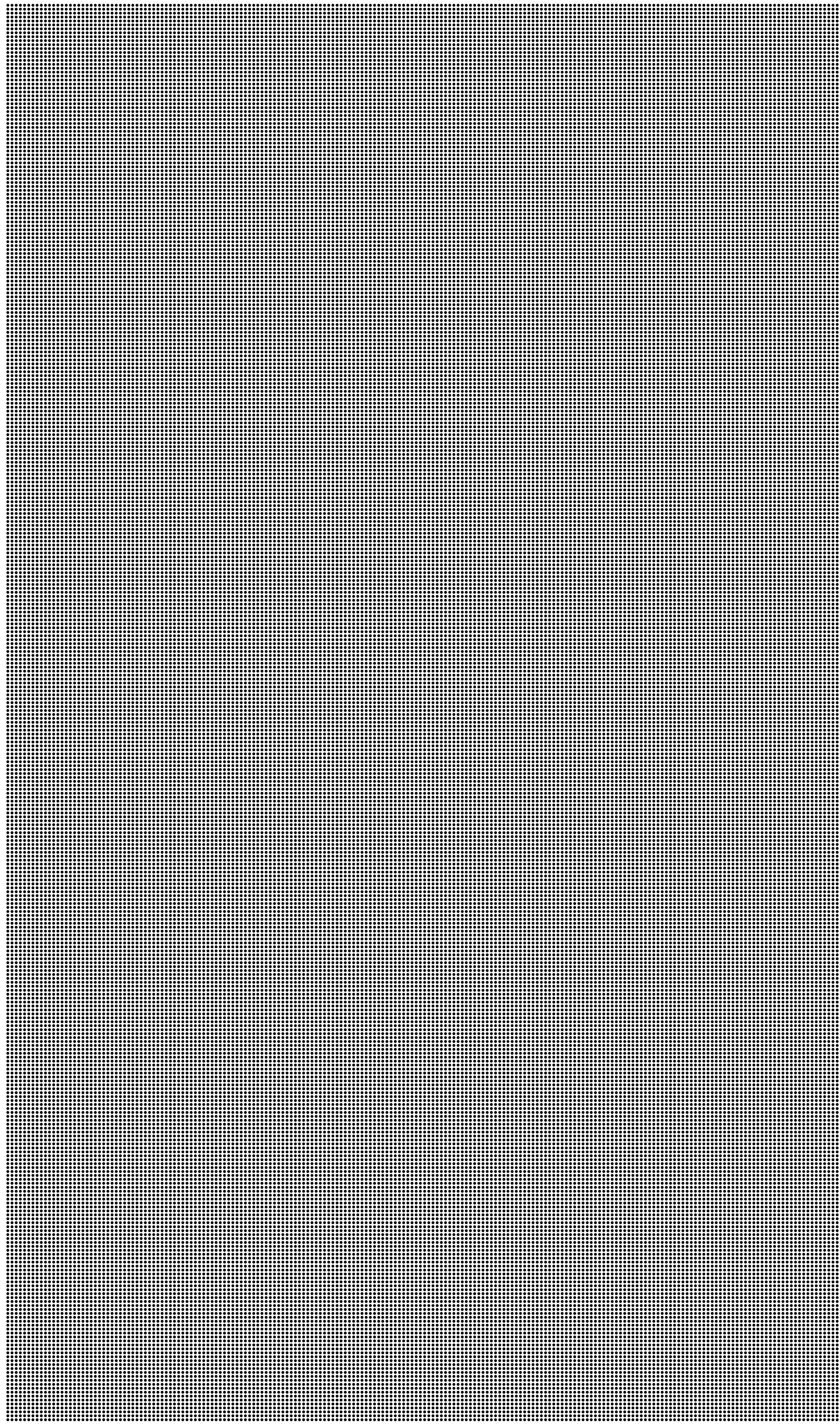
Figure 59. Each move in the Go presents around 250 possible moves in response.

1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 atoms in the universe
71,300,000,000 Burr puzzle iterations

< possible moves in Go

Figure 60. 80,000 dots. If one dot represented one Burr puzzle iteration, this figure will need to be printed on 891,250 a4 pages to illustrate all 71.3 billion iterations - a book that is approximately 53.5m thick. If one dot represented one set of 71.3 billion Burr puzzle iterations, a book that will illustrate the number Burr puzzle iterations that is equivalent to the number of atoms in the universe will be 8.415147 x 10^65km thick. For reference, the distance from the earth to the sun is only a mere 1.4755 x 10^8 km long.



3. AlphaGo vs Lee Se-Dol

In 1997, when IBM's Deep Blue beat the reigning world champion, Gary Kasparov, in the game of Chess, Deep Blue used brute force computing - it simply calculated all of the possible moves. Since then, challenging a professional in the game of Go has been labelled as the 'Holy Grail' of artificial intelligence (DeepMind, 2016). However, the technique used in Deep Blue for Chess could not be applied to Go. This is because the sheer number of possible moves made it impossible for brute force calculations. Demis Hassabis, the co-founder and CEO of DeepMind, explains the difficulty that rises from the incomparable complexity of Go: ...even if you took all the computers in the world, and ran them for a million years, that wouldn't be enough computer power to calculate all the possible variations (Kohs, 2017).

As brute force computing was not possible, there was a need to re-establish how a computer could play games. The team at DeepMind decided to create a search algorithm "much more human-like than previous approaches" (Silver, Hassabis, & Google DeepMind, 2016, para. 5). Instead of calculating every possible move, it aims to imitate human imagination and intuition, by 'imagining' several possible moves that could be played and calculating the future implications of the move on the game, before deciding on the most successful move to play (Silver et al. 2016)

In March 2016, DeepMind's computer programme by the name AlphaGo challenged Lee Se-Dol, an 18-time world champion, in a five-game match of Go. Upon the challenge, very few expected AlphaGo to pose a serious threat to Lee Se-Dol. A computer playing the 'most abstract' and 'creative' game against a world champion renowned for his unconventional and creative play, many, including Lee Se-Dol himself, predicted an easy match. In fact, many experts claimed that such technology was at least another decade away.

"Go on a computer? - In order to programme a computer to play a reasonable game of Go, rather than merely a legal game - it is necessary to formalise the principles of good strategy, or to design a learning programme. The principles are more qualitative and mysterious than in chess, and depend more on judgement. So I think it will be even more difficult to programme a computer to play a reasonable game of Go than of chess." (Good, 1965)

However, to the surprise of the majority, AlphaGo convincingly won the match four games to one.

4. Learnings from AlphaGo – Quantification & Qualification

While the relatively simple rules and large numbers of possibilities make the game of Go seem quite mathematical and logical, the game itself is seen otherwise. It is considered to be a game of abstraction, intuition, art, and creativity.

In ancient China, Korea, and Japan, Go was considered as one of the four noble arts alongside music, poetry, and painting (Nam Chi-Hyung, in Kohs, 2017). Furthermore, in a discussion on using a computer to play Go, mathematician I. J. Good wrote: "the principles are more qualitative and mysterious than in chess, and depend more on judgement." (1965). As mentioned earlier in the chapter, the game has also been labelled as 'hypnotic', 'most abstract', 'intuitive', and 'creative'; Lee Se-Dol himself has expressed his gameplay as a 'creation' (Kohs, 2017).

Due to this qualitative perception towards Go, AlphaGo's victory was considered even more remarkable. How did a quantitative computer play a qualitative game, and win against an unconventional, creative human that is Lee Se-Dol? There could be several hypotheses based on broad abductive reasoning:

- The game of Go is a qualitative game. Computers are capable of processing qualitative information. In the game of Go, the computer's ability to process qualitative information surpasses that of humans.

- The game of Go is a quantitative game. Computers are not capable of processing qualitative information but excel at quantitative information. Go is seen qualitative by humans because its quantitative information surpasses humans' quantitative comprehension.

- The game of Go is a qualitative game. Computers are not capable of processing qualitative information. However, qualitative information can be turned to quantitative information. Computers excel at processing quantitative information. In the game of Go, the computer's ability to convert qualitative information to quantitative information is superior to the human's ability to process qualitative information.

Should the game of Go be a qualitative game, there are two possible implications. (A) The computer processes qualitative information, or, (B) the computer can convert qualitative information to quantitative information.

Should the game of Go be a quantitative game, there are also two possible implications. (C) The computer processes quantitative information, or (D) the computer can convert quantitative information to qualitative information.

The computer, in its most fundamental structure, consists of binary codes - the on/off behaviours of electrical circuits. Binary codes simply measure the quantities of on/off signals; therefore, it is reasonable to assume that computers fundamentally process quantitative data.

Such reasoning eliminates options (A) and (D) that find their logic on the 'qualitative computer'.

Now, each of the remaining possibilities can also incur additional explanation:
B - The game of Go is a qualitative game. The computer can only process quantitative information. Qualitative information can be converted to quantitative information for the computer to process. In the game of Go, the computer's ability to convert qualitative information to quantitative information is superior to the human's ability to process qualitative information.

C - The game of Go is a quantitative game. The computer can only process quantitative information. The computer's ability to process quantitative information is superior to that of the human's. The game of Go is seen as a qualitative game because its quantitative information surpasses human's quantitative comprehension.

While both possibilities will be speculated in the rest of the chapter, the fact that there is a set number of possible moves in the game of Go (regardless of the capability to quantify them all) strongly suggests that Go is a quantitative game. This results in possibility (C) as an explanation of the game of Go in relation to Alpha Go. In this context, the reason that Alpha Go was able to beat Lee Se-Dol was that its ability to process quantitative information is superior to that of Lee Se-dol's ability.

Through the reasoning above, it was concluded that:
The game of Go is a quantitative game.
The computer (of the present) can only process quantitative information
The computer's ability to process quantitative information is superior to the human's ability to process quantitative information.

The question that this exercise aimed to answer was: 'How did a very quantitative computer play a qualitative game, and win against an unconventional, creative human?'
The exercise above addresses the need for the question to be rephrased: 'How did a quantitative computer play a quantitative game, and win against an unconventional, creative human?'. This rephrasing of the question also raises another question: 'why is the game of Go heavily linked to qualitative aspects such as abstraction, intuition, art, and creativity?'

This thesis proposes that the game of Go is seen as a qualitative game because its quantitative information surpasses the human's ability for quantitative comprehension. In other words, the logical quantification of the possible moves within the game of Go surpasses the human's ability to process and comprehend quantitative information.

In light of this, it can be speculated that abstraction, intuition, art, and creativity may be present in quantification. This will be further investigated through a specific move that occurred in Game Two of the match between AlphaGo and Lee Se-Dol.

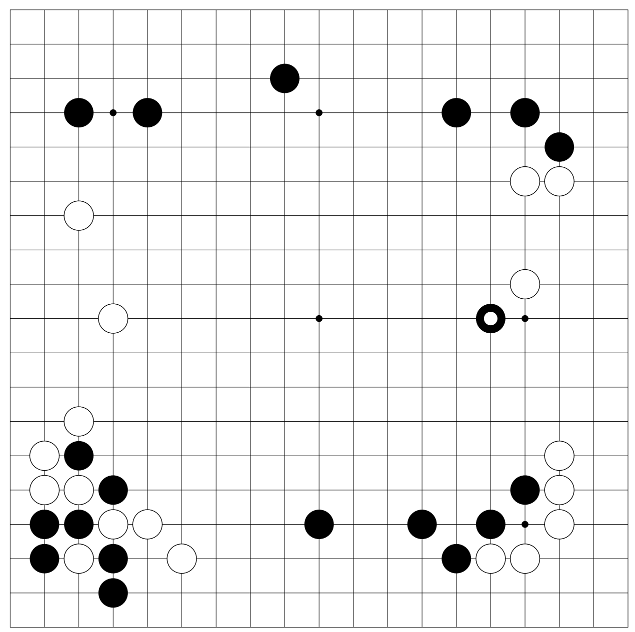


Figure 61. Move 37.

5. Learnings from AlphaGo – Move 37

While AlphaGo's victory was an unexpected result, it was not the single most significant news of the event. Game Two of the match between AlphaGo and Lee Se-Dol was an enlightening moment for both Go and artificial intelligence. In the 37th move of the game, AlphaGo placed its stone at a seemingly bizarre location on the board (Figure 61). The move was received by the commentators as a "...a very surprising move" and "... a mistake". AlphaGo it-self estimated that there was only a 0.01% chance of a professional player playing that move in the same context. This move left Lee Se-Dol stunned for over 12 minutes, and consequently became the key move in winning the game. Indeed, after the match vs AlphaGo, Lee Se-Dol explained: "What surprised me the most was that AlphaGo showed us that moves human may have thought are creative, were actually conventional. I think this will bring a new paradigm to Go" (Kohs, 2017). This move has since been labelled as Move 37 and has been widely publicised and analysed.

In a similar manner to the conclusions derived from the abductive exercise conducted prior, in Game Two of the match between AlphaGo and Lee Se-Dol, creativity was present in quantification. Such speculation can be explained through a metaphor from studies in dynamical system theory that describes "how a single underlying process can lead to qualitatively different outcomes" to explain how "products that differ enormously in their creativity levels could arise from the same basic underlying process" (Amabile, 1996, p.39):

"The system used in this metaphor is that of a horse on a treadmill where the treadmill increases its speed at a constant rate. When the treadmill begins moving slowly, the horse walks. At some point the speed of the treadmill becomes great enough that the horse's movements become qualitatively different; the horse is now trotting. At some later point the horse breaks into a canter and, finally, into a gallop. A quantitative change in the speed of the treadmill has produced a qualitative change in the gait pattern of the horse. An observer glancing at the horse at Time 1 (walking) would see movement that looked quite different from what she might see if she glanced at Time 3 (cantering). Each of these movement patterns looks qualitatively different, yet the underlying system in the treadmill (and in the horse) has remained the same)." (Amabile, 1996, p.39).

AlphaGo's Move 37 phenomenon is similar to the metaphor of the horse on the treadmill. AlphaGo's constantly evolving quantitative change (in the form of computational-calculations) that led to simple, conventional moves did not present the quality of creativity as perceived by people. However, **at a certain point, when AlphaGo's quantitative change has reached a specific moment that led to the calculation of Move 37, the qualitative perception of AlphaGo's move suddenly became creative.**

Should creativity exist in quantification, it is possible for people to perceive the game of Go as creative. Furthermore, under such a model, Move 37 can indeed be labelled as a creative move made by AlphaGo in the creative game of Go.

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Figure 62. The Horse in Motion by Eadweard Muybridge.

6. Revisiting the Polyomino Question – An attempt at answering the question of creativity

The study of AlphaGo revealed that creativity might be present in quantification. In this context, it is possible to answer the question of creativity raised at the end of the Polyomino chapter. Should the algorithm use the existing 138 solutions to generate the remaining six solutions, are these solutions considered to be new information? If so, could it be considered as a creative creation?

First, it is important to recognise that the six remaining solutions were existing solutions. Move 37 was not new information created by AlphaGo; it was undiscovered information discovered by AlphaGo. In theory, Lee Se-dol, or any other professional Go player could have played the same move under the same circumstances. Likewise, the 6 Polyomino solutions that are suggested by the algorithm are not created by the algorithm; they are only undiscovered information discovered by the algorithm.

Whether these discovered solutions can be considered as a creative solution is dependent on the context at which the solutions are discovered. Below is the famous story of the Egg of Columbus often used to allude to creativity:

"Columbus being at a party with many noble Spaniards, where, as was customary, the subject of conversation was the Indies: one of them undertook to say: —"Mr. Christopher, even if you had not found the Indies, we should not have been devoid of a man who would have attempted the same that you did, here in our own country of Spain, as it is full of great men clever in cosmography and literature." Columbus said nothing in answer to these words, but having desired an egg to be brought to him, he placed it on the table saying: "Gentlemen, I will lay a wager with any of you, that you will not make this egg stand up as I will, naked and without anything at all." They all tried, and no one succeeded in making it stand up. When the egg came round to the hands of Columbus, by beating it down on the table he fixed it, having thus crushed a little of one end; wherefore all remained confused, understanding what he would have said: that after the deed is done, everybody knows how to do it; that they ought first to have sought for the Indies, and not laugh at him who had sought for it first, while they for some time had been laughing, and wondered at it as an impossibility. (Benzoni & Smyth, 1857, p.17)

The story emphasises the importance of the context of discovery. The Spaniards did not find the discovery of the Indies as enlightening once Columbus returned from the expedition. However, Columbus emphasises the importance of the context of discovery through the egg: "that after the deed is done, everybody knows how to do it". In essence, the story suggests the importance of the relationship between the insight (the discovery) and the perceiver in determining creativity - that with greater insight, the perceiver's appreciation diminishes.

Similarly, the question of creativity in the six solutions generated by the algorithm is highly dependent on the perception of the perceiver. As the polyomino exercise only involved the use of simple one-dimensional three-piece polyominoes, it is relatively easy for a person to discover cognitively, or at least estimate, the six missing solutions and the missing piece for each of the queries. However, should a person be oblivious to the existence of the six remaining solutions, or should the polyomino be perceived as a complex system that surpasses one's quantitative comprehension, the thesis suggests that the six solutions generated by the algorithm will be considered creative.

AlphaGo's simple and conventional moves were not perceived as creative. It was only when Move 37 was made, a winning move that commentators thought was "... a mistake", that AlphaGo's move was perceived as creative.

Redacted due to copyright reasons.

Figure 63. Columbus Breaking the Egg by William Hogarth.

Studies have suggested the importance of the perceiver in the context of creativity. Creativity is said to be judged by "the magnitude of the emotional response it evokes" (Wilson, 2017). As such, the assessment of creativity can only be bound within a context. In a cultural, social, or historical vacuum, the assessment of creativity cannot exist (Amabile, 1996).

Furthermore, creativity is often closely correlated to heuristic tasks over algorithmic tasks. However, the determination of whether a task is heuristic or algorithmic is highly dependent on the individual. If an individual has no knowledge of the existing algorithmic task solution, the task can be considered heuristic for the individual. Hence the task can be considered creative (Amabile, 1983). This idea also correlates with the notion of P-creativity (P for psychological), which only concerns whether an idea is novel to the mind of the individual/s concerned (Boden, 1998).

Therefore, it is a matter of perception whether the generation of the six solutions is creative. Likewise, it is a matter of perception as to whether the 37th move made by AlphaGo is a creative move. Hence, the question of creativity is dependent upon the perceiver – whether that be an individual or the world of Go. Ultimately, creativity inherently has an element of subjectivity, as it is not possible to articulate objective criteria for measuring or identifying something as creative (Amabile, 1983).

7. A Brief Conclusion

This chapter used AlphaGo and Move 37 as a case study to provide resolution to the question of creativity raised at the conclusion of the previous chapter. AlphaGo's Move 37 provided an insight into the possibility of creativity within quantification because ultimately, creativity is dependent on the context of the perceiver.

In light of such findings, the following chapter will aim to address a more direct relationship between mass-tailorisation and the learnings from AlphaGo and Move 37.

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CHAPTER SIX.

MASS-TAILORISATION AND THE MOVE 37 PHENOMENON.

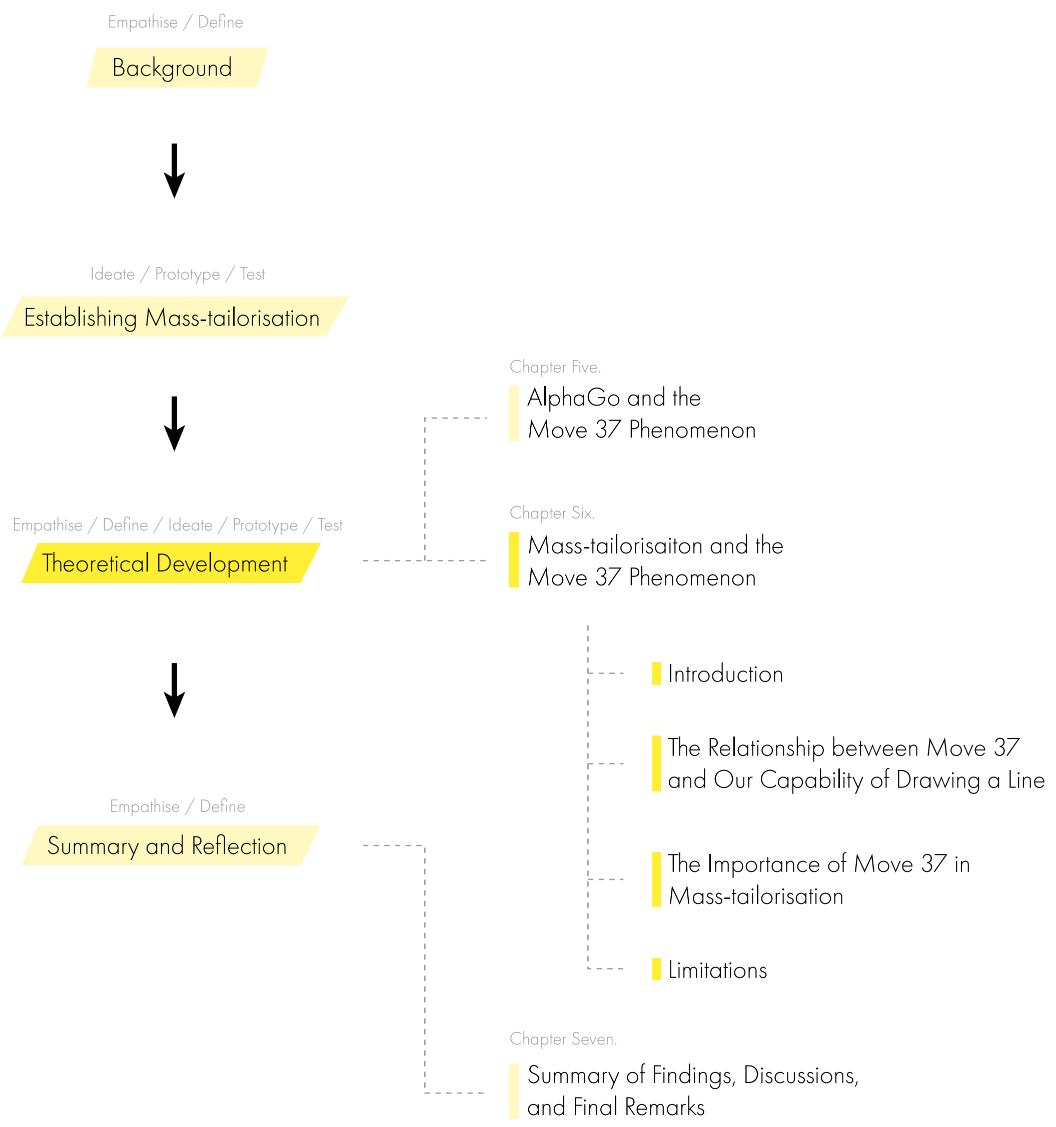

Figure 64. Chapter Six Structure.

"Perhaps, the designers in the age of artificial intelligence will not be praised for their mystified creativity but praised for their enlightening discovery."

Objectives addressed in this chapter:

2/ Critically define mass-tailorisation as it pertains to architecture.
3/ Undertake research into literature and case studies relevant to establishing a digital continuum or mass-tailorisation
6/ Speculate on future possibilities of mass-tailorisation in the architectural context.

1. Introduction

Upon the findings from the previous chapter, this chapter aims to refine the theoretical framework of mass-tailorisation by speculating on the potential relationship between mass-tailorisation and the Move 37 phenomenon. First, the chapter will suggest the potential for the possibility of generating the Move 37 phenomenon in the field of architecture through a series of case studies and logical reasoning. This is followed by discussing the potential implications of the Move 37 phenomenon in the field of architecture as an enabler of expanding the creativity of the designer in the design process. Lastly, the importance of the Move 37 phenomenon in mass-tailorisation systems is addressed and speculated upon, emphasising the decision-making process of the designer.

2. The Relationship between Move 37 and our capability of drawing a line.

This thesis suggests that phenomena such as Move 37 could be possible in the field of architecture, and more importantly, that Move 37 has a close relationship to mass-tailorisation.

The following is a simple exercise as an analogy to illustrate the possibility of Move 37:

The exercise asked for participants to draw a single line on a white canvas. It is then followed with the instruction to draw as many different lines on the white canvas as they deemed possible. Expectedly, both instructions were completed with relative ease. In the case of the first instruction, the exercise was completed with little to no difficulty and was not time-consuming. Individuals were able to quickly draw a line on a white canvas without much trouble. In the case of the second instruction, there were differences in the number of lines being drawn. However, most were able to draw multiple iterations of a line.

In light of the completion of the second instruction, the first gains much greater significance. The second instruction exemplifies that individuals can cognitively generate multiple variations of a line. However, when the individual was tasked with drawing only a single line on the canvas, they were able to avoid the Paradox of Choice and draw a single line that was deemed the best fit for this particular task – they have performed mass-tailorisation.

The figure below illustrates some iterations of a single line on a white square canvas (Figure 65).

Figure 65. Iterations of a line.

This thesis argues that these lines are simple analogies to explain the phenomenon and significance of Move 37, and why digital tools will be able to help us in the decision-making process as explained hereafter.

Kahneman, a Nobel Prize-winning psychologist and economist, suggests that humans place too much confidence in our judgement (2011). Our perception of ourselves is that of logical and systematic thinkers; however, we are more likely to be framed within our own biases and preconceptions of thinking. Psychologists that study the unconscious goal pursuit of humans state that "people automatically select and execute behaviours available in their repertoire when a goal is primed, and unconsciously adjust their behaviour based on perceptual input in the current situation to reach it" (Custers & Aarts, 2010). Therefore, should we truly want to think logically and systematically, there is a necessity for a more logical and systematic way of thinking than our cognition. Digital tools such as computational processes are designed to be logical and systematic in their way of 'thinking'. In-fact, drawing every single possible iteration of a line within a given canvas is theoretically not an impossible feat. If no additional context is given other than the formal properties of a line, using the processing power of a computer, a given canvas can be divided into a set number of elements (eg. pixels, squares, dots) to which the computer can run through a permutational exercise of linking the elements together in a systematic way. In this sense, a line such as below is also possible through the aid of digital tools (Figure 66).

Redacted due to copyright reasons.

Figure 66. Anonymous Portrait Drawing by Ngupakarti.

One might suggest that this line is humanly capable. Indeed, the practicality of drawing this line is not an impossible feat. However, drawing this line when asked to draw a single line on canvas requires great creativity. Likewise, the stone that was placed in the 37th move of Game Two was not difficult in its practicality – laying the stone on a specific part of the board was like any other move in the game. However, placing the stone on a specific location at a very specific situation as in the 37th move of Game Two required greater creativity than that of the 18-time world champion.

2.1. What is a line? – A short discussion on semantics

One may also suggest that the examples of lines provided are in fact, not valid examples of a line. Validity exists in such observation, encouraging a discussion on the semantics of a line. In fact, as a vital element of the architectural design process, the semantics of a line in the context of architecture is worthy of comprehensive research in itself. Therefore, this thesis simply suggests that the call for the discussion on the semantics of a line in itself provides for the case that designers could be constrained by their own biases and preconceptions of thinking. The validity for one to claim that a drawing may or may not be considered as a line frames them within their perceived understanding of what a line is. In the field of semantics, it has been revealed that people may downplay co-occurring properties in the environment if it does not fit their implicit theories and enhance the importance of features properties that fit within their theories (Rogers, 2004). Therefore, through the use of digital tools, we may be able to break these boundaries and possibly discover the Move 37's in the drawing of a line, and perhaps more broadly, in architectural design also.

2.2. Rhoda Kellogg's collection of Children's Art

Perhaps, fortunately, it is not only designers that pose the possibility of being framed within their own biases and preconception of thinking. Through a worldwide collection of children's art, Rhoda Kellogg concluded that all art produced by children consists of a combination of one or more of The Basic Scribbles - a collection of 20 simple scribbles (Figure 67). Interestingly, The Basic Scribbles are not learnt through external stimuli. Kellogg explains that the "capacity for creating art is innate, is entirely self-taught in early childhood" through the "spontaneous products of the individual's own eye-hand-brain development and visual feedback from their own scribblings" (1973, pg. 8).

Redacted due to copyright reasons.

Figure 67. The Basic Scribbles by Rhoda Kellogg.

In support of such claims, an analysis of 2951 drawings of a house revealed that the children's perception of a house was remarkably similar regardless of the child's original culture or community's architectural construction. Kellogg concludes that 'child art' is "the common language of art that transcends barriers of time and place" (1973, pg.9).

Such strong connections in the artistic nature of children may suggest that we, as human beings, are framed within our own biological biases and preconception of thinking. Perhaps, regardless of our degree of expertise in design innovation, we are bound within the limitation of human-creativity.

2.3. OpenAI's Hide and Seek Algorithm.

Recently, OpenAI's Hide and Seek Algorithm has shown that digital tools may aid us in extending our comprehension. In a multi-agent hide-and-seek algorithm, the researchers have discovered multiple unexpected behaviours that the agents used to win the game of hide-and-seek. The unexpected behaviours spanned to agents 'exploiting the game' and 'finding loopholes' that the researchers did not expect. The hide-and-seek agents revealed alternative ways to hide or seek that were beyond the preconception of the researchers. (Baker, et al, 2019)

Such interesting behaviours are reported commonly in artificial intelligence research. Often referred to as the Unpredictability, Unknowability, or Cognitive Unaccountability of Artificial Intelligence, many experiments reveal that the behaviours of artificial intelligence could span beyond the preconceived 'rules of the game' set by the researchers (Yampolskiy, 2019). Furthermore, if one accepts the role of unpredictability and accidents in creative discovery and innovation, studies suggest that digital tools could be used to encourage such accidental innovation (Austin et al., 2012). Could it be possible that through the aid of artificial intelligence that we may find loopholes within our preconceived notion of 'architecture design'? Furthermore, could the aid of artificial intelligence perhaps span beyond our 'rules of the game' for architecture design that we have set?

2.4. Discovery - the possible role of the designers of the future?

It is said that the way people play the game of Go has dramatically changed since Move 37.

The thesis suggests that through the use of digital tools, we may be able to discover the undiscovered. As stated previously, Move 37 was not new information created by AlphaGo; instead, it was undiscovered information discovered by AlphaGo. Likewise, the six polyomino solutions suggested by the algorithm are not created by the algorithm; instead, it is only 'undiscovered' information 'discovered' by the algorithm.

In light of this, and continuing on the discussion of semantics, perhaps the validity of the term creativity needs to be re-examined in the age of artificial intelligence. Perhaps, in the age of artificial intelligence, there is little for designers to create, but an abundance for designers to discover. **Perhaps, the designers in the age of artificial intelligence will not be praised for their mystified creativity but praised for their enlightening discovery.**

Perhaps in the age of artificial intelligence, we may expand our design capabilities through the science of artificial intelligence and the humanity of the designer converge further. "The realm of science is everything possible in the universe; the realm of the humanities is everything conceivable to the human mind" (Wilson, 2017).

3. The importance of Move 37 in mass-tailorisation

The last two chapters extensively covered the Move 37 phenomenon and its relationship to creativity. In the last section of this chapter, the discussion on creativity and Move 37 will be redirected to refine the theoretical framework of mass-tailorisation. Specifically, the importance of the pursuit of Move 37 phenomenon to mass-tailorisation systems will be discussed in two steps:

- The Move 37 phenomenon is important in mass-tailorisation because it has the potential to expand the solution space beyond the preconceived notions of the designer.

- Therefore, such an expansion of the solution space in a mass-tailorisation system will provide a more tailorised design output.

The Move 37 phenomenon is an important notion for mass-tailorisation as it has the potential to expand the solution space beyond the preconceived biases of the designer. As explained earlier, the possibility for a designer to approach a design problem with a set of preconceived biases may limit the possibilities considered by the designer. It is at these instances that the Move 37 phenomenon can aid the designer in breaking those preconceptions and discovering the undiscovered abundance to expand the solution space. As explained in Chapter Three, a larger solution space will provide a more resolved mass-tailorised output (Refer to pg.49). In turn, customer sacrifice is reduced in a more resolved mass-tailorisation system – the reduction of the gap between the requirements of the brief and the delivered design output. This leads to a higher likelihood that the designed intent of the output is satisfactory, reflecting a better decision-making process.

It is important to note again that the thesis does not speculate on the possibility of Move 37 creating 'something from nothing', rather, the thesis only speculates on the possibility of Move 37 discovering the undiscovered due to the designer's preconceived biases or the surpassing of comprehension as the case of AlphaGo vs Lee Se-Dol.

It is also important to note that the thesis does not disapprove of the designer's preconceived biases. Design, and more specifically, creativity, is inherently subjective, as discussed in Chapter Four. Thus, the preconceived biases can be used as a subjective driver by the designer for creativity. However, the thesis suggests the need for the awareness of the whole prior to the designer's biases to ensure that they are in fact, informed biases rather than biases formed from unawareness. As a simple analogy, two individuals may perceive a black Ford Model T as a great coloured Model T. However, if one is not aware of the availability of other colour options, their perception is less credible than of the other who is aware of the availability of other colour options. The latter is a more explicit portrayal of the intentions of the decision-maker. Hence, the more informed to begin with, the stronger the designer's subjective decision-making has to be. As such, the former is a product of bias from unawareness; the latter is a product of explicit and informed bias.

4. Limitations

AlphaGo is the product of many years of work by the team at (now Google's) DeepMind, a world-leading artificial intelligence company. Furthermore, the 37th move of Game Two was a phenomenon that even the team at DeepMind did not plan or expect - it was the product of AlphaGo itself.

The research into the possibility of the Move 37 phenomenon in mass-tailorisation was limited to a theoretical exercise that speculates on the possibility and its implications. While practical studies and investigations to reinforce the argument would have benefitted, the complexity of imitating Move 37 is not possible within the scope of the research environment.

Therefore, while this thesis cannot provide practical evidence for the possibility of Move 37 in mass-tailorisation or in the field of architecture in general, the aim of the last two chapters was to set a theoretical framework for mass-tailorisation inviting the possibility of the Move 37 phenomenon into the future of the field of architecture.

SUMMARY AND REFLECTION

CHAPTER SEVEN.
SUMMARY OF RESEARCH FINDINGS, DISCUSSIONS, AND FINAL REMARKS.

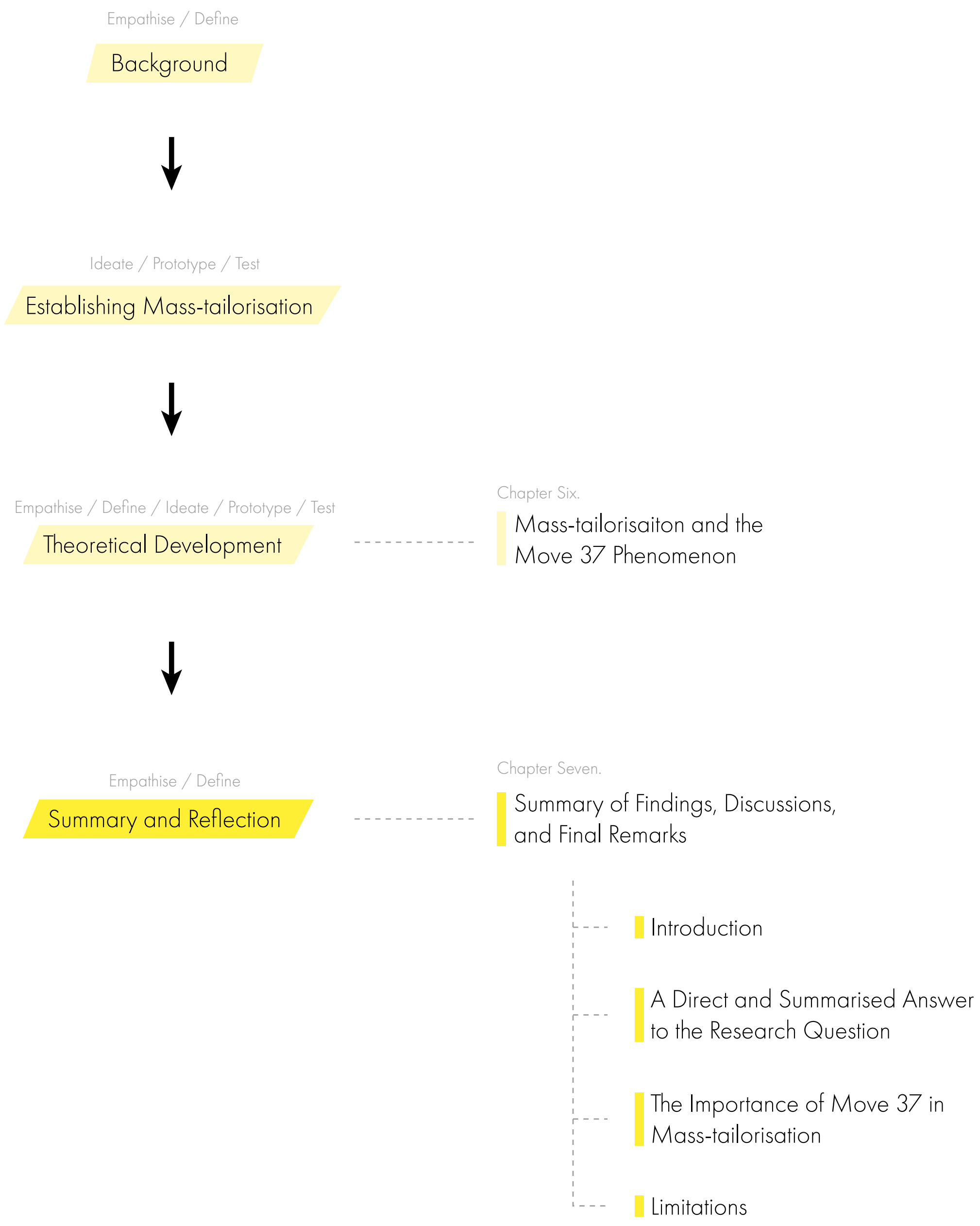

Figure 68. Chapter Seven Structure.

"The thesis proposed the idea of mass-tailorisation as a system to aid in the decision-making of the designer - the companion that will guide the designer in the Monstromart of architecture."

Objectives addressed in this chapter:

2/ Critically define mass-tailorisation as it pertains to architecture.
6/ Speculate on the future possibilities of mass-tailorisation in the architectural context.

1. Introduction

The final chapter of this thesis summarises the research findings introduced throughout the thesis in order to explicitly provide a direct discussion in response to the research question of:

How can a mass-tailorised system, founded on a Design-Fabrication-Assembly Digital Continuum, aid in the decision-making typically undertaken in the architectural design process?

The discussion is then followed by discussing the limitations of the research. The thesis concludes with a short conclusion.

2. A direct and summarised answer to the research question:

This section provides a direct and summarised answer to the research question addressed in this thesis.

Upon the review of the literature at the beginning of the thesis in Chapter 2, the term decision-making was scoped to four key components of the Determinant of Success, the Exploration of Solution-Space, the Selection of Solution(s), and the Critique of Work. Mass-tailorisation can aid the designer in the decision-making process by supporting the designer in all four components to various degrees.

The Determinant of Success – The first stage of the decision-making process is determining the evaluative criteria that will be used throughout the process. More specifically, the evaluative criteria scope the solution space of the options being explored for the decision-making process. It is important to note that this does not assess the success of the decision that is made but only determines the boundaries required for the exploration of options.

For example, a decision-making process for designing the Ford Model T may include determinants such as aesthetics, materials, and cost. These determinants of success will define the options being explored in the next stage of the decision-making process. However, these determinants in themselves do not assess the success of the decision that is made through this process.

This stage of the decision-making process is an important stage as the quality of the following stages are highly dependent on the clarity and relevance of the evaluative criteria in relation to the problem. Irrelevant or unclear evaluative criteria will cause a decision-making process that does not adequately satisfy the design problem.

In this context, as mass-tailorisation systems are heavily reliant upon digital tools that are systematic and quantitative, the use of mass-tailorisation systems will require clear evaluative criteria. The 'specific contextual criteria' as discussed in chapters Three and Four support the establishment of clear evaluative criteria.

In the example of the Burr puzzle, should one Burr puzzle be chosen on the basis of its difficulty in assembly or its aesthetic appeal, these terms need to be clearly defined for the operation of mass-tailorisation. As discussed in Chapter 3, the six most aesthetically pleasing pieces that form a single iteration of the puzzle might be well different from the most aesthetically pleasing version of the Burr puzzle (Refer to pg.52).

The same rigour was applied to the polyominoes phase. During the polyomino exercise for the two-piece, one-dimensional polyomino it was found that depending on the context, the polyomino can have three different answers to the question of: 'How many solutions does a two-piece, one-dimensional polyomino have?'. If only the 'form' of the polyomino was concerned, the polyomino only had a single solution. If 'form' and 'orientation' were concerned, the number of solutions expanded to four, and if 'form', 'orientation', and 'sequence' were concerned, the number of solutions expanded to eight. As such, without having clear evaluative criteria, the rest of the decision-making process may follow an unclear and inapplicable path. The use of mass-tailorisation systems encourages the designer to critically investigate the evaluative criteria, leading to a stronger decision-making process.

The Exploration of Solution Space – The second stage of the decision-making process is exploring the possible options that satisfy the criteria that were set in the previous stage. Mass-tailorisation can aid the designer in this stage of the decision-making also. Notably, the Design-Fabrication-Assembly Digital Continuum of mass-tailorisation plays an integral part in this stage. The successful establishment of a Design-Fabrication-Assembly Digital Continuum increases the credibility of the options by ensuring that any option explored in this stage is able to be accurately carried out to completion. In other words, the Design-Fabrication-Assembly Digital Continuum allows for a robust process of screening – the process of ensuring that the options admitted to the solution space meet the lowest standard set by the decision-maker – as explained in Chapter 2 of the thesis. It is often the case that a proposed design needs to be revised in the later stages of the architectural design process due to the unforeseen impacts of one stage on to another. Often, in mass-customised designs in the field of architecture required constant real-time assessments of buildability as the design was being customised (Kolarevic, 2019). However, by considering all three components from the beginning by establishing a Design-Fabrication-Assembly Digital Continuum, the designer is able to make a decision with increased certainty of delivery, knowing that the solution space has been created upon a robust screening process.

In this thesis, the Burr puzzle was used as an example for establishing the Design-Fabrication-Assembly Digital Continuum. The establishment of the continuum allows the transfer of the same digital information between all three stages, creating a seamless connection. Under such conditions, any iteration of the Burr puzzle that the designer chooses in response to the evaluative criteria is guaranteed to be delivered. In this sense, the Design-Fabrication-Assembly Digital Continuum of a mass-tailorisation system aids the Exploration of Solution Space stage by increasing the credibility of the options that are being explored.

Secondly, the pursuit of the Move-37 phenomenon in mass-tailorisation systems can also aid in the exploration by proposing unforeseen potential solutions. The inherent biases of the designers, as well as the limits of the designer's cognitive comprehension of the evaluative criteria, may limit the solution space being explored. Therefore, through the use of artificial intelligence that is able to process information in a more systematic and logical method, potential solutions that were unforeseen by the designer may present itself – just like the 37th move of the second game between AlphaGo and Lee Se-Dol.

The Selection of a Solution(s) – The third stage seeks to select one or more solutions from the solution space explored in the previous stage. Through the use of artificial intelligence algorithms such as machine learning, mass-tailorisation is able to provide a quantified evaluation of the solution space in response to the evaluative criteria defined in the first stage in order for the designer to make a more informed selection.

This is the stage of the decision-making process at which the Paradox of Choice is most likely to occur, especially if the solution space is large or if many solutions are very similar in responding to the evaluative criteria. The use of artificial intelligence algorithms in the mass-tailorisation system allows for a more precise differentiation between the options in the solution space, broken down to a logical and systematic arrangement that clarifies the differences between the possible solutions.

The beginning of the thesis introduced a question that was addressed to Greg Lynn's Embryological House: "Which house is best?". While it is understandable that Lynn cannot choose a single house because of his affection to all the houses, the use of artificial algorithms in mass-tailorisation will be able to provide a systematic array of houses that will rank them from best to worst subject to the definition of 'best' – the evaluative criteria for the decision-making process.

IIn the example of the Burr puzzle, a mass-tailorisation system will be able to rank the 71.3 billion iterations from best to worst subject to the definition of 'best'. A straightforward example would be 'best' defined in terms of the level of difficulty in assembly. In such a context, the iteration could be ranked on the number of moves required to assemble the puzzle fully. Obviously, it is the duty of the designer to determine whether the iteration with most moves (hardest) or least moves (easiest) is regarded as the 'best' puzzle.

The Critique of Work – The final stage of the decision-making process seeks to reflect on the implications of the selected solution(s) as a response to the evaluative criteria, and evaluate the evaluative criteria itself.

In a similar argument to the Determinant of Success stage of the decision-making process, the use of mass-tailorisation systems will provide systematic and often very quantitative information in regards to the previous three steps of the decision-making process. As such, with the inclusion of more rigorous evaluative criteria to begin with, the information produced throughout the decision-making process can be analysed in easier terms. Therefore, it provides another method of insight for the designer to evaluate the implications of the selected solution as a response to the set criteria as well as evaluating the quality of the set criteria itself.

3. Mass-tailorisation as a tool for the designer of the future – It's all right, the machines aren't taking over the world.

The research takes a very strong pragmatic view on design and design process. However, design is not just programmatic as subjectivity is required by the designer (Amabile, 1983). Such subjectivity encourages the "inherent ambiguity", where "anything is possible" as discussed in Chapter Two (Pressman, 2012, p.19). It is important to note that mass-tailorisation aims to be a tool to aid the designer and not replace the role of the designer. The authorship, as well as the duty of design, still lies with the human designer. Below are three simple reasons to illustrate this argument:

The Decision-making Process – A mass-tailorisation system cannot make a decision by itself. The first stage of the decision-making process needs to begin from the designer – the designer is required to identify the Determinants for Success. As explained earlier in this chapter, the role of mass-tailorisation in this stage is to aid the designer in critically clarifying the evaluative criteria. A mass-tailorisation system as it stands, cannot identify the Determinants for Success on behalf of the designer.

The subjectivity and perception of creativity - A mass-tailorisation system cannot provide a 'creative' solution. As discussed in Chapter Five, creativity is strongly dependent on the perceiver (Refer to pg. 101). As such subjectivity is inherent in a 'creative' solution. This means that without a method to quantify creativity, mass-tailorisation systems will only provide solutions that respond to the evaluative criteria. Whether the generated solutions are perceived as creative is dependent on the context.

The designer's outright ability to ignore the outputs of mass-tailorisation – A mass-tailorisation system only offers an optimum value to the evaluative criteria that is in the specific decision-making context. It is the role of the designer to determine whether the optimum value is the correct value for the overall design context. The designer is not required to follow the most optimum throughout the design process unless quantitative and qualitative efficiency is sought out by the designer.

Finally, while mass-tailorisation systems may be able to provide solutions that are perceived to be 'creative', it is only limited to the cognitive dimension of quantification. The designer's motivation, emotion, cultural context, and personality factors also play an important factor in the human designer's creativity (Boden, 1998). Such factors contribute to the "inherent ambiguity" of the designer, as discussed prior. Therefore, while mass-tailorisation systems may generate creative solutions in the cognitive dimension, it does not harbour the ability nor the self-awareness that enriches the human designer.

4. Current Research Limitations for Future Research

The current research provided a theoretical foundation for the framework of mass-tailorisation that can be used within the architectural context. However, it is limited in its research evidence in providing a practical application for architecture. In addition to the limitations discussed in each chapter, the following are current research limitations that have been identified as future research material.

The Design-Fabrication-Assembly Digital Continuum - the research investigated the establishment of the Design-Fabrication-Assembly Digital Continuum on an independent element – the Burr puzzle. Most works of architecture, as well as the design processes behind them, are complex systems of various elements that have been carefully unified to create a whole. While the Burr puzzle provides complexity of its own nature, there is a need to investigate the Design-Fabrication-Assembly Digital Continuum on a system composed of multiple elements.

The Polyomino and Mass-tailorisation – the research was limited to addressing quantitative factors related to the polyominoes. However, architectural design processes constitute of quantitative and qualitative factors. Therefore, future research could focus on mass-tailorising qualitative aspects of design with a focus on quantifying the qualitative aspects of architectural design processes for it to be used on digital tools.

The Algorithmic Understanding of Mass-tailorisation - As addressed in the Polyomino chapter, this research was limited in gaining an in-depth understanding of the algorithmic processes that are occurring behind the 'black-box'. This has often been described as a challenge in the field of computer science when researching artificial intelligence (Adadi & Berrada, 2018; Samek et al., 2018). Continuous research is required in this aspect of mass-tailorisation to gain a greater understanding of the process inside the 'black box'.

The Move 37 phenomenon - The possibility of Move 37 within the architectural context has been speculated in this research but has not been verified due to limitations caused by timeframe and technical knowledge required to create an algorithm of such complexity. Should the research environment be suitable, this would be important research to undertake.

Finally, the thesis exemplifies the need for multi-disciplinary research.

It is often referred to since the early days of the study of artificial intelligence that computers and artificial intelligence research run in parallel to the study of our minds and thought processes (Hunt, 1968). As such, this thesis, in its most basic elements, is involved with the field of architecture, computer science, and psychology. Furthermore, such research can easily be expanded to incorporate the fields of neuroscience, philosophy, and economics.

Therefore, the thesis has strength in the breadth of research but has a weakness in the depth of the research. The researcher does not assume backgrounds in these various fields; hence, in some instances throughout the thesis, the research of other fields may be elementary and informal. As such, the research can be an educated conjecture in some parts. To comprehensively test such a thesis, a multi-disciplinary research team that can engage with the idea of mass-tailorisation in multiple facets will employ mass-tailorisation in its full potential.

5. Final Remarks - Conclusion

To design is to create - to conceive and plan out in mind in order to bring into existence the product of the decision-making processes of the designer (Refer to pg.21). In this sense, perhaps every designer navigates the Monstromart of architectural design in order to 'find' the best design decisions from the possibilities of the mind. To navigate such Monstromarts can be daunting and even paralysing - one can easily lose their path or face the Paradox of Choice. In response, the thesis proposed the idea of mass-tailorisation as a system to aid in the decision-making of the designer - the companion that will guide the designer through the Monstromart of architecture.

The thesis investigated the theoretical framework of mass-tailorisation through several phases of case studies that aimed to critically assess the viability and the implications of the components that constitute the mass-tailorisation system. Thus, the findings of the case studies led to an integrative theoretical statement on the validity of mass-tailorisation.

A mass-tailorisation system, through the use of artificial intelligence and founded on a Design-Fabrication-Assembly Digital Continuum, will empower the designer with tools to aid the decision-making process in architectural design. More specifically, mass-tailorisation will aid the designer with:

- **clearer evaluative criteria** (through the specific contextual criteria, and the systematic and quantitative nature of the digitally based mass-tailorisation system),

- **robustly screened potential options** as well as **the possibility of introducing any unforeseen options** (through the Design-Fabrication-Assembly Digital Continuum and the pursuit for Move 37 phenomenon),

- **systematically differentiating the options to reduce the risk of facing the paradox of choice** and increase the ease of selection (through the use of artificial intelligence algorithms), and

- **analytical evaluation of the decision** that has been made (through the systematic and quantitative nature of the digitally based mass-tailorisation system).

It is important to note that this thesis establishes the theoretical framework for the idea of mass-tailorisation. Thus, the scope of the research was insufficient in testing the practical implications of the theoretical framework. Therefore, current research limitations and opportunities for future research have been identified that mainly aim to investigate the practicalities of mass-tailorisation. However, perhaps the most significant limitation to this research and the most significant opportunity for the future lies in a multi-disciplinary approach to the investigation of mass-tailorisation in order to understand the multiple facets involved with the theoretical and practical implications of the system.

The practicalities of architecture, in reality, may not allow most designers to create 50000 design solutions like Greg Lynn (1999) and say in absolute confidence that they are all perfect in their own way. However, mass-tailorisation will be able to ensure that the realised design solutions, although limited in quantity, consider both the quantitative and perceived qualitative process and outcomes of the decision-making contained in the architectural design process.

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Mass-tailorisation

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