COMPUTATIONAL DESIGN IN INDUSTRIAL DESIGN: AN INITIAL INVESTIGATION

Master of Science Thesis
Computational Design in Industrial Design: An Initial Investigation

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ABBREVIATIONS

CD: Computational Design
DP: Design Process
ID: Industrial Design
PD: Parametric Design
AD: Algorithmic Design
GD: Generative Design
GPD: Generative Product Design
SGs: Shape Grammars
SI: Swarm Intelligence
TO: Topology Optimization
AM: Additive Manufacturing
AI: Artificial Intelligence
ML: Machine Learning
GANs: Generative Adversarial Networks
CE: Circular Economy
MOO: Multi-Objective optimization

The thesis cover is a tribute to "Neri Oxman: Material Ecology — The Catalogue" by Paola Antonelli and Anna Burckhardt, designed by Irma Boom. This book deeply inspired me to choose this graduation topic. The images are created with Midjourney.

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EXECUTIVE SUMMARY

The project aims to understand the relationship between computational design (CD) and industrial Design (ID). A secondary objective is to investigate initial possibilities for CD adoption in ID.
CD can be defined as a shift in design representation and thinking that has significant implications for the design process and its outcome.

"COMPUTATIONAL DESIGN IS **DESIGN REPRESENTATION** IN ITS **COMPUTATIONAL LOGIC** RATHER THAN ITS GEOMETRIC ASPECTS."
CAETANO ET AL. (2020)

Traditional CAD only supports human decisions, while, with computational and generative approaches, machines become active participants in the design process, arriving at the point of producing actual design content in collaboration with the designer. (Mountstephens & Teo, 2020).
CD allows designers to approach design problems from a different angle. Instead of focusing on a single artifact, they can define a process or system able to generate a series of outputs, related to a design problem.
This approach requires a change in the designers' mindset. The first step is defining the constraints and goals necessary to create the computational system in charge of exploring the design space. These boundary conditions can be associated with project requirements, environmental factors, user preferences, and the personal sensitivity of the designer.

CD can increase efficiency during the design process by automating design tasks. Furthermore, CD also stimulates creativity by encouraging designers to frame design problems differently and by exposing them to a large number of solutions that are sometimes beyond human imagination. The exploration of the design space depends on the generative capabilities of the algorithm used and is often unrelated to past products. Therefore, the solutions created through CD can go beyond typology, resulting in unexpected outcomes such as those typical of topology optimization.

The project is a research about the role of CD in ID at 360 degrees. The thesis covers CD origins and theoretical aspects, such as those linked to applying evolutionary processes inspired by nature to design. Comprehending these concepts is fundamental to understanding the thinking behind CD and its relevance in ID. Furthermore, these theoretical notions can help in applying CD beyond the opportunities or cases presented in this thesis.

The project also investigates CD methodologies. Among these, genetic algorithms stand out for optimization and design space exploration, while architected materials enable higher levels of control over geometry.

The potential of CD in ID is outlined through a series of opportunities, such as the ability to:
Explore a vast solution space, which can lead to new and innovative designs, augmenting creativity.
Optimize technical requirements, from mechanical performances to those related to sustainability.
Achieve hyper-control over geometry, which can lead to structures that can enable different mechanical properties and functions using a single material.
Automate parts of the design process, which can increase efficiency and scalability.
Create mass-customized products and configurators meeting the specific needs of individual users.

The first part of the thesis discusses CD's present and past; the second part instead focuses on testing the water for possible adoption of the methodology among industrial designers.

The collaboration with VanBerlo (Accenture Industrial Design) was fundamental to outline the perspectives of industrial designers on CD and in particular their view on opportunities and barriers to adopting the methodology. The research revealed a deep interest in CD: participants identified a vast range of opportunities from sustainability to using configurators for user research. However, there is a need to explore CD nature and its future opportunities.

The thesis concludes with a series of recommendations for making CDs more accessible and usable in a professional context.

Since CD enables possibilities that were never imagined before, this report aims to give the reader a greater understanding of the relationship between CD and ID. Furthermore, the report examines practitioners' views on the opportunities and barriers to CD adoption in order to understand the basis for future integration in ID. This thesis intends to contribute to making CD more accessible, hence spreading its use in ID.

CONTENTS

1 INTRODUCTION

1.1 MOTIVATION AND PROBLEM DEFINITION

Computation permeates almost every aspect of our lives and has changed, at an exponential rate, how we communicate, work, and use products and services.
The integration of computational methods has also impacted fields that may appear distant from computation and disciplines like digital humanities have emerged. For example, algorithms have been utilized to explore philosophical questions (MIT News, 2022).
Architecture, a field often closely linked to industrial design (ID), has a substantial history of being influenced by computational techniques, that have impacted both the theoretical and practical aspects of the discipline (Savov, 2020). The use of computational tools, from parametric design to generative algorithms, influenced the architectural landscape in our cities and how buildings look, perform, and are designed (Caetano & Leitão, 2019).
While in architectural design Computational Design (CD) has been explored both in academic and professional practice, in ID this has been only partially investigated. Therefore, researching the CD ecosystem and narrowing it down to product design is a worthwhile research topic. (Mountstephens & Teo, 2020).
Computational and generative approaches could profoundly change the industry, influencing the design process and the creation of products with new performance levels. (Saadi, 2023)
However, further research is needed to fully understand its impact. Collaboration between academia and industry, as well as real-world testing, is crucial (Mountstephens & Teo, 2020).

One of the main challenges in adopting the methodologies is the lack of knowledge in the design community, and the economic and time investment in understanding theory and techniques might be considered prohibitive. (Zhang & Huang, 2023)
Nevertheless, a growing number of companies like Nike, Adidas, HP, Apple, and Samsung are exploring CD's potential.
CD is emerging as a transformative force in industrial design, with growing interest from both academia and industry. Bridging the gap between these two realms and addressing knowledge barriers are critical steps toward unlocking the full potential of this approach.

A problem that the thesis wants to address is the lack of a source collecting information relating to CD in the context of ID. This collection of information is necessary to unveil CD methodologies relevant to ID, the implications for the design process, and the opportunities that are created in the design of industrial products.

The thesis also aims to gather information about industrial designers' attitudes toward CD and the consequent development of strategies aimed at facilitating CD adoption.

"TODAY, I FEEL AN IMPERATIVE IN OUR NEED TO RETHINK THE IMPLICATIONS OF COMPUTATIONS IN THE DESIGN OF PRODUCTS AND SERVICES BECAUSE WE'RE AT A TURNING POINT THAT WILL IRREVERSIBLY IMPACT THE FUTURE OF HUMANKIND. WE ARE CURRENTLY ON COURSE TO REACH THE SINGULARITY IN A COMPLETELY INEQUITABLE WAY FOR THE MANY HUMAN BEINGS WHO DO NOT SPEAK MACHINE. AT OUR CURRENT RATE OF PROGRESS, AND WITH A MINORITY OF COMPUTING HAVES WHO WILL LORD THEIR VISION OVER THE COMPUTING HAVE-NOTS, WE WILL PERMANENTLY CHISEL INTO THE CLOUD THE BIASES OF A NARROW BAND OF FLUENT CREATORS."
(MAEDA, 2019, P. 99)

1.2 INTRODUCTION TO COMPUTATIONAL DESIGN

In a Computational Design (CD) approach, designs, or parts of a design are produced by algorithms. The key difference with traditional CAD is that actual design content is produced by a machine without the need for the designer's active manipulation. (Mountstephens & Teo, 2020)

"THE PROCESS IS MORE IMPORTANT THAN THE OUTCOME. WHEN THE OUTCOME DRIVES THE PROCESS, WE WILL ONLY EVER GO TO WHERE WE HAVE ALREADY BEEN. IF THE PROCESS DRIVES THE OUTCOME, WE MAY NOT KNOW WHERE WE ARE GOING, BUT WE WILL KNOW WE WANT TO BE THERE."
BRUCE MAU, MANIFESTO FOR GROWTH, 1998, AS CITED BY TEDESCHI (2014)

When adopting a computational approach to design, the designer focuses on formulating the methodology or the process for generating a design rather than the design itself (Tedeschi, 2014). In addition to saving time thanks to more efficient exploration, the designer is exposed to a greater quantity of solutions that can be completely new and therefore stimulate creativity and innovation.

Jacobs and Buechley (2013), as cited in (UniGe, 2021), identify three groups of advantages that a computational approach could bring to design:

- "Precision and automation: Computation affords high levels of precision and allows for automation of repetitive tasks, enabling the rapid development and transformation of complex patterns and structures.
- Generativity and randomness: Computation allows for the programmer to design algorithms which, when run, allow for the computer to autonomously produce unique and often unexpected designs.
- Parametrization: Computation allows users to specify a set of degrees of freedom and constraints of a model and then adjust the values of the degrees of freedom while maintaining the constraints of the original model."

The definition of the term Computational Design (CD) will be further investigated in Chapter 2.

1.3 PROJECT CONTEXT: VANBERLO PART OF ACCENTURE

The project has been conducted in collaboration with the design agency VanBerlo (Accenture Industrial Design). The project aimed to leverage the collaboration with VanBerlo to gain an understanding of Industrial Design (ID) practitioners' perspectives on Computational Design (CD). VanBerlo is one of the largest design agencies in the Netherlands and, in a certain sense, represents a continuously ongoing design process. Thus, developing the project in collaboration with the agency was instrumental in investigating the design process in a real-life context to understand where CD can contribute. Furthermore, VanBerlo brought diverse expertise to the project. For these reasons, the agency represented the perfect ecosystem for developing the graduation project. Working daily at the agency enabled the possibility to collect direct feedback from the industry. The agency is willing to create a CD group and wants to invest time and effort into better understanding this field. VanBerlo is noticing these tools' impact on the design process and is convinced that their influence will increase in the future. On the one hand, there is an interest in discovering CD's creative potential. On the other hand, there is a need for a prepared framework and a lens to analyze the CD tools that appear at a fast pace. The agency is interested in integrating and testing CD tools/approaches and their opportunities in ID. Furthermore, VanBerlo is interested in gaining a better understanding of this topic and finding a framework and methodology to engage with it effectively. According to the research, one of the main issues is designers feeling overwhelmed by the abundance of information when approaching this topic. The lack of clarity associated with the term CD seems to limit the exploration of the possibilities of the approach itself. For this reason, obtaining significant results in a short time frame can be challenging and may even discourage one from approaching the topic at all.
Thus, through this report, the project aims to create more clarity about the CD domain, since this can serve as a basis to approach CD cohesively and efficiently.
Thus, through this report, the project aims to create more clarity on the CD domain that can serve as a basis to approach CD cohesively and efficiently.

1.4 RESEARCH QUESTIONS AND OBJECTIVES

The project was developed between two main research fields: Computational Design (CD) and Industrial Design (ID). The research has focused on CD and its intersection with ID.

The research space of the project is represented in Figure 1

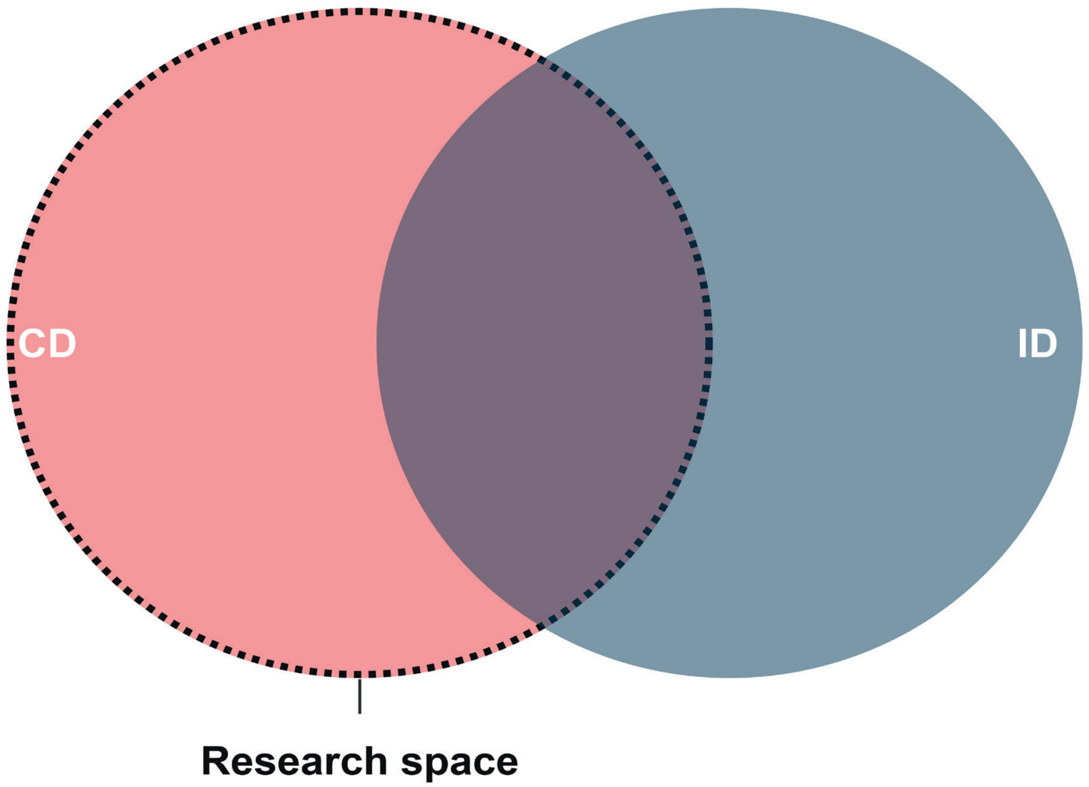


Figure 1: The project's research space

The primary objective of the thesis is to understand CD as a discipline and consequently its implications in the field of ID. The research questions linked to this objective and addressed through literature research and CD expert interviews are:

RQ 1: WHAT ARE THE **THEORETICAL CONCEPTS** THAT CONTRIBUTED TO CD DEVELOPMENT?
RQ 1.1: WHAT ARE THE RELEVANT **CD METHODS** FOR ID?
RQ 1.2: WHAT ARE THE IMPLICATIONS OF IMPLEMENTING CD FOR THE **DESIGN PROCESS** AND THE **ROLE OF THE DESIGNER?**
RQ 1.3: WHAT ARE THE **OPPORTUNITIES** THAT CD CREATES IN THE DESIGN OF INDUSTRIAL PRODUCTS?

The secondary objective of the thesis is to explore possibilities for the future adoption of CD in the field of ID. To achieve this, interviews and a focus group were conducted to understand the perspective of VanBerlo's industrial designers toward CD. These research questions aimed at understanding ID professionals' point of view on CD:

RQ 2: WHAT IS THEIR **BASE KNOWLEDGE ABOUT CD**?
RQ 2.1: WHAT ARE THEIR **LEARNING HABITS** WHEN ACQUIRING A NEW SKILL?
RQ 2.2: WHERE DO THEY SEE **OPPORTUNITIES** IN INCORPORATING CD INTO THEIR PROCESSES?
RQ 2.3: WHAT ARE THE MAIN **BARRIERS** TO IMPLEMENTING CD IN INDUSTRIAL DESIGN?

As part of the efforts to explore possibilities for future adoption of CD, preliminary design activities, aimed at communicating knowledge about CD to VanBerlo designers, were carried out.
The next group of research questions are:

RQ 3: HOW TO VISUALIZE CD POSSIBILITIES AND THEIR INTERSECTION WITH THE DESIGN PROCESS?
RQ 3.1: HOW TO GIVE AN IMMEDIATE SENSE OF CD POSSIBILITIES?
RQ3.2: HOW CAN CD POSSIBILITIES BE CATEGORIZED AND VISUALIZED, GIVING A SENSE OF THE ENTIRETY OF CD?
RQ3.3: WHAT TOOL CAN BE USED IN THE FUTURE TO BETTER UNDERSTAND AND UTILIZE CD IN ID?

The thesis is divided into two parts. The first part covers the research on CD in ID (RQ1). The second part discusses RQ2 and RQ3: the future adoption of CD from the perspective of ID professionals and recommendations for integrating CD. It should be kept in mind that the research aspect on CD has been prioritized as a precondition for the project. Consequently, the strategies remain in a preliminary state and are not intended as complete design solutions, but as recommendations for a possible future development of this thesis. The relationship between objectives, RQs, methods and thesis chapters is visualized in Figure 2.

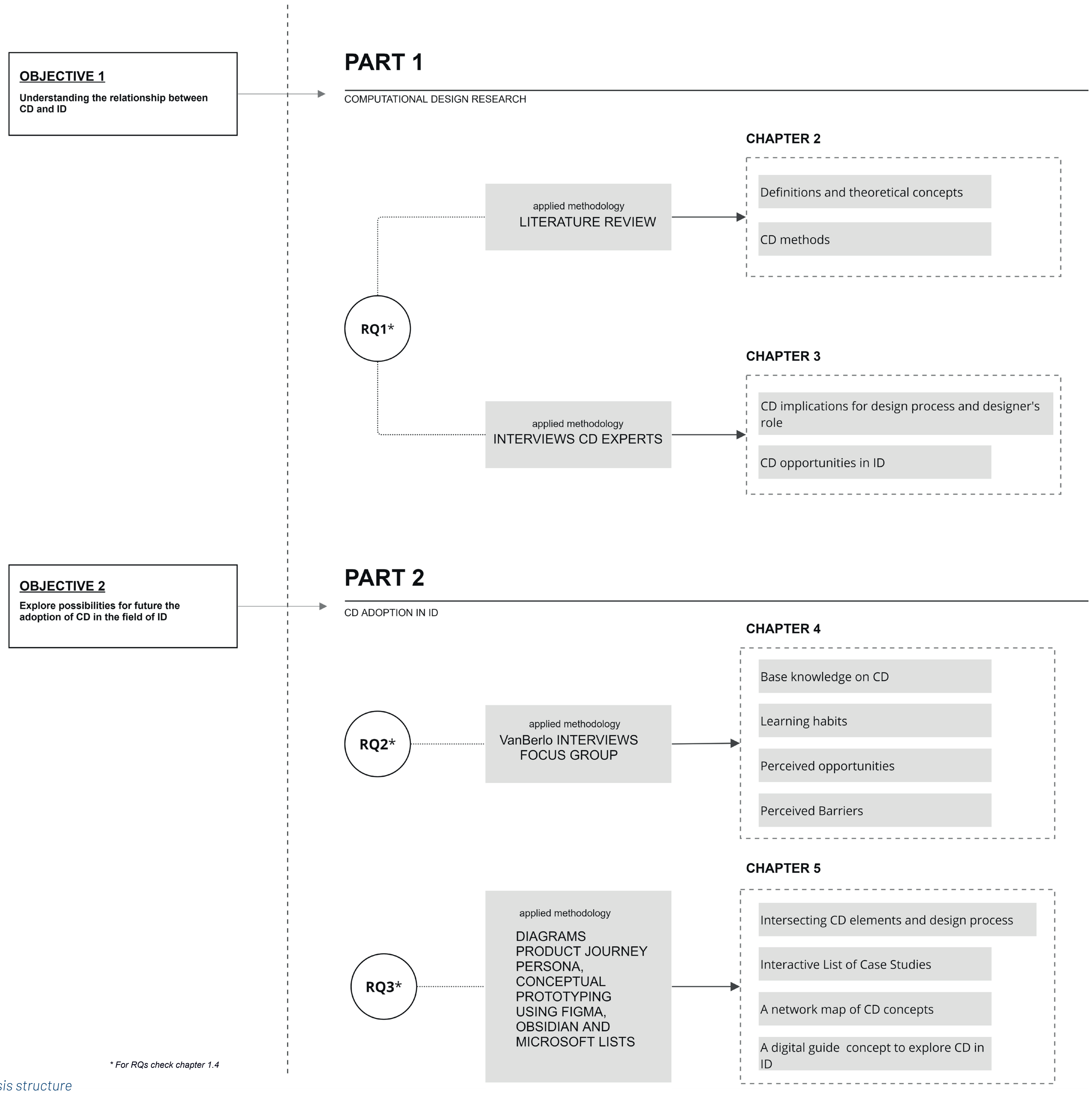


Figure 2: Relationship between RQs and thesis structure

1.5 RESEARCH METHODOLOGY

This section gives an overview of the research methodology used to answer the research questions described in the previous section. Detailed descriptions of the methodologies adopted during the research can be found in sections 2.1 and 4.2.

The first block of research, addressing RQ1, focused on comprehending the significance of the term Computational Design (CD), its background, principles, techniques, and its relevance in designing industrial products. The methods used to explore this theme were literature research, CD expert interviews, and some practical experiments that aimed at creating a connection between the opportunities identified and VanBerlo activities. While the literature research uncovered important aspects of CD theory and methodologies, expert interviews were instrumental to understanding the point of view of CD practitioners and focused on tools, processes, skills, and opportunities.

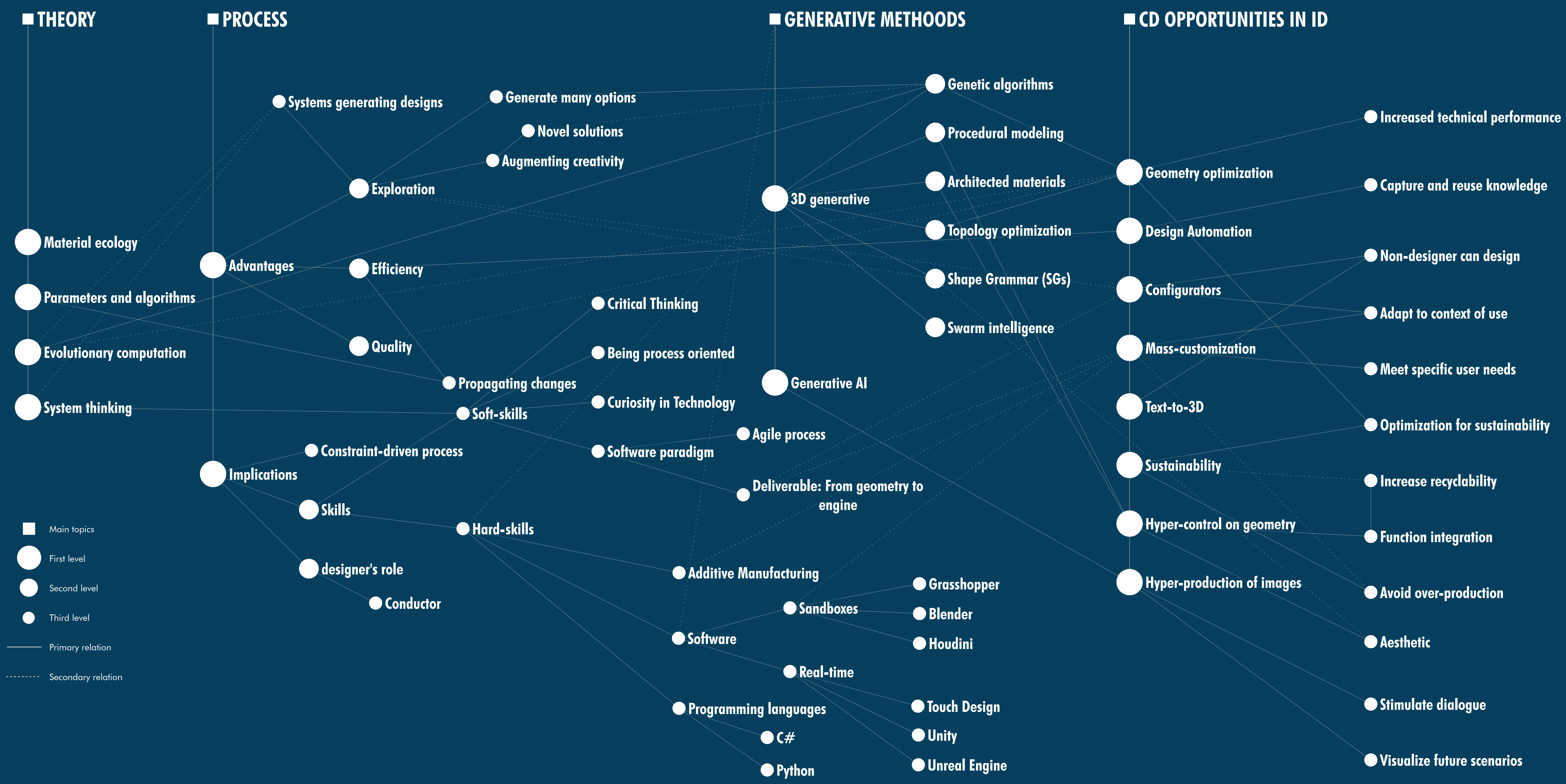
The secondary objective of the thesis is to explore possibilities for future the adoption of CD in the field of ID. Therefore, research was conducted with designers at VanBerlo who are considered in this thesis potential future users of CD.

The second part of the research, addressing RQ2, focused on gaining insights into the perspective of VanBerlo professionals toward CD. Research in collaboration with a design agency was necessary to outline professionals' perspectives toward CD. In this phase, the professionals were involved in interviews and group conversations to discuss and explore various aspects of the subject: from their current vision on CD to opportunities and barriers concerning the potential adoption in the professional world.

The third block of activities, addressing RQ3, focused on outlining initial strategies to empower CD novices to navigate the topic's information space following their needs. The structures of the designs presented are informed by discussions, interviews, and focus group within the agency and are aimed at facilitating the understanding and application of CD in a professional context. Visual and interactive artifacts were developed to illustrate the interconnections between CD and Industrial Design (ID).
These suggestions aim to illustrate CD and its benefits to spark interest and willingness to invest time in exploring the approach. In this phase, the following works have been developed:

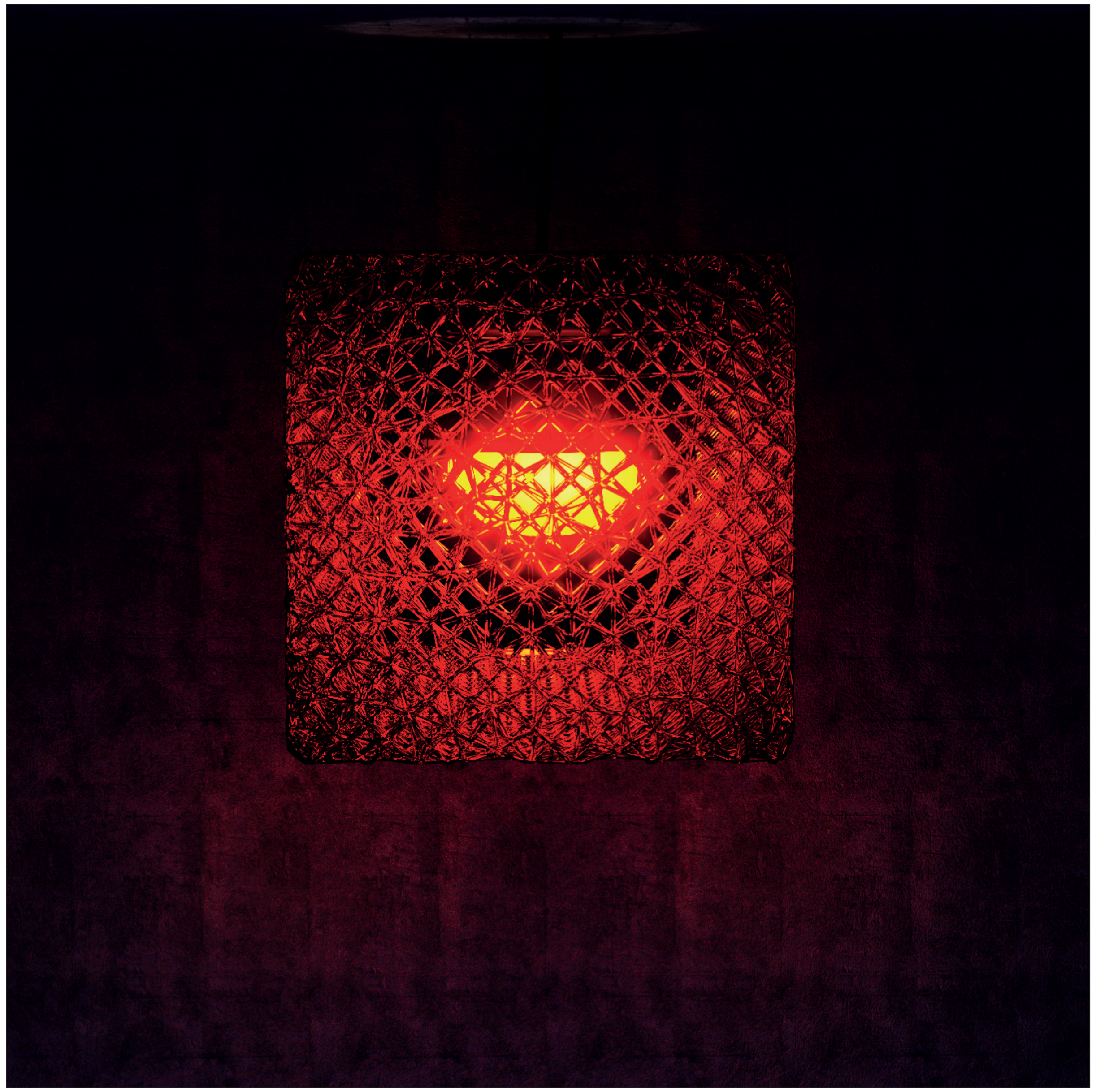
1. A visual diagram intersecting characteristic elements of CD with a classic representation of the design process (the Double Diamond model).
2. An interactive list of case studies visualizing the applications of computational techniques in ID through industry case studies. Practitioners might use the list to explore some products designed using CD while tracing a link between the product and the computational strategy used.
3. A network map of the main concepts in CD and their effect on ID to illustrate the topic's complexity and its interrelationships.
4. A digital guide concept to assist individuals in navigating the use of various strategies and discovering the benefits of CD in their profession. This concept has been developed in a limited amount of time and has not been tested yet.

These artifacts (Chapter 5) should be seen as recommendations for future development, and they are not the project's culmination but instead, just a glimpse of what visuals and tools to integrate CD in ID could be.



PART 1 RESEARCH ON COMPUTATIONAL DESIGN

Network diagram of the concepts in Part 1



Lamp and render from the thesis's author. Generative method: lattice structures. Software: Grasshopper

2
COMPUTATIONAL DESIGN THEORETICAL CONCEPTS AND METHODS

This chapter aims to answer these research questions:

RQ 1: WHAT ARE THE **THEORETICAL CONCEPTS** THAT CONTRIBUTED TO CD DEVELOPMENT?
RQ1.1: WHAT ARE THE RELEVANT **CD METHODS** FOR ID?

This chapter seeks to address these questions, initially approaching them from a broad, abstract standpoint. It starts by exploring the **definitions and theoretical concepts** (2.3) that have played instrumental roles in shaping CD as a field of research. The understanding of these concepts is necessary to create the proper mindset to adopt CD and possibly explore it beyond the opportunities presented in this thesis.

As the discussion progresses, the focus narrows to examine **generative methods** (2.4) within the industrial design domain. Generative methods in CD refer to a set of techniques and algorithms used to generate, optimize, explore, and manipulate designs through automated processes. (Mountstephens & Teo, 2020 The identification of these methods was deemed necessary, to identify long-lasting methods independent from specific software that might quickly change with the discipline development.

2.1 METHODOLOGY: LITERATURE REVIEW

The first step toward building an understanding of CD consisted of extensive literature research to gain a comprehensive overview of previous academic works on computational design to create a solid foundation and understanding of the field's current state while identifying gaps in existing knowledge.

After analyzing the numerous definitions of CD in the academic literature, the research continued to clarify the terminology commonly used in the field (Generative, Parametric, Algorithmic Design), which might be confusing at times (Caetano et al., 2020).
After an analysis of CD's definitions and terminology, the literature review continued examining the history and development of the field. Two key factors emerged as significant drivers of its advancement:

• The development of theoretical concepts that defines the reasons and significance of applying digital tools in design.
• Technological advancements in tools and methods have opened new possibilities for solving design problems.

The first part of the literature review was essential to explore how academics and practitioners worked to develop a framework for utilizing digital technologies in design. Specifically, the investigation aimed to identify how computational tools could enhance the design process, the intended applications of these tools, and how this shift would impact the role of designers, architects, and creativity in general.

Given that most of the sources focused on architectural design, after an initial analysis of CD, the research shifted to locating literature exploring the role and utilization of computational design in industrial design. In this regard, two specific papers were chosen for in-depth analysis. The first paper (Mountstephens & Teo, 2020) examined the development of computational design in the context of designing physical products through an overview of case studies. The second paper (Isgrò et al., 2022) provided a comprehensive overview of artificial intelligence (AI) tools for design not specific to industrial design. The paper offered an overview of AI tools associated with phases of the design process and design activities.
The literature review was fundamental in extracting the main theoretical concepts (section 2.3) and generative methods in CD (section 2.4). In addition to this, from this research emerged an interesting concept: blending the phases of the design process, using technical requirements to inform conceptual explorations. (Mountstephens & Teo, 2020)

The literature review effectively clarified various definitions (section 2.2) and terminologies associated with CD (section 2.2.1). It delineated the pivotal theoretical concepts that have been instrumental in CD's development (section 2.3). Comprehending these concepts is crucial to understanding the rationale behind adopting a Computational Design approach.
The benefits of leveraging CD, as outlined in academic literature, were identified, as were the primary generative methods that can be harnessed to generate and optimize geometry. In parallel, the role of Generative AI in the context of CD and industrial design was analyzed. However, given the complexity and breadth of this topic, a comprehensive analysis exceeds the scope of this project. The focus remains on gaining an understanding of CD's role and potential in industrial design, with the intention of fostering further exploration in this domain in the industrial design community, especially within VanBerlo and Accenture.

2.2 OVERVIEW OF COMPUTATIONAL DESIGN DEFINITIONS

Outlining a univocal definition for computational design (CD) is a challenging task due to the multidisciplinary nature of the discipline and the continuous advancement in technology. Moreover, there are multiple definitions online and in academic literature; they often overlap to a certain extent and address various aspects of the approach with different levels of abstraction. (Caetano et al. 2020) At the same time, the definition of "design" is often multifaceted. This section attempts to define computational design by collecting and comparing the definitions found during literature research.

Computational Design: Computation + Design.

The first word of the term (computational) refers to the act of performing computations and calculating, while the second one (design) refers to the act of designing, representing how a product, a service, or a building should be built or produced. (Cambridge, 2023)

MIT's design and computation group describes its goal as it follows:

"THE DESIGN AND COMPUTATION GROUP INQUIRIES INTO [...] THE WAYS IN WHICH DESIGN MEANING, INTENTIONS, AND KNOWLEDGE ARE CONSTRUCTED THROUGH COMPUTATIONAL THINKING, REPRESENTATION, SENSING, AND MAKING. WE FOCUS ON THE DEVELOPMENT OF INNOVATIVE COMPUTATIONAL TOOLS, PROCESSES, AND THEORIES, AND THE APPLICATION OF THESE IN CREATIVE, SOCIALLY MEANINGFUL RESPONSES TO CHALLENGING DESIGN PROBLEMS."
(DESIGN AND COMPUTATION GROUP, MIT, N.D.)

In the above-mentioned quote, the first term, associated with the word computational is the word thinking . This quote highlights the importance of computational thinking as a fundamental aspect and a requirement for comprehending the field of computational design. Computational thinking could be defined as the mental skills and practices to designing computations that get computers to do jobs for us and explaining the world as a complex information process. (Denning & Tedre, 2019)

The job of a designer comprehends a diverse set of tasks. However, representation plays a central role in bringing an idea from conceptualization to realization.

"ARCHITECTS DO NOT MAKE BUILDINGS, THEY MAKE DRAWINGS OF BUILDINGS." (EVANS AS CITED BY TEDESCHI, 2014)

In industrial design, a significant aspect of the job involves capturing and representing an idea or concept with an increasing level of detail as the design process evolves, ultimately resulting in a fully engineered and production-ready design.

Caetano et al. (2020) give a definition of CD centered around the role of representation in design:

"COMPUTATIONAL DESIGN IS DESIGN REPRESENTATION IN ITS COMPUTATIONAL LOGIC RATHER THAN ITS GEOMETRIC ASPECTS." CAETANO ET AL. (2020)

The professional application of Computational Design methods can provide insights into how the discipline can play a valuable role throughout design representation. Algorithm Aided Design (Tedeschi, 2014) presents a fine example of the paradigm shift in design representation, in this case, through three main stages (Figure 3):

Sketch:
The direct link between an idea and signs on paper is mediated by the hand's gesture and a drawing tool.
Digital drawing:
The simulation of the hand in a digital environment, with the mouse as an extension of the brain. Still a manual process, with an incredibly increased level of precision and ink substituted by pixels and bits.
Algorithmic Design:
In this form of representation, computational logic is used to give life to the system, representing the design idea. This system can respond to variation allowing the designer to explore a wider solution space.

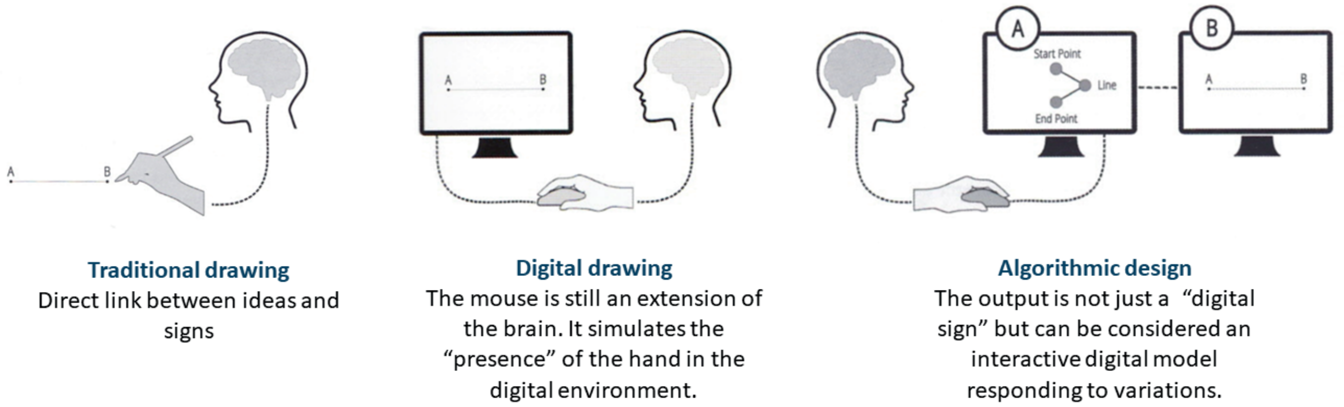


Figure 3: Shift in design representation from (Tedeschi, 2014)

Distinguishing between traditional CAD -or "digital drawing" in the stages mentioned above- and CD can sometimes be challenging. The unclarity is partly because some traditional software incorporates certain aspects of CD and possesses parametric capabilities. A parametric model is one where components of a design are interconnected and change simultaneously in a harmonized and organized manner (Woodbury, 2010). However, such software is limited to simulating the presence of the hand in a digital environment through the mouse -sometimes with the addition of parametric associations- and lacks traditional or visual programming (Figure 4) as the primary interaction tool with the geometry, thus, missing the generative aspect, an integral part of the computational design practice. These differences are schematized by Tedeschi (2014) in Figure 3. Parametric and generative capabilities will be further analyzed in sections 2.2.1 and 2.4.

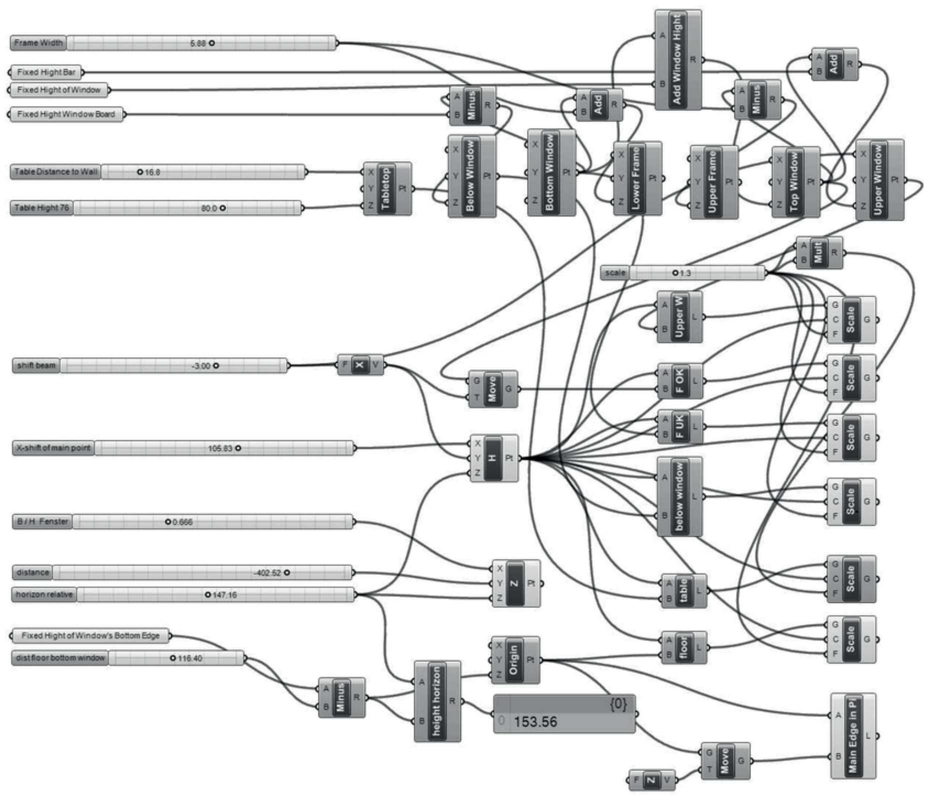


Figure 4: Visual programming in Grasshopper from Lordick (2012)

Oxman (2006) suggested that the term CD applies to design processes that make full use of computers, leveraging their computational abilities, rather than just using them as digital and precise drafting tools, as often happens with traditional CAD tools. Through this approach, it is possible to steer and influence the design process by increasing the degree of information in the system rather than reorganizing it. (Menges & Ahlquist, 2011) In this framework, distinguishing between traditional CAD and CD is fundamental to discerning between computerization (traditional CAD) and computation in design (Menges & Ahlquist, 2011). The differences are highlighted in Figure 5.

The definitions from Caetano et al. (2020) and Oxman (2006) helped outline computational designing as a shift in design representation enabled by leveraging computational tools instead of using them as electronic drawing boards. The following definition will focus on a change in thinking regarding the goal of the design process goal: designing the process instead of designing the output.

Figure 5: Differences between Computation and Computerization adapted from (Menges & Ahlquist, 2011)

Computerization		Computation
• **Compile**	**VALUES**	• **Deduce** results
• Same level	**INFORMATION**	• Increases the amount and specificity
• A computer-aided approach: **methods of organising information**		• A computational approach: enables **specific data** to be **realised out of initial abstraction**

" ALGORITHMIC DESIGN ENABLES USERS TO DESIGN A PROCESS RATHER THAN A SINGLE OBJECT"
(TEDESCHI, 2014)

This last definition from Menges & Ahlquist (2011) aims to define the underlying reasons for applying a CD approach:

"THE APPROACH FOR COMPUTATIONAL DESIGN IS ONE WHICH FOCUSES ON THE EXECUTION OF VARIATIONAL METHODS FOR THE PURPOSEFUL INTENT OF RESOLVING COMPLEXITIES THAT EXIST IN THE INTERRELATIONS AND INTERDEPENDENCIES OF MATERIAL STRUCTURES AND DYNAMIC ENVIRONMENTS." (MENGES & AHLQUIST, 2011)

According to Menges & Ahlquist (2011), computation in relation to design is the processing of information and interactions between elements that constitute a specific environment. In the book, Computational Design Thinking by Menges & Ahlquist (2011), the definition above of computational design is preceded by a perspective on architecture seen as a system developed through "the understanding of materials parts, and social engagement, shaping form space and structure." Arguably, a similar framework could be applied to industrial design where the interactions and information mentioned above take the form of to the multitude of requirements of a design problem, like sustainability, appearance, technical and economic performance, ergonomics, and more. In physical product design, most of these requirements can be met through the design of product geometry.

Therefore, CD consists of using tools to design the process of exploring (some) of these relationships and solving the complexities characterizing design problems.

Each definition offered is essential in constructing a comprehensive understanding of CD, encompassing both theoretical and practical perspectives that are equally necessary for the adoption of CD in the industrial design practice.

Using computational and generative tools in design could lead to work more efficiently, fostering a "fail fast" approach and opening a design space of possibilities and solutions beyond human possibilities (Saadi & Yang, 2023).

Conclusions

In essence, the definition of computational design is complex due to the multifaceted nature of the term and its ever-evolving technological landscape. CD combines the act of computation with the process of design. It requires a blend of computational thinking and representation skills to conceptualize and manifest ideas into reality. CD is not solely a representation of the design in its geometric aspects but also in its computational logic. CD provides an approach that allows designers to work more efficiently and explore a broad range of solutions beyond human capacity, thereby reshaping the traditional design process. The adoption of CD in industrial design necessitates a comprehensive understanding of its theoretical and practical aspects.

2.2.1 DEFINING CD RELATED TERMS: PARAMETRIC, ALGORITHMIC AND GENERATIVE DESIGN

Breaking down the term computational design further, we find three terms that are sometimes confused and overlap with each other: Parametric Design (PD), Generative Design (GD), and Algorithmic Design (AD).

The following definitions are extracted from (Caetano et al., 2020):

PD: "WE CAN SYNTHESIZE PD INTO A DESIGN PROCESS BASED ON ALGORITHMIC THINKING (JABI, 2013); (JABI ET AL., 2017) THAT USES PARAMETERS AND RULES TO CONSTRAIN THEM. THEREFORE, PD IS AN APPROACH THAT DESCRIBES A DESIGN SYMBOLICALLY BASED ON THE USE OF PARAMETERS."

GD: " WE DEFINE GD AS A DESIGN PARADIGM THAT EMPLOYS ALGORITHMIC DESCRIPTIONS THAT ARE MORE AUTONOMOUS THAN PD. IN GD APPROACHES, AFTER STARTING THE GENERATIVE PROCESS, THE SYSTEM EXECUTES ENCODED INSTRUCTIONS UNTIL THE STOP CRITERION IS SATISFIED. CONSEQUENTLY, GD-BASED METHODS CAN GENERATE COMPLEX OUTPUTS EVEN FROM SIMPLE ALGORITHMIC DESCRIPTIONS."

AD: " WE CONSIDER AD A DESIGN PARADIGM THAT USES ALGORITHMS TO GENERATE MODELS AND, THEREFORE, WE ALSO CONSIDER IT GENERATIVE. NEVERTHELESS, IN AD, A CORRELATION BETWEEN THE ALGORITHM AND THE GENERATED MODEL EXISTS, THUS PROVIDING TRACEABILITY AND ALLOWING THE USER TO IDENTIFY THE PARTS OF THE ALGORITHM THAT GENERATED A GIVEN PART OF THE MODEL. IN A SENSE, IN AD, THE ALGORITHM IS ISOMORPHIC TO THE MODEL. ACCORDING TO THIS DEFINITION, AD IS A SUBSET OF GD, WHERE THE ALGORITHMIC DEVELOPMENT FOCUSES ON THE ENVISIONED DESIGN AT THE EXPENSE OF PRODUCING FEWER SURPRISING RESULTS. NONETHELESS, IT PROVIDES A FINER DEGREE OF CONTROL, FACILITATING DEBUGGING AND MAINTENANCE TASKS. "

Figure 6, adapted from Caetano et al., (2020) represents the intersecting definitions of Parametric Design (PD), Generative Design (GD), and Algorithmic Design (AD).

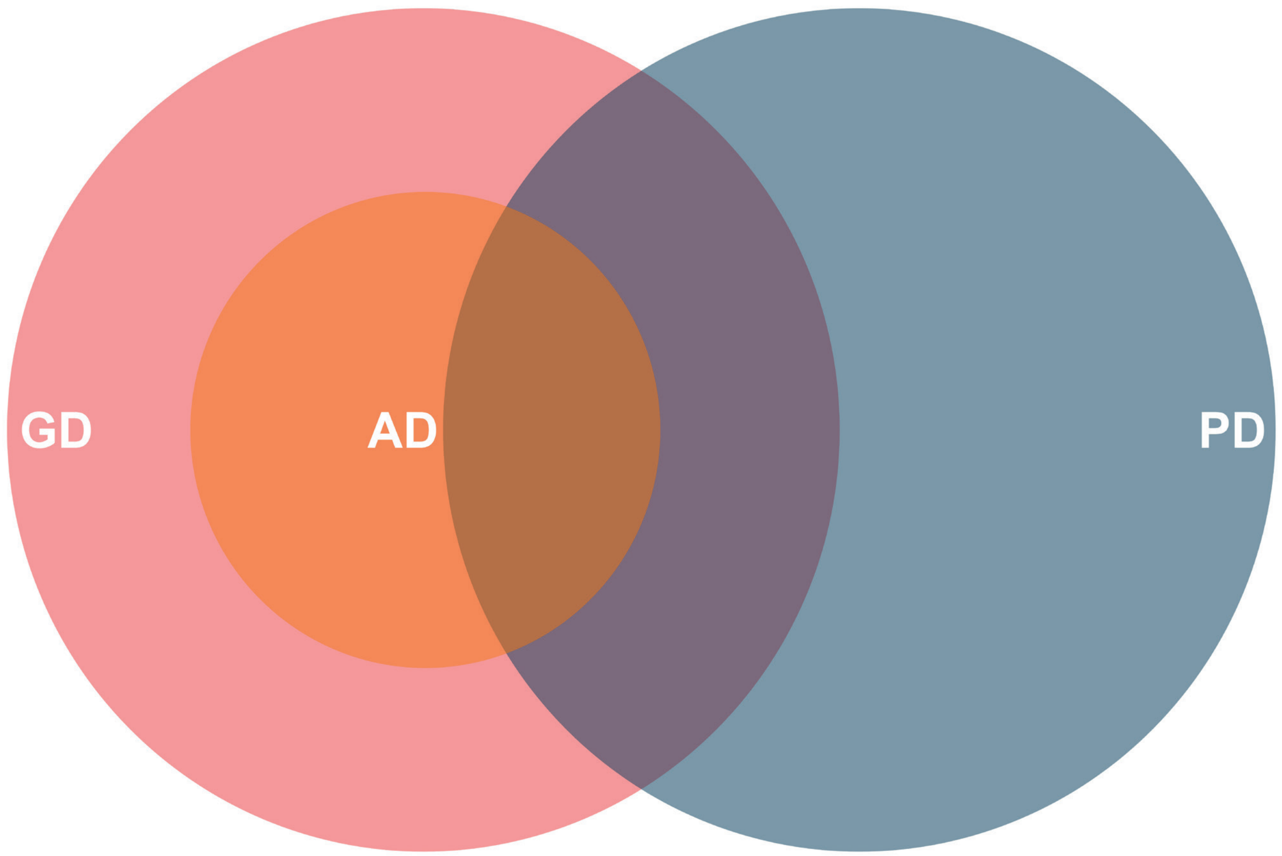


Figure 6: The intersecting definitions of Parametric Design (PD), Generative Design (GD), and Algorithmic Design (AD). Adapted from Caetano et al.,(2020)

In synthesis, Caetano et al. (2020) propose an overlapping model of the three terms. AD is a GD method satisfying the traceability requirement between the system outcome and the algorithm. Lastly, if the design is described through a set of parameters, it can be considered PD.

Gün (2022) highlights an increase in embedded "intelligence" from Parametric to Algorithmic to Generative. With generative, that adds the optimization component to the approach's capability.

The same author also illustrates the differences and the *touchpoints* between the terms. All the terms refer to "rule-based design systems." In all of these systems, the rules may determine :

• the part properties,
• the part-to-part relationships,
• the part-to-whole relationships.

While among the *differences*, the rules may be:

• static or flexible
• subjective or objective
• Computer and/or human instructed
• Algorithmically smart.

Consideration should also be given to the fact that software companies can inadvertently contribute to the ambiguity of terminology by utilizing buzzwords like 'Generative Design' or 'AI' for marketing purposes. The actual incorporation of Artificial Intelligence in these products often remains unclear, and 'Generative Design' has frequently been employed as a catch-all term to describe Topology Optimization applications. (Starck, 2019)

Conclusions
In conclusion, a clear difference can be drawn between PD and GD (Figure 7). PD allows the exploration of variations of a design by manipulating predefined parameters. GD enables the creation of new designs based on rules, boundary conditions, and goals.
Despite the clear difference between GD and PD no watertight definition of PD, AD, and GD can be drawn from the research. These definitions overlap as represented in Figure 6, and the approaches can be used in combination. However, these definitions contribute to a better understanding of CD and its subterms, a prerequisite for understanding the field of CD. GD thanks to its explorative qualities might potentially bring the most novel solutions confronted to PD or AD, enabling the fundamental exploration quality of CD. The relevant method for generative design in ID are described in section 2.4.

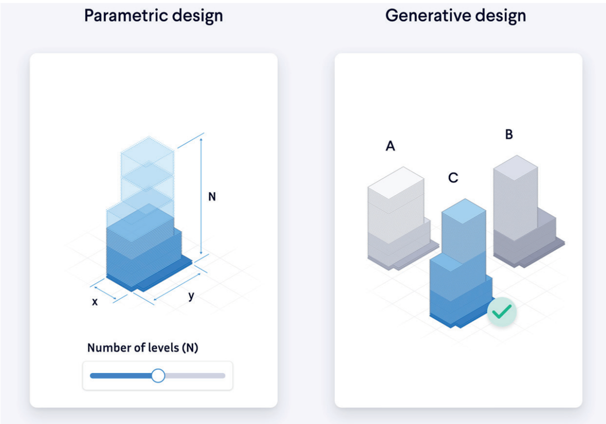


Figure 7: Comparison between PD and GD from (VIKTOR | Parametric Design | Engineering & Construction | VIKTOR.ai, 2021)

2.3 THE THEORETICAL CONCEPTS INSTRUMENTAL TO THE DEVELOPMENT OF COMPUTATIONAL DESIGN

2.3 THE THEORETICAL CONCEPTS INSTRUMENTAL TO THE DEVELOPMENT OF COMPUTATIONAL DESIGN

RQ 1: WHAT ARE THE **THEORETICAL CONCEPTS T**HAT CONTRIBUTED TO CD DEVELOPMENT?

This section introduces the key factors that have contributed to the definition of computational design as a field.
Caetano and Leitão (2019) suggest three main currents of developments that contributed to the rise of the computational design practice:

- Technological and scientific development creating the enablers for the practice.
- Research development, conferences, and publications discussing CD design itself, its tools, and its implications for society and the environment.
- Theoretical development concerning the theory and methodology around CD and its implications for designing. (Figure 8)

Today, the intellectual conversation regarding CD is thriving, with the conference on AI in architecture at this year's (2023) Venice Biennale and the first Computational Design Symposium that took place in June 2023.
The theoretical development, outlined by Caetano and Leitão (2019) is fundamental to creating a mental and framework to understand CD, its role and its potential in designing physical objects, and in seeing it as an enabler to solve design problems from a different angle. Menges & Ahlquist (2011) mention that the main challenge in teaching CD is not the learning of technical skills but rather approaching a design problem within the theoretical framework and concepts of CD, which they call Computational Design Thinking.

The theory of computation in design encompasses a collection of intricate ideas ranging from system theory to biology. (Menges & Ahlquist, 2011) These concepts are instrumental to understanding the methodologies and opportunities presented in the thesis. For instance, the concept of evolutionary computation can help in understanding CD opportunities in optimization and creativity, whereas form-finding ideas are relevant to mass customization. Furthermore, these theoretical concepts can contribute to creating what Menges & Ahlquist (2011) define as Computational Design Thinking. These ideas might help to apply CD beyond the opportunities or cases presented in this thesis stimulating exploration and innovation. These concepts will be explored in the following sections (from 2.3 to 2.3.7).

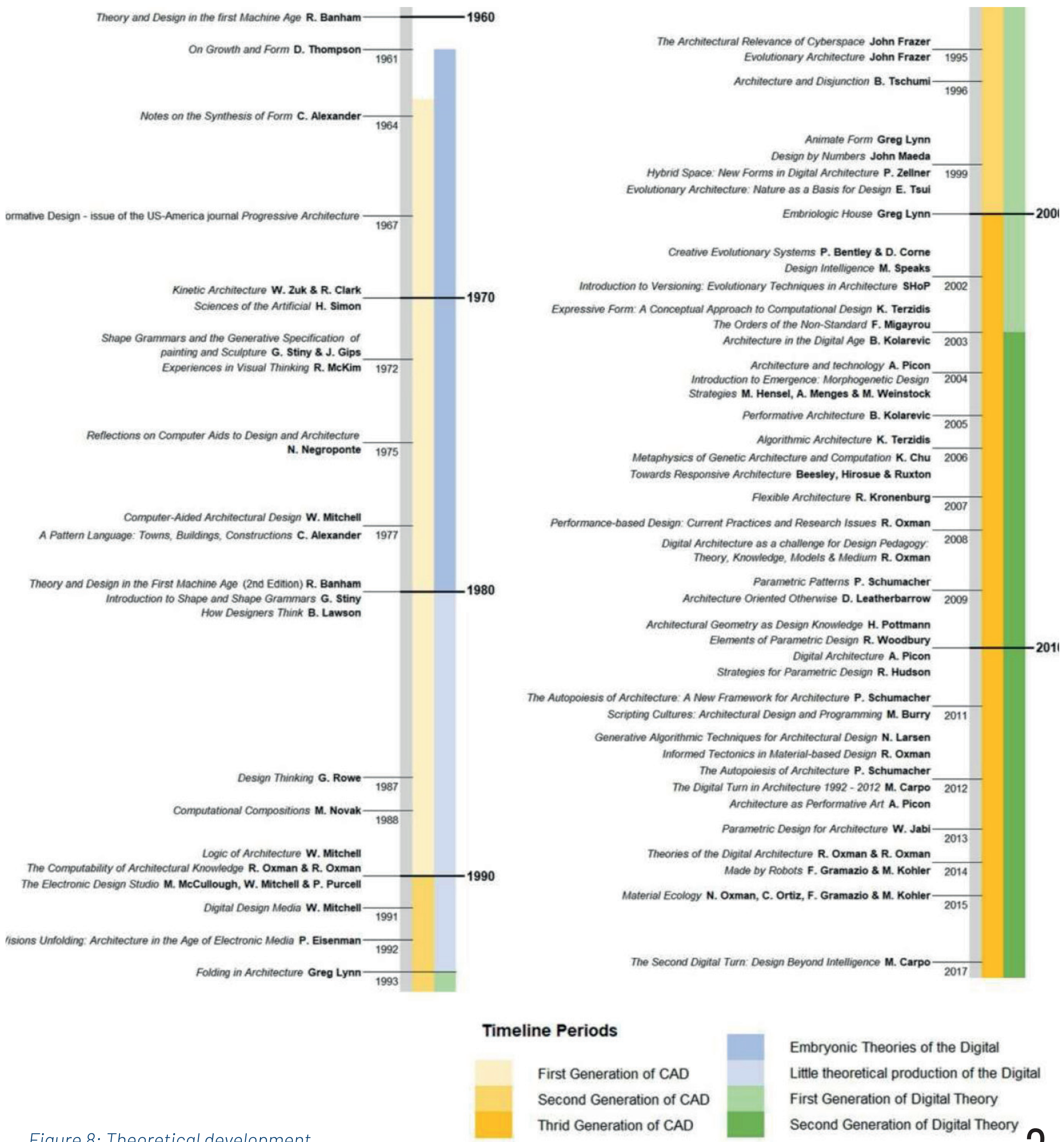


Figure 8: Theoretical development timeline from (Caetano et al., 2019)

2.3.1 SYSTEM THINKING

A prerequisite for this section's concepts is system thinking. System thinking is a crucial skill of every designer to look at the bigger picture of a design problem and address its causes rather than the symptoms. (Norman, 2023)
System thinking is relevant in the context of Computational Design (CD) when put in perspective with the idea of describing CD practice as the act of designing the system that generates the design solution and exploring the solution space instead of designing the artifact.
The concept of system thinking also helps highlight the importance of interdependencies and interrelationships (section 2.3.5), arguably the fil rouge connecting the concepts debated in this section.

"AN OPEN SYSTEM IS DEFINED AS A SYSTEM IN EXCHANGE OF MATTER WITH ITS ENVIRONMENT PRESENTING IMPORT AND EXPORT, BUILDING UP AND BREAKING DOWN OF ITS MATERIAL COMPONENTS"
LUDWIG VON BERTALANFFY, GENERAL SYSTEMS THEORY (GST)

Computational design could be the mean to explore the interaction among parts of a design problem (which could be defined as a system) using parameters to define the design system and using simulation and feedback loops to investigate and eventually predict viable solutions. (Menges & Ahlquist, 2011)

2.3.2 PARAMETERS AND ALGORITHMS

The concept of parameters in design literature made its first appearance in 1939, with the term -"Parametric architecture" introduced by Luigi Moretti in 1939 (Lo Turco, 2012) (Tedeschi, 2014).
The architect used this framework to design a proposal for a soccer stadium, in which the design parameters were linked to viewing angles and the economic feasibility of the stadium.

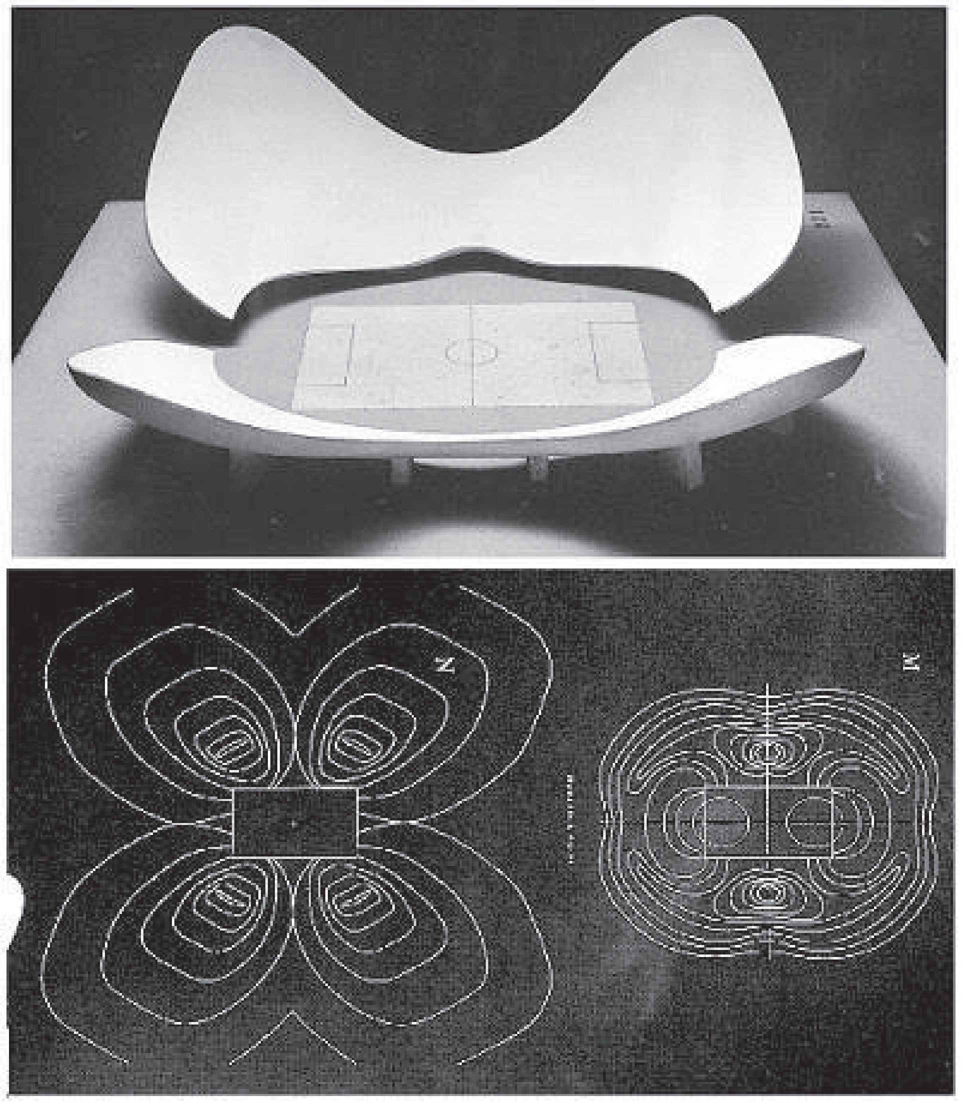


Figure 9: Solutions developed by Moretti in 1939 for a soccer stadium and diagrams to generate the geometry. From Tedeschi,(2014)

The concept of parameters creates a shift in the logic behind design representation from additive (drawing) to associative (parameters) logic (Tedeschi, 2014). The first software using this approach was Sketchpad, developed by Ivan Sutherland at MIT in 1963, which was based on a logic of constraints to represent 2D geometry; Sutherland was awarded the ACM Turing Award in 1988 for his work (Ivan Sutherland - A.M. Turing Award Laureate, n.d.). According to Menges & Ahlquist (2011) with Sketchpad, *"the description of design was no longer symbolically the representation of the physical elements as they lie against each other but rather a summation of the forces, pressures, and constraints which realize the form."*
The first widespread use of parametric software arrived with Pro/Engineer in 1987, which allowed the manipulation of 3D geometries through parameters. The next step arrived with interacting directly with code to find unexplored solutions and manage complexity beyond human capability; this started the rise of algorithmic and generative design, detaching further the use of computational tools as an imitation of analog tools in the design practice. (Tedeschi, 2014)(Caetano & Leitão, 2019).
In this last paradigm, architects, designers, and engineers started to use algorithms in addition to parameters; this led to the addition of output to the design process, with the first being the algorithm's output in the form of geometry and the second being the algorithm itself. (Tedeschi, 2014)

Conclusions
In conclusion, the concept of parameters has significantly evolved the logic of design representation from an additive to an associative approach. The advent of Sketchpad, the first software utilizing this approach, was a pivotal development, shifting the design description from a symbolic representation of physical elements to a compilation of forces, pressures, and constraints influencing the form. Subsequent developments, such as Pro/Engineer, further advanced the use of parameters, allowing the manipulation of 3D geometries. This evolution conducted in the era of algorithmic and generative design has distanced computational tools from simply mimicking analog tools in design practice. This paradigm has enabled architects, designers, and engineers to utilize algorithms with parameters, thereby introducing algorithmic output into the design process. This advancement has added another layer to the process and pushed the boundaries of design beyond human capabilities, enabling the exploration of uncharted solutions and managing complexities
Parameters might be seen in design as the representation of the elements to describe the forces of form and formation described by Goethe e Thompson in the following paragraph.

2.3.3 FORM AND FORMATION: THOMPSON, GOETHE, AND THE BIOLOGY ANALOGY

Goethe, through his concept of morphology, was the first to propose a direct link between geometric behavior and functional logic in plants. For instance, he proposed that the function of pollination in certain plants was strictly related to geometric relationships (parameters) expressing verticality. (Menges & Ahlquist, 2011) Goethe's morphology aimed to understand the processes that governed the form rather than the form itself. This perspective could help in seeing the previously mentioned definition of CD –"designing the process rather than a single object" (Tedeschi, 2014) with different eyes.
Multiple authors (Oxman, 2009)(Menges & Ahlquist, 2011) cite the book of the Scottish biologist D'Arcy Wentworth Thompson On Growth and Form (1917) as the second pillar, after Goethe's morphology, to understand the idea of exploring in design the mathematical and physical laws behind the formation and transformation of organic structures.
Included in the book are various fascinating topics, unveiling and explaining the rules behind the formation of biological structures The impact of scale on the shape of animals and plants, the role of surface tension in shaping soap films and similar structures like cells, the presence of logarithmic spirals observed in mollusk shells and ruminant horns; Thompson uses the cartesian grid (Figure 10): to explain the alteration in shaper of biological structures. (Thompson, 1917).

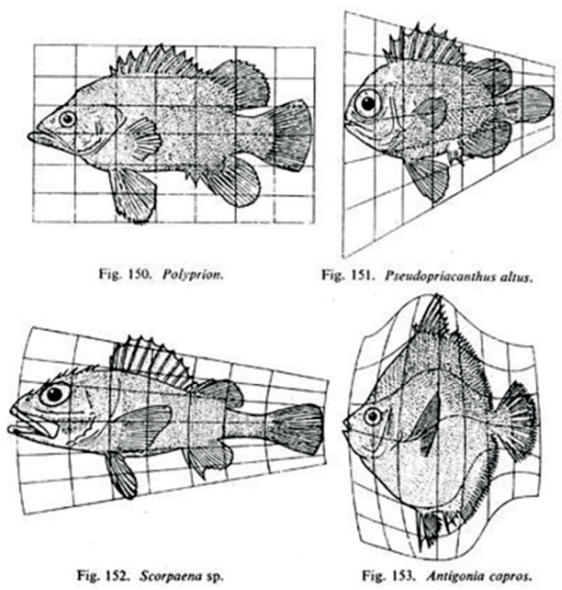


Figure 10: From D'Arcy Wentworth Thompson On Growth and Form (1917)

Ahlquist and Menges (2011) explain that Thompson's work is particularly relevant in computation and design for adding another dimension to the concept of parameters and associative logic, in addition to the idea of geometrical constraints, the Thompson's work investigates "the methods for particular interrelating behaviors of forms and forces and how they might be represented as associated mathematical rules." Ahlquist and Menges (2011)

The complete understanding of biological formation arrived with the development of genetics, which contributed to the development of an architecture inspired by the evolution of biological systems, with processes of evolution guiding the design process. (Oxman and Oxman, 2014, as cited by Caetano et al., 2019).
The idea of evolution in design is almost taken to an extreme by John Frazer in his book An Evolutionary Architecture (1995), in which architecture is considered a form of artificial life.

Conclusions
In conclusion, Goethe's innovative concept of morphology and D'Arcy Wentworth Thompson's examination of the mathematical and physical laws behind forming organic structures have significantly contributed to our understanding of Computational Design. Goethe was the pioneer in associating geometric behavior with functional logic in plants, hinting for design a focus on designing processes rather than single objects. Thompson further expanded this concept, emphasizing the mathematical rules interrelating forms and forces. The later development of genetics opened new doors for design inspired by biological evolution

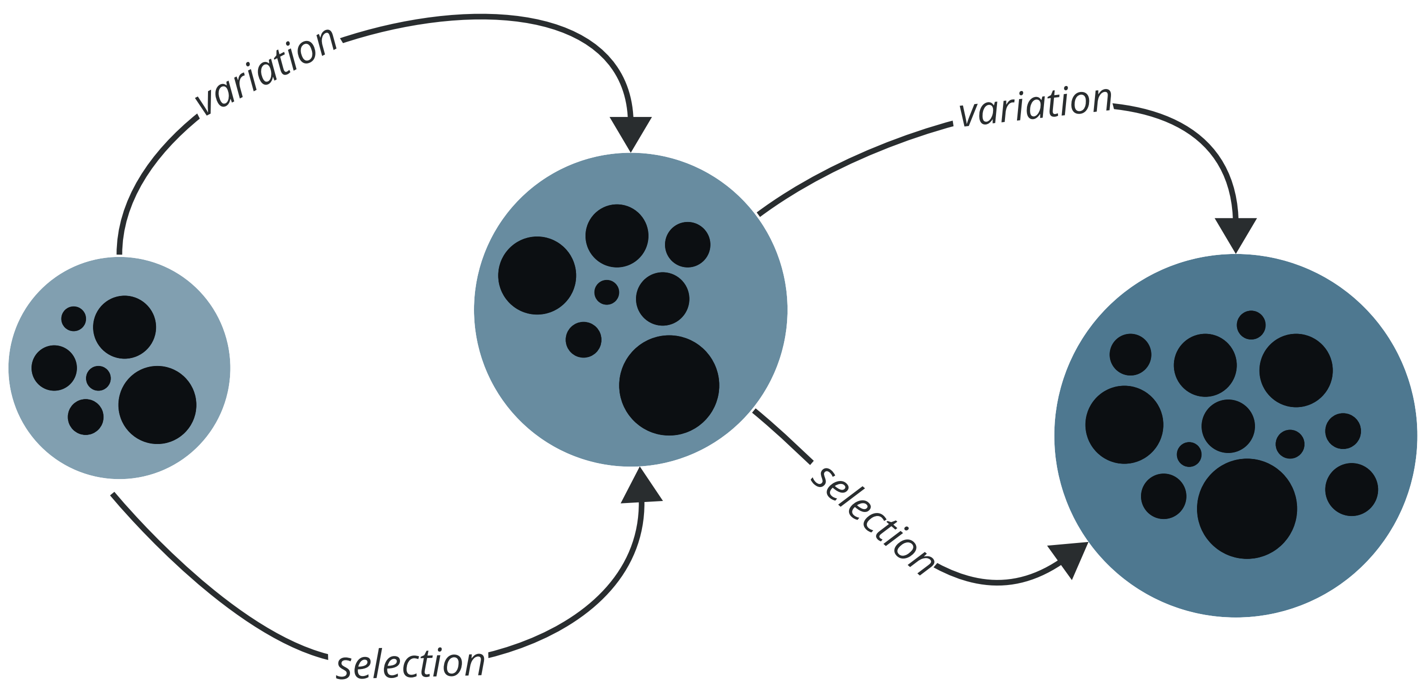


Figure 11: Author's interpretation of the evolutionary process in design described by (Menges & Ahlquist, 2011)

2.3.4 EVOLUTIONARY COMPUTATION: BEYOND TYPOLOGY

Usually, the design process has to tackle a complex multidimensional problem space, in which each decision taken during the process adds a dimension to the design problem. (Nagy, 2017). Considering this multidimensional space could be daunting for humans, the traditional solutions to tackle this complexity are augmenting the time (iteration and testing) and the number of people invested in a project or using what worked in the past (typology). (Nagy, 2017) (Tedeschi, 2014) (Kyser, 2018).
Nature has been a source of inspiration for designers for a long time. It could be interesting to look at how nature solves the multidimensional problem of having organisms always adapted to their environment. For instance, the shape of a tree is optimized for wind direction, slope, and solar radiation. Natural systems achieve their functionality with minimal material input and are inherently resource-efficient. (Hyperganic,2020)
The key to nature's design is an evolutionary process based on variation, selection, and heredity. (Menges & Ahlquist, 2011)(Shiffman, 2012)(Nagy, 2017)
The high-dimensional problem space mentioned at the beginning of the paragraph, the design space, could be considered a computational search space. (Menges & Ahlquist, 2011)
This search space could be explored by mimicking nature's evolutionary processes computationally through Genetic Algorithms (GA's) (Nagy, 2017). GAs are further described in section 2.4.1. (Nagy, 2017)
One of the primary features of evolutionary processes is working via populations of solutions through generations, with the main drivers of change between a generation and a new one being the forces of variation and selection. (Menges & Ahlquist, 2011)(Shiffman, 2012). This process is visualized in Figure 11. The implications of this process in design are particularly disruptive because the notion of historical precedents), is not an active participant in the generation of new populations of solutions, with the forces of variations and selection driving the solutions' generation and allowing for a more innovative and explorative design process. (Menges & Ahlquist, 2011) (Tedeschi, 2014)
The differences between a traditional product following typology and one designed through populations of solutions are represented in figure 12

Evolutionary Computation's open-ended capabilities can help approach a design problem that could be challenging to describe entirely with traditional means by turning it into a computational search space within a given brief. (Menges & Ahlquist, 2011)

In using principles of evolution to generate populations of design options, the rules that define the designs' looks and performances are called genotypes. The individuals in a population who are the most successful have their genes changed through mutation and recombination, which leads to the creation of the next generation. This process is referred to as "survival of the fittest." (Savov, 2020) In architecture, the fitness functions are often based on environmental factors, cost, and structure.
It would be interesting to find similar recurrent optimization objectives -in addition to mechanical strength- in the industrial design practice, use multi-objective optimization, and evolve product design(s). Some of these could be in the sustainability domain, for instance, using LCAs (Life Cycle Assessment) parameters or ease of disassembly as optimization goals. The possibilities could be endless. This approach is described in section 3.7.5.

Conclusions
To summarize, the inherent complexity of a design brief can be seen as a multidimensional problem space. A strategy for addressing this complexity, borrowed from nature's design processes, are evolutionary algorithms. Nature, through evolution, handles multidimensional problems by always adapting organisms to their environment, optimizing functionality with minimal resource input. This process can be emulated computationally through Genetic Algorithms, working via populations of solutions and driven by forces of variation and selection. Such an evolutionary approach allows for innovative and exploratory design processes, going beyond traditional typology-based methods. This could offer a new perspective in addressing various optimization objectives in industrial design, potentially including factors related to sustainability.

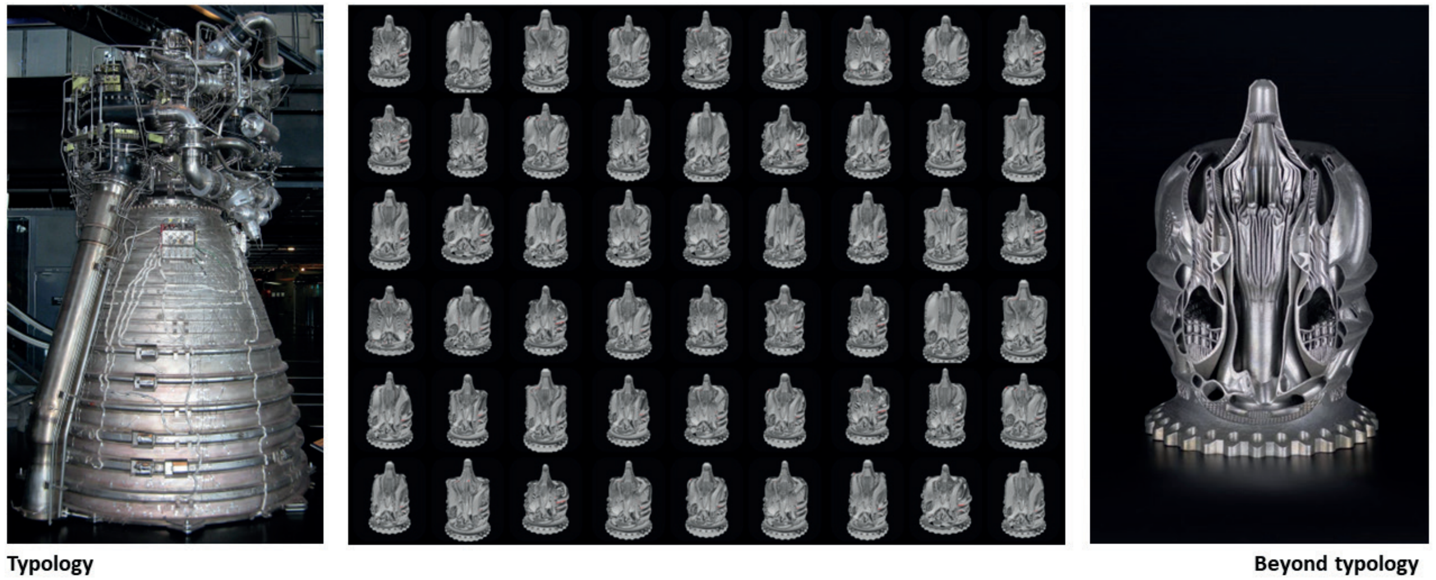


Figure 12: Beyond Typology: Composition of images from Wikipedia and Hyperganic (2022)

2.3.5 FORM FINDING IN DESIGN

Computationally enabled form finding is a recurrent theme of the literature research and arguably a common framework in applying computational design to create 3D forms. It is based on the principle of designing a process that gives life to the form instead of designing the form directly. Environmental analysis and the derived constraints are the system's boundary conditions that generate the form.
To understand form findings, revisiting the ideas of interdependencies and interrelationships discussed in the preceding paragraphs is essential.
In ecology, the environment influences and shapes the organism and vice-versa. (Menges & Ahlquist, 2011)
In cybernetics, these interdependencies are called feedback loops. (Menges & Ahlquist, 2011)
Morphology explains the inextricable link between form and formation, and it's based on the processes that govern form rather than the form itself. (Menges & Ahlquist, 2011)
Ahlquist and Menges (2011) condense the idea and importance of interdependencies in Computational Design with this definition (Figure 15):

"COMPUTATIONAL DESIGN CAN BE DEVELOPED AS A SET OF INSTRUCTIONS REGARDING THE PROCESS OF FORMATION, WITH THE TRIGGER BEING THE INTERACTION WITH INTERNAL AND EXTERNAL FORCES." (MENGES & AHLQUIST, 2011)

This definition is particularly relevant to specifying the crucial relationship between form-finding and computational design. In this context, the word form finding will be used to describe the process of finding the optimal form based on the external and internal forces shaping the design object, arguably what we call requirements in industrial design. The requirements are related to the purpose and context of a design.
Drawing has been the primary tool to represent designs, partly thanks to the use of typology or historical precedent: preconceived solutions that worked in the past. (Tedeschi, 2014)(Kyser, 2018).
Form-finding was the first approach not relying on typology but on finding novel and optimized structures through materials form and structure interdependencies. (Tedeschi, 2014)

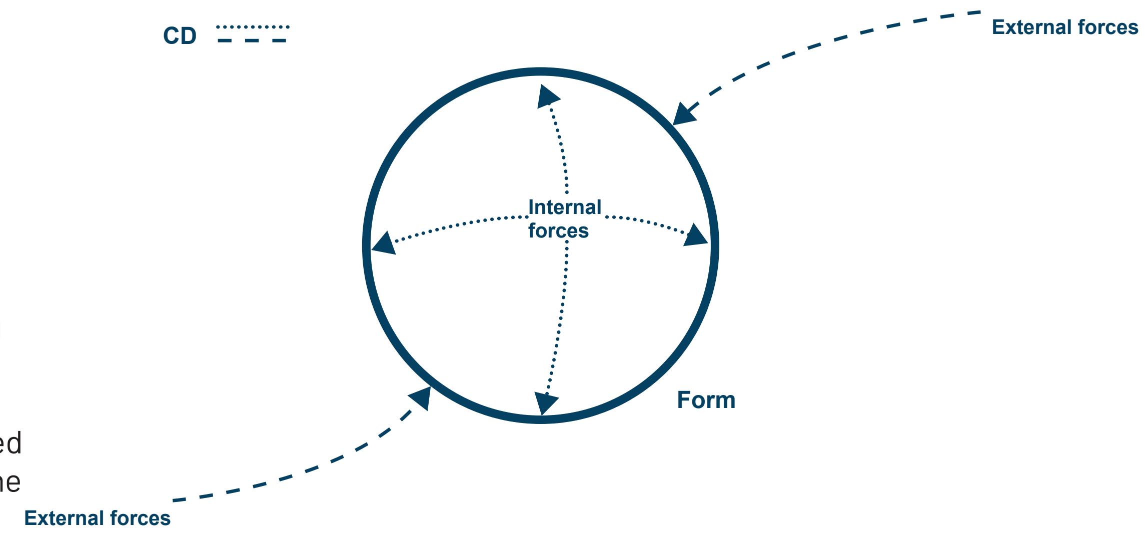


Figure 15: Author's interpretation of the definition of CD described by Menges & Ahlquist, (2011)

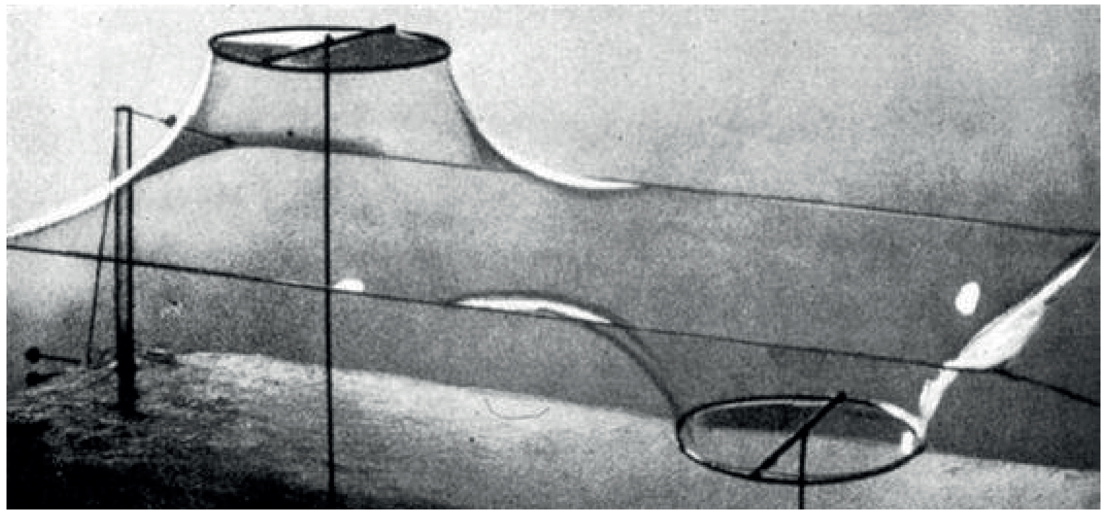


Figure 13: Frei Otto's experiments on minimal surface form finding using bubbles. From Tedeschi, (2014)

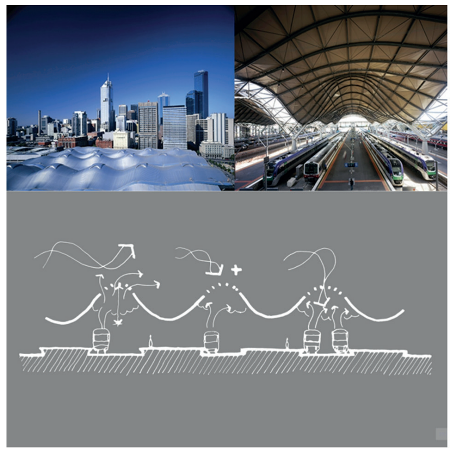


Figure 14: Southern Cross Railway Station roof ,Grimshaw and Partners, 2002, Melbourne

The practice of "computing" a shape could be traced back to before the use of computers in design.
Material computation-form finding is the practice of letting the nature of a material compute the form (Savov,2020). Fundamental to this approach is the work of some pioneers, among the most famous Gaudi (1852-1926) and Frei Otto (1925-2015). The latter, for instance, experimented with forming bubbles (Figure 13), in which the soap films take the shape of a minimal surface (Zexin & Mei, 2017) or in a 1972 experiment in inspired by Otto's work was demonstrated that "any granular material falling from a fixed point forms a cone on the surface below and a funnel within the granulate mass with the same angle of inclination, the natural angle of repose, 35 degrees" (Tedeschi, 2014)
The approach is deeply rooted in the ideas of form and formation explained before and in the concept that nature created processes instead of forms.

"NATURE CREATES PROCESSES, NOT FORMS." (OXMAN, 2009)

"Nature creates processes, not forms."
(Oxman, 2009)
This idea has clear common points with the definition of CD mentioned in the first paragraph of the chapter, according to which CD is about creating the process and not the final artifact. (Tedeschi, 2014)
Returning to form finding and using Oxman's words, computationally enabled form finding is not about asking "what an object wants to be" but" where materials and environment want to be."
In this framework the object's from is determined by the interrelationships between materials and the environment. (Oxman, 2009).
The role of Computation in form finding could lie in simulating environmental factors, physical properties, and the consequent generation of form. In order to simulate this complex system, the computational form-finding approach should be multi-parametric and alimented by different forms of data: geometry, dynamic forces, environment, and social data. (Tedeschi, 2014).
In this context, computational analysis or simulation does not occur only at the end of the process to validate a design result. It becomes the starting point for the generative process, with performance being its final goal. (Oxman, 2009)
An example of this approach in architecture with performances and environmental factors guiding the form-finding process is the design of the Southern Cross Railway Station roof (Figure 14)(Grimshaw and Partners, 2002). The wind analysis influenced the final design of the roof, allowing for natural ventilation and giving the roof an organic shape. This results in a design shaped by environmental factors and fulfilling the functions of covering from the sun and stormy weather while, at the same time, allowing for the extraction of stale air from the diesel trains. (Caetano & Leitão, 2019).

A similar approach at the product design scale could often be seen in close-to-body applications, especially in healthcare or sports. The human body dictates the environmental factors (ergonomics, temperatures, pain profiles, and more) which are used to create ultra-personalized products discussed in section 3.7.2 (Figure 16)

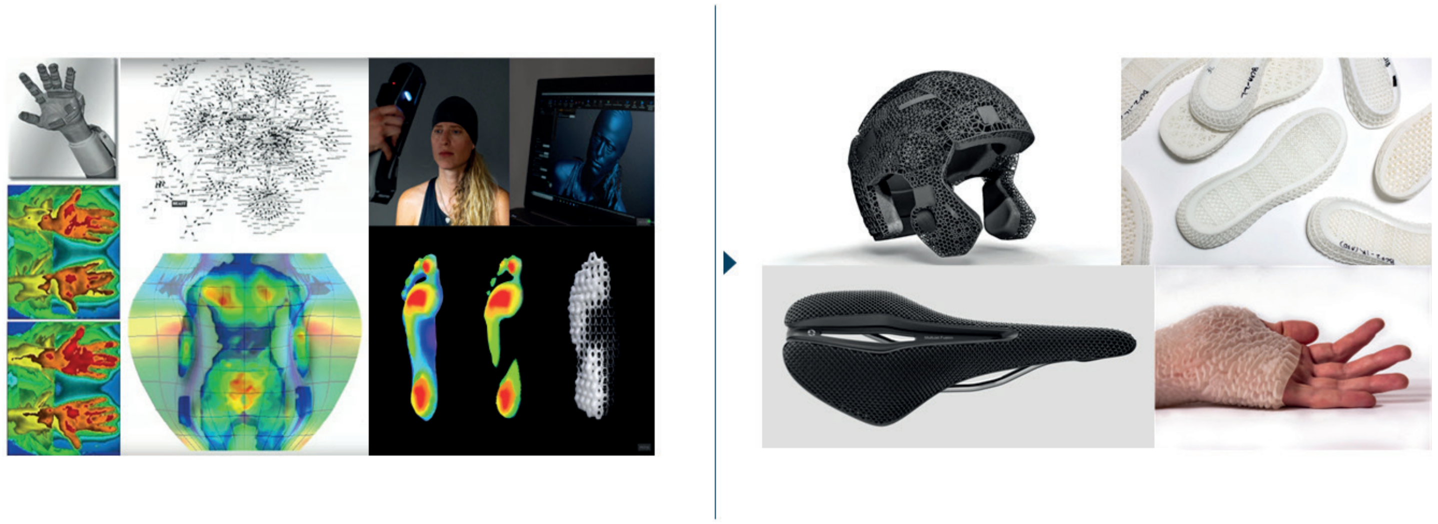


Figure 16: Human body parameters (ergonomics, temperatures, pain profiles, and more) used to create ultra-personalized products. Images from Oxman, Nolan Kim, Kiska, Hyperganic,

"COMPUTATION AS A DESIGN METHODOLOGY IS TO FORMULATE THE SPECIFIC. WHERE COMPUTER-AIDED PROCESSES BEGIN WITH THE SPECIFIC AND END WITH THE OBJECT, COMPUTATIONAL PROCESSES START WITH ELEMENTAL PROPERTIES AND GENERATIVE RULES TO END WITH INFORMATION WHICH DERIVES FORM AS A DYNAMIC SYSTEM" (MENGES & AHLQUIST, 2011)

According to Antonelli et al. (2020), Computation in design is the key to making specificity accessible and enabling personalized or mass-customized products accommodating different requirements and conditions using "the same adaptable algorithm-based design." This paradigm of mass customization could ideally lead to avoiding overproduction, reducing waste, and meeting specific users' needs.

Conclusions

The goal of computational design could be resolving complexities and interdependencies characterizing a design problem. In this framework, the use of Computation to create a 3D geometry -to compute the form- could be seen as a way to leverage computational power to take into account in the design/formation process multiple parameters (internal qualities, such as weight, or external requirements such as applied forces, ergonomics), too complex to be tackled without computational power.
In this context, Computation becomes an enabler for design to apply nature's growth, organization strategy, or logic.

2.3.6
MATERIAL ECOLOGY

The most recent theoretical approach related to CD is Material Ecology, developed by Neri Oxman and the Mediated Matter Group at MIT (Oxman et al., 2015). The approach is relevant in the context of CD might represent the latest development and the future in CD theory as represented by Caetano and Leitão (2019) in Figure 8.
Oxman introduced biology in the context of computational and performance-based design not only as a source of inspiration in the processes of form and formation but also as a design material, which, combined with computational practices, opens innovative design possibilities. The computer becomes a tool that ignites interdependencies between nature and the designer. (Antonelli et al., 2020)
One of the main pillars of the approach is having nature as a client: "The natural environment constitutes the "client" for every commissioned project as well as its "site" and material source" (Antonelli et al., 2020)

"MATERIAL ECOLOGY AIMS TO... INCREASING THE DIMENSIONALITY OF THE DESIGN SPACE THROUGH MULTIFUNCTIONAL MATERIALS, HIGH SPATIAL RESOLUTION IN MANUFACTURING AND SOPHISTICATED COMPUTATIONAL ALGORITHMS. IN DOING SO, A HOLISTIC VIEW OF DESIGN EMERGES THAT CONSIDERS COMPUTATION, FABRICATION, AND THE MATERIAL ITSELF AS INSEPARABLE DIMENSIONS OF DESIGN WHICH RESULTS IN OBJECTS THAT ARE ECOLOGICAL FROM THE OUTSET." (OXMAN ET AL., 2015)

Conclusions

In conclusion Material Ecology presents a groundbreaking interplay between biology, computational design, and material science, creating an innovative design landscape where nature is considered the client, site, and material source for design projects, thus expanding the multidimensionality of the design space.

2.3.7 CONCLUSIONS ON COMPUTATIONAL DESIGN THEORETICAL CONCEPTS

The goal of this section of the report was to outline the elements of the concepts behind CD theoretical development that were encountered during the research, with the aim of defining the reasons for using this approach in the design and creating an appropriate mindset to engage with CD. In synthesis, CD could be the tool to tackle some of the multiple dimensions of a design problem, leveraging computational power and techniques to deploy nature-inspired strategies in designing 3D geometries that meet design requirements and fit in their environment.

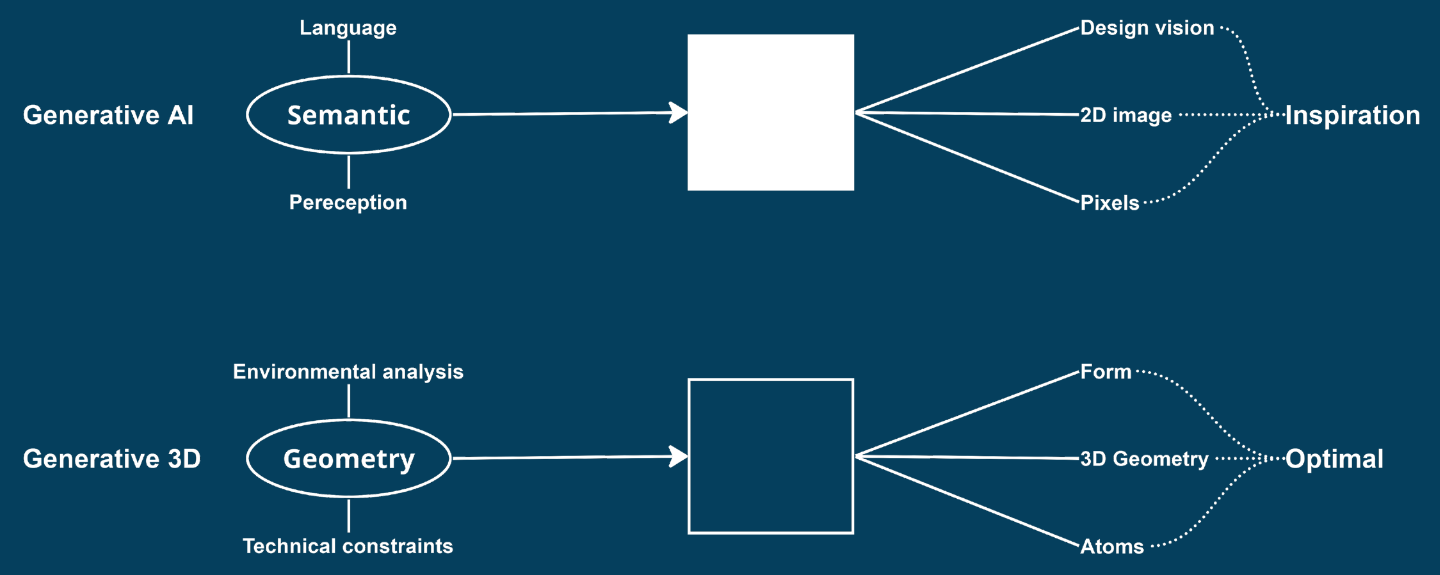


Figure 17: Personal interpretation of the relationship between 3D generative systems and Generative AI

2.4 GENERATIVE METHODS

Introduction

Generative methods in Computational Design (CD) refer to a set of techniques and algorithms used to generate, optimize, explore, and manipulate designs through automated processes. (Mountstephens & Teo, 2020
The research question behind this section is:

RQ1.1:WHAT ARE THE RELEVANT **CD METHODS** FOR INDUSTRIAL DESIGN?

The cognitive level of the task solved from computational tools increased enormously. If the task solved by software like AutoCAD could be solved by a kid rich in patience, a team of engineering graduates would be needed to solve the optimization tasks achieved with GD software like Fusion 360. (Conti, 2017)

Digital tools are becoming increasingly active in the design process. Especially in the case of generative AI, this shrinks tremendously the time between an idea and its execution. (Accenture, 2023) Something that tools like Midjourney and 3D generative methods have in common is the word " generative". In the context of the design process, the word "generative" could be associated with the concept of divergence analyzed in section 3.5. In addition to this, another touch point between the two is the use of parameters to be tweaked and isolated to understand and control the generative system. (Gün, 2022) Arguably, tools AI tools, like Midjourney, can be particularly valuable when there is much uncertainty in the project, in the early phases of the design process. While generative 3D can enter the game when more certainty is gained and can be used to define the boundary conditions of a generative system.
This section will analyze 3D generative systems and generative AI with a focus on text-to-image

2.4.1 GENERATIVE METHODS FOR 3D DESIGN IN INDUSTRIAL DESIGN

Singh and Gu (2012) propose that the majority of generative design (GD) systems in CD are based on five techniques: **Shape Grammars (SGs), L-systems, Cellular Automata (CA), Genetic Algorithms (GAs), and Swarm Intelligence (SI)**. These systems are primarily analyzed in the architectural realm by Singh and Gu (2012. Mountstephens and Teo (2020) suggest that Cellular Automata are irrelevant to industrial design and add **Topology Optimization** and **lattice structures** to the list. Arguably topology optimization is at a different level and could be considered an application of generative methods that, in some cases, make use of them, for instance, GA's (Porterfield, 2019). The generative methods will be defined and described with relevant industrial design use cases.

Genetic Algorithm

Genetic Algorithms (GAs) are meta-heuristics inspired by nature's evolutionary processes. GAs, which use biological processes like mutation, crossover, and selection, are commonly used to create optimal solutions for search and optimization problems. (Nagy et al., 2017)(Mountstephens & Teo, 2020). GAs, as described previously in the "Evolutionary computation" paragraph, use mutation, crossover, and selection to drive the evolution between generations of design solutions (Mountstephens & Teo, 2020)(Nagy et al., 2017)(Shiffman, 2012).

GAs differ from other methods as they explore and select designs at each cycle, making them easier to model compared to SG or LS, which require identifying specific rules. The main challenge with GAs lies in selecting suitable alleles, chromosomes, and fitness functions. (Singh & Gu, 2012)

GAs have shown successful application in industrial design, providing designers with additional solutions even considering the creative factor in addition to technical requirements. (Sáez-Gutiérrez et al., 2019). GAs can contribute to fulfilling sustainability requirements in industrial design, as demonstrated by Ren and Su (2020). The topic of GAs and sustainability will be covered with the relevant tools in section 3.7.5.

An interesting example of GAs applied in industrial design is the airplane partition developed by Nagy, Zhao, and Benjamin (2017) for Airbus using Autodesk software (Figure 18). This project utilized a hybrid approach combining agent-based growth processes inspired by natural systems (slime mold) with a genetic algorithm for optimization. The authors highlight that this hybrid approach ensures high performance while allowing designers to explore a broader range of novel designs compared to traditional methods.

Some software to implement GAs are Grasshopper plug-ins such as Octopus, Wallacei, Opossum, Optimus and Galapagos.

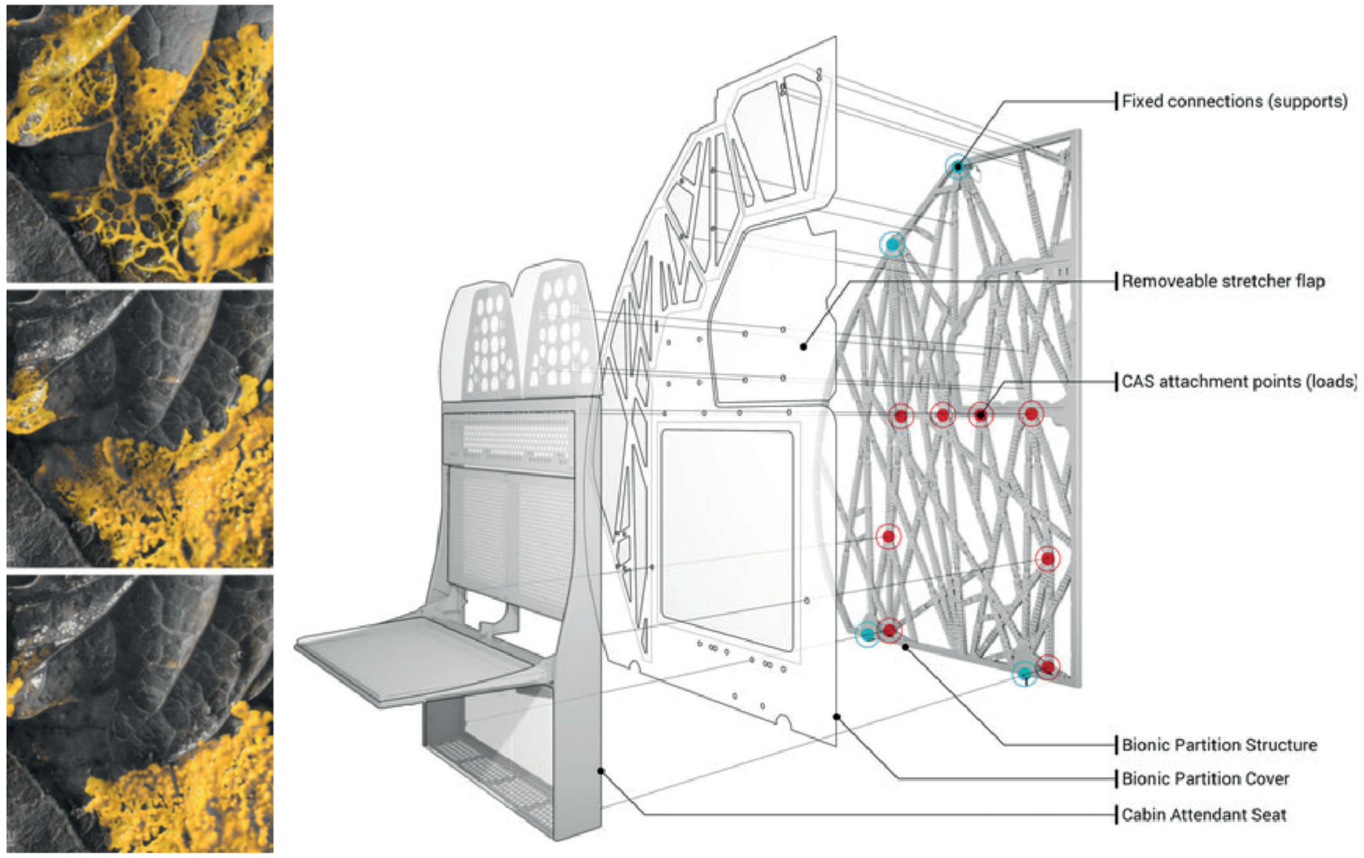


Figure 18: airplane partition developed by Nagy, Zhao, and Benjamin (2017) for Airbus using Autodesk software

Shape Grammars

Shape Grammars (SGs), created by George Stiny and James Gips, are generative systems that define a set of visual rules to generate designs (Mountstephens & Teo, 2020). For Singh and Gu (2012) SGs can be used both generatively and as tools for analysis to formalize existing designs.

Alcaide-Marzal et al. (2020) used SGs to generate iterations of three industrial products based on an aesthetic vocabulary of products (Figure 19). The study presents a novel approach to exploring product shapes during the early design phases. The approach relies on three fundamental principles: employing SG to capture product aesthetics, implementing transformation rules to generate design variations, and utilizing a parametric modeler (Rhino Grasshopper) to construct shapes. The researchers represent product solutions as 3D sketches, employing basic shapes combined in straightforward and schematic structures. This methodology enables the generation of numerous diverse configurations using a limited set of shapes and demonstrates the adaptability of the generative model to different types of products.

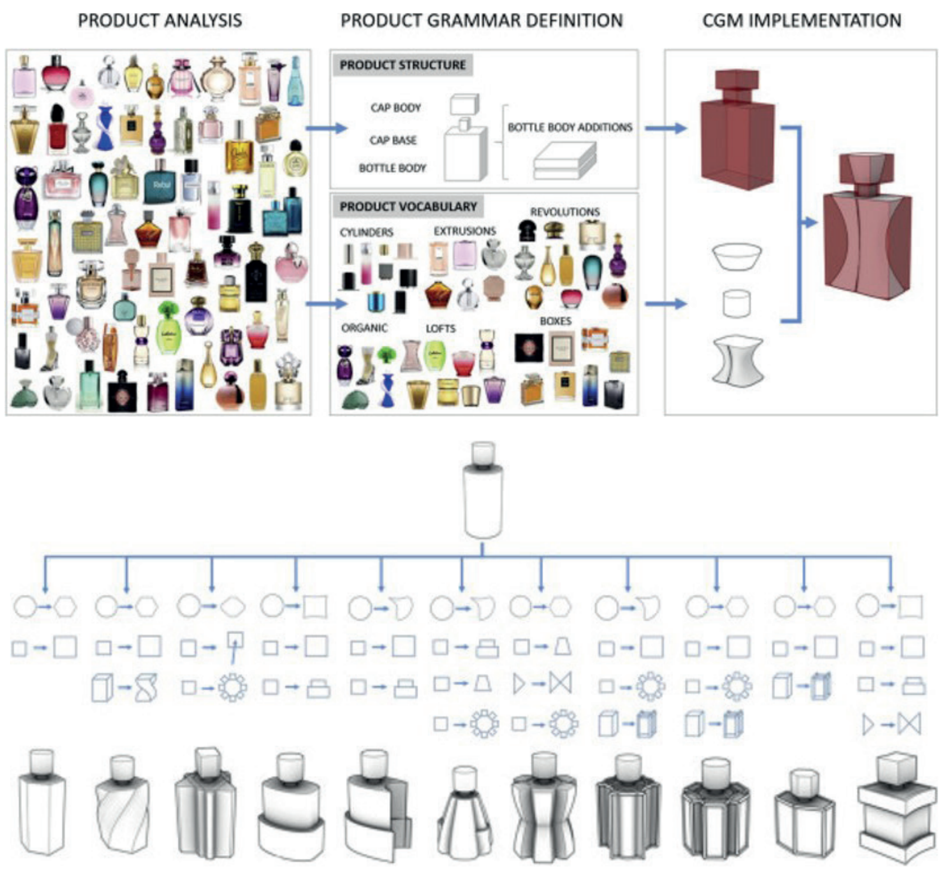


Figure 19: 3D SGs generative system from Alcaide-Marzal et al. (2020)

This case study demonstrates how SGs can be particularly interesting in industrial design to establish an aesthetic vocabulary based on design DNA or brand identity, allowing the generation of aesthetically coherent designs within a bounding box. This approach could help generate design options to support creativity and overcome design fixation. However, the shapes in the case study might result too constrained to the initial rules, and additional design work is probably needed to arrive to a final product.

L-systems
L-systems, were introduced by the biologist Aristid Lindenmayer in 1968 and are described by Mountstephens and Teo (2020) as "generative systems that can be used to generate designs by recursively rewriting strings of symbols."
L-systems have also been used to model the morphology of various organisms, especially plants.

In Mountstephens and Teo (2020) review, there is only one case study in which L-systems were used to generate an object.
In 2004 NASA used the L-systems and GAs to generate a table (Figure 20). The design selection was based on a fitness function that considers various physical characteristics of the table, including its balance, cost, height, surface area, stability, and materials used. (Hornby, 2004)

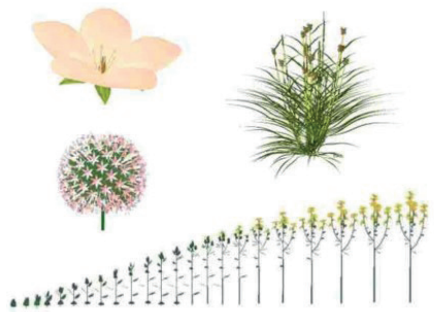


Figure 20: L-systems in nature from Wikipedia

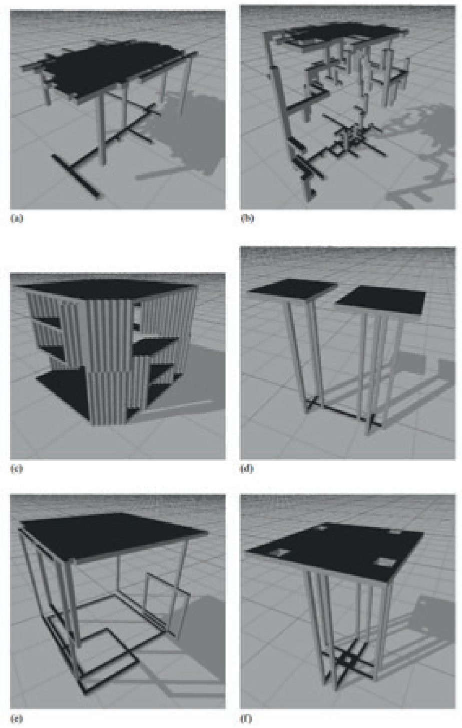


Figure 21: Table generated using a combination of L-systems and GAs (Hornby, 2004)

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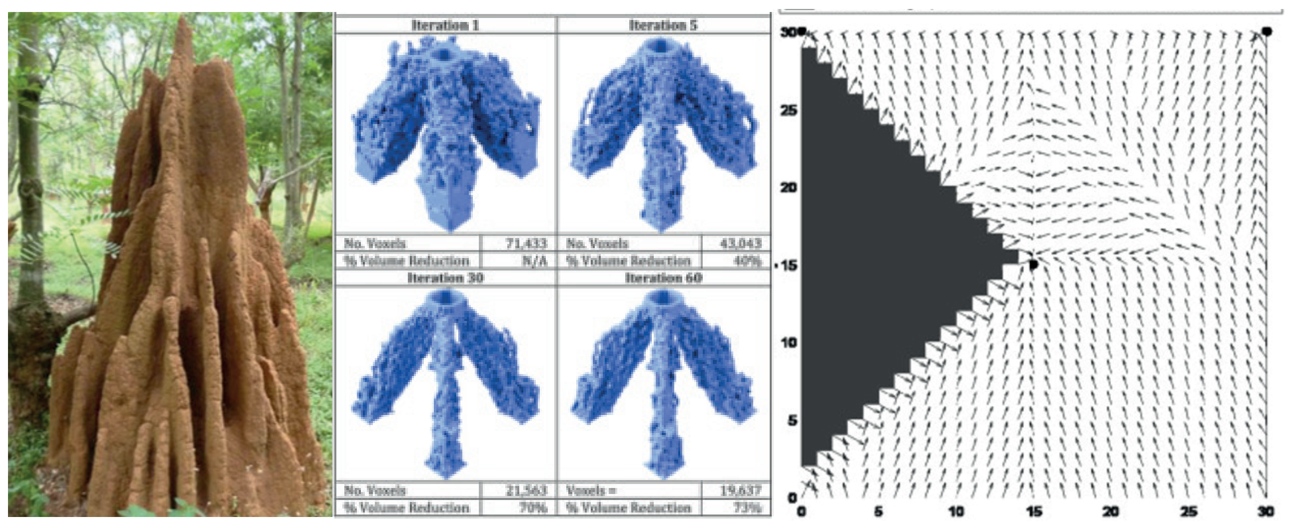
Swarm intelligence
Swarm intelligence refers to the collective behavior of many simple agents interacting with their environment to produce coordinated behavior patterns at higher levels. These systems are designed to solve problems without requiring centralized control or a global model. (Mountstephens & Teo, 2020)
For Singh and Gu (2012), this system could be relevant in design for functionalities such as:
- Nest building and self-assembly
- Division of labor and task allocation
- Trail-laying and trail-following behaviors

Examples of Swarm Intelligence in industrial design include the bracket developed by Dhokia, Essink, and Flynn (2017), which utilized Swarm Intelligence, termite nest behaviors, finite element analysis, and pheromone gradients to simultaneously design, optimize, and evaluate the manufacturability of a bracket (Figure 22).
This case study demonstrates how SI can automatically generate a structurally optimized design for additive manufacturing.

Figure 22: Bracket structurally optimized design for additive manufacturing from by Dhokia, Essink, and Flynn (2017)



Topology optimization

The method of Topology Optimization (TO) involves multiple iterations to determine the most effective distribution of materials within a structure's volume, taking into account various factors, such as applied loads, boundary conditions, and other constraints, in order to achieve optimal structural performance without requiring the user to provide an initial concept. (Mountstephens & Teo, 2020)(TU Delft, 2023)

Topology optimization research has demonstrated its versatility in various applications. In addition to improving structural performance, it can also be utilized to create compliant mechanisms, dynamic motion systems, and heat exchangers. Furthermore, manufacturing constraints can be used within the system. Additive manufacturing technologies can potentially create highly complex and high-performance parts resulting from topology optimization. (TU Delft, 2023)(Autodesk, nd)(nTop, 2023)

With lattice structures, this is probably the most common system currently used in industrial design.

Decathlon utilized TO to create an optimized front fork and bicycle body that can be 3D-printed from aluminum. Decathlon is utilizing TO and 3D printing to create lightweight bicycles with reduced environmental impact. Traditional carbon fiber frames a difficult to recycle, so Decathlon aimed to develop a bike frame that is both lightweight and environmentally friendly.(Autodesk, 2023)

Figure 23: Decathlon's optimized bicycle fork

At VanBerlo, experimentation has already taken place in the domain of topology optimization, specifically in two projects: the optimization of a foot prosthesis for hiking and the topological optimization of the rescue device Resqtec, both developed in the context of Andrea Marsanasco's graduation project at VanBerlo (Figure 24). In the foot prosthesis, TO was used to link multiple elements and obtain the lightest sole using the user weight as input. While to increase ResQtec spreader maneuverability, TO was used to lighten the spreader's jaws.

In terms of design process, TO allows for generating an array of initial design candidates. This array guides designers and engineers, expanding their possibilities beyond what they could imagine on their own. By exploring a broader design space, topology optimization saves engineering time and helps overcome design fixation, enabling innovative and optimized solutions to emerge. (McKinsey, 2021)

Designing products based on validated geometries is another benefit of topology optimization. By leveraging this technique, designers can ensure that their designs meet the desired performance criteria and are structurally sound. The optimized geometries obtained through topology optimization provide a solid foundation for product development, minimizing the risk of design flaws and facilitating successful implementation.

Another potential benefit of TO might be the facilitation of communicating the decision-making process to clients. By presenting optimized designs based on rigorous engineering principles, designers can effectively demonstrate the rationale behind their design choices.

Probably the most significant advantage in terms of product performance is lightweight, which involves reducing the weight of a product while maintaining its structural integrity.

Another advantage is part consolidation, which simplifies assemblies by merging multiple components. Topology optimization enables designers to optimize a product's shape and structure to eliminate unnecessary parts and integrate their functionalities into a single component. This consolidation streamlines the manufacturing process and reduces material usage and associated costs. (General Motors, n.d.)

From a sustainability perspective, topology optimization reduces the use of materials. By optimizing the distribution of material within a product, designers can achieve the desired performance with minimal material consumption. This reduction in material usage reduces costs and lessens the environmental impact associated with material extraction, production, and disposal. (Bezpalko, 2019)

Furthermore, by reducing the weight of products through topology optimization, there is a decrease in fuel consumption during transportation and usage. This has positive implications for the environment, particularly in terms of carbon emissions and energy consumption. Topology optimization also enhances the structural integrity and durability of designed products. By optimizing the distribution of material within a structure, designers can ensure that it can withstand the required loads and stresses while minimizing the risk of failure. This improved structural integrity increases the product's lifespan and reduces the need for frequent replacements, resulting in extended durability and reduced material waste. (Bezpalko, 2019)

Some software to implement TO are Fusion 360, nTop, Altair, and Grasshopper.

Limits

During a meeting on Topology Optimization at VanBerlo the approach's limits were discussed. When optimizing geometry using software, it is essential to keep in mind that it only considers the defined load cases. If a load case is overlooked during the boundary conditions definition, the structure could be fragile in that area. To avoid this, continually testing and validating the geometries in real-life scenarios is crucial. This testing allows load cases to be further defined and iterated for better results. It is important to remember that this process should be iterative and ongoing.

Figure 24: Topology optimization used for a foot prothesis and a rescue device, Marsanasco's graduation project for VanBerlo part of Accenture

Lattice structures

"LATTICE STRUCTURES ARE DEFINED AS THREE-DIMENSIONAL STRUCTURES COMPOSED OF CONSECUTIVELY AND REPEATEDLY ARRANGED INTERCONNECTED CELLS, WHICH CAN ALSO BE UNDERSTOOD AS POROUS MATERIAL STRUCTURES COMPOSED OF INTERCONNECTED STRUTS AND NODES IN THREE-DIMENSIONAL SPACE. "(PAN ET AL., 2020

There is a wide range of unit cell types, from graph to surface-based lattice structures, each appropriate for different applications, such as lightweight heat exchangers, energy absorption, osseointegration, ergonomics, and aesthetics. (nTop,2023)
Lattice structures are widely used in industrial design applications, from footwear to ultra-personalized products in sports and healthcare.
Tian, Wan & Gün (2020) developed a midsole (Figure 27) optimizing structural performances through lattices structures informed by pressure and deformation data.
New Balance in 2019 launched a 3D Printed Triple Cell Collection with the midsole and lattice design designed by Gün and the CD team at the company (Figure 25). (New Balance 2019)

Specialized, a bicycle brand, recently launched a saddle using lattice structures to enhance the comfort and performance of the saddle (Figure 26). (Specialized, n.d.)

Oescheler used lattice structures to design a backpack (Figure 28) that recently won the RedDot Award. (Ag, 2023)

The 3D-printed back pads and hip fins have an open cell structure that improves air ventilation, reduces heat accumulation, and lowers temperature and humidity at the contact area with the hiker's back. Additionally, the lattice structure allows for adjustable damping characteristics by varying the lattice geometry, strut thickness, and size, enabling different areas of the lattice to have varying degrees of hardness. This enhances damping properties and overall comfort for the user. (Ag, 2023)
Lattice structures are also widely used in the healthcare industry by leading companies such as HP to design and 3D print orthotics, prosthetics, and dental implants. (HP, n.d.).
In synthesis, lattice structures can increase as the level of control, intricacy, and complexity of a product's geometry, which can allow the design of specific properties or behaviors of a product.
Some software to implement Lattice structures are Crystallion, nTop, Fusion 360.

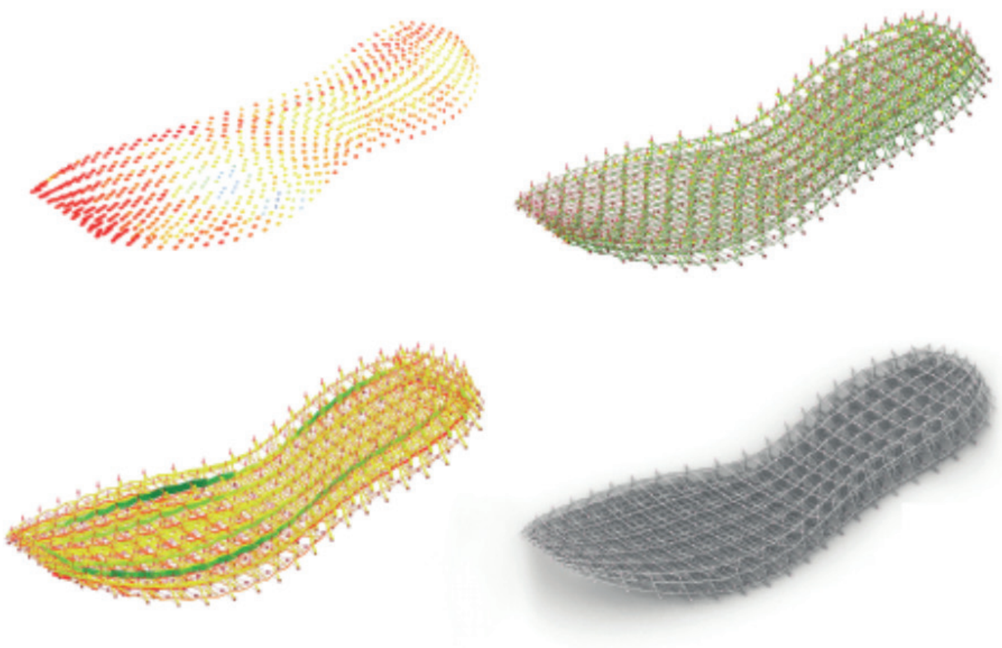


Figure 27: Data driven midsole from Tian, Wan & Gün (2020)

Figure 25: 3D Printed Fuelcell Echo Triple midsole and forefoot from Gün and New Balance, 2019

Figure 26: Mirror saddle, Specialized

Conclusions

In conclusion, SI is particularly suited for behavior-driven design processes, while SG and LS are better suited for form-driven design processes. GA allows for an undirected exploration of the design space and ensures quality assurance by searching the fitness function. (Singh & Gu, 2012)
Topology optimization and lattice structures are probably the generative methods most used in industrial design at the moment. The generative methods described above should be selected based on the design goal or problem, considering their different potentials. It might also be interesting to experiment with mixing and matching the various methods.
While these generative methods offer valuable opportunities and benefits in industrial design, it is essential to acknowledge their limitations. Continued testing, validation, and real-life scenario considerations are crucial for ensuring the reliability of designs generated through these methods.

Figure 28: Oescheler backpack using lattice structures

2.4.2 GENERATIVE AI IN INDUSTRIAL DESIGN

The relationship between computational design and generative AI, albeit nebulous, will be discussed in this section. In light of this, discussing generative AI among the other CD generative methods presented in the previous section was considered appropriate. Undeniably, generative AI facilitates designers in generating design content, especially during the preliminary stages of the design process.
Generative AI has undergone significant advancements since the beginning of this project. It is a topic with an intrinsic high level of complexity more extensive than computational design and a topic on its own. It is challenging to trace clear boundaries between AI and computational design.
Isgrò et al. (2022) define AI as "the ability of machines to think or act either humanly, i.e., performing tasks traditionally carried out by humans (Verganti et al., 2020), or rationally, i.e., based on mathematical principles."
The words "AI" and "computational" are undoubtedly part of the same domain: computer science. The role of the word "design" in relation to AI is being defined at a large scale at the moment (2023) and will likely change the design world in the coming years or even months.
For MIT Technology Review (2023), Generative AI is a broad category of large AI algorithms that create original content based on instructions, usually written and submitted in natural language.
Natural language processing (NLP) involves using machine learning algorithms to analyze and understand human language, opening a more discursive process while interacting with the machines.

Relationship between AI and Computational Design
AI differs from other computational tools in many aspects, from its "black box" nature and NLP capabilities. However, it is undoubtedly a powerful tool that fully uses computational capabilities, possibly even more than other computational design tools. Therefore, it can be considered as falling within the definition of CD as defined by Oxman (2006) -which refers to design processes that maximize the use of computers for their computational potential rather than merely as electronic drawing boards- and for its "generative" nature arguably it would fall in the generative design cluster proposed by Caetano et al., (2020) described in section 2.2.1. An additional touch point between generative AI and other CD methods is the use of parameters. The practice of isolating them to create a controlled

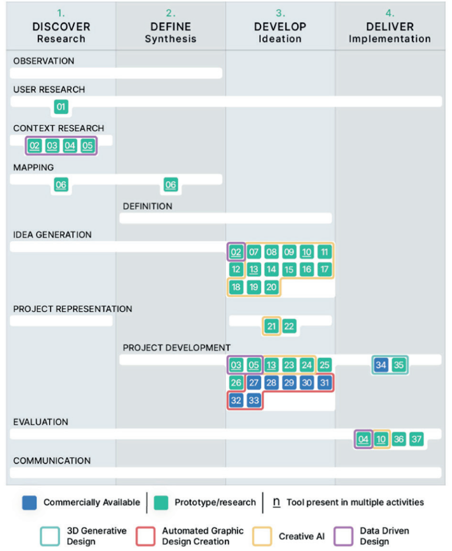
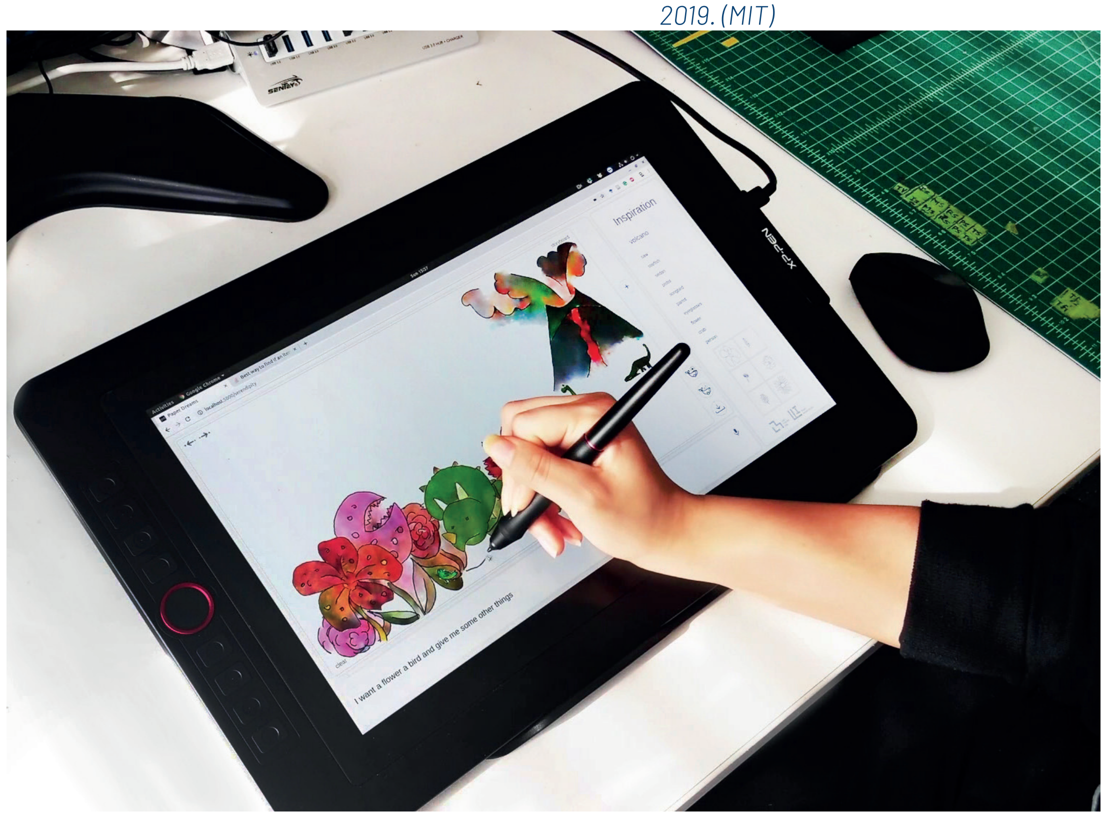


Figure 29: Isgrò, F., Ferraris, S.D., Colombo, S. (2022). AI-Enabled Design Tools: Current Trends and Future Possibilities

Figure 30: Paper Dreams: An Interactive Interface for Generative Visual Expression Bernal, Guillermo, Lily Zhou, Haripriya Mehta, and Pattie, 2019. (MIT)



experiment and understand the inner working of the tool and the algorithm's response is common in most CD design tools. (Gün, 2022)

AI's influence on the design process
With the recent advancements in Generative AI, it is evident that this technology will influence the design process. However, it's challenging to determine the extent of its impact.
For MIT Technology Review (2023), Generative AI models can enhance design process precision, efficiency, and creativity. Additionally, Generative AI has revolutionized the application of machine learning, going beyond data analysis and interpretation to creating original and distinctive content. (MIT Technology Review, 2023)
In a study conducted by Isgrò et al. (2022), an overview of AI's role in the design process was presented (Figure 29). The study presents a collection of case studies showcasing AI's application in the design process, utilizing the double diamond model as a framework.
Isgrò et al. (2022), emphasize that most AI tools are currently focused on the ideation phase. This trend can be attributed to the capabilities and limitations of narrow AI, which excels at specific and well-defined tasks with explicit constraints and utilizes extensive datasets to generate new materials.
Beyond the augmentation of existing design activities, AI also has the potential to introduce entirely new tools to support designers. For example, generating images from words (DALL-E 2021) can stimulate human creativity in unforeseen ways. AI can also facilitate new forms of interaction with users, conduct research, and enable hybrid collaborations. Chatbots, for instance, can serve as creative assistants for inspiration, analysis, or assessment. (Isgrò et al., 2022)

Tools like Paper Dreams (Figure 30), developed by Bernal (2019) at MIT Media Lab, allow interaction with the AI system through sketching. The system suggests semantic association based on the designer's sketch. The designers can also tweak the "randomness" of the suggested associations through a serendipity wheel. Tools like this could increase communication between designers and AI tools.
Isgrò et al. (2022) confirms that AI's potential in design still needs to be explored. It highlights design activities, such as user observation and behavioral research through image recognition, that have not been fully explored for AI augmentation. Leveraging AI for these purposes could enable designers to investigate larger cohorts of users from different socio-demographic groups, fostering inclusivity. Tools such as ChatGPT could be used to analyze user interviews and extract data relevant to the design process. (Bratanic, 2023)
Text-to-image is also being integrated into well-established design tools such as Adobe Photoshop, with functionalities such as generative fill that will likely streamline the visualization work in design even more. (Adobe, 2023)

Applications of AI, such as sketch-to-render, explored by Tedeschi (2023), could unfold even more possibilities in design visualization and idea communication (Figure 31).

In a case described by MIT Technology Review (2023), AI models are trained by architects to " check rules quickly" regarding specific health and safety regulations. Design specifications for these requirements can be inputted into generative models so that the model uses these instructions to generate a floor plan from an existing drawing that is up to regulation. It is plausible to think that ID requirements could follow the same logic.

Text-to-Image Generation: Applications in Design
The most common Generative AI tools in design can be considered text-to-image generators such as OpenAI's DALL-E and Midjourney. When given a text prompt in Natural language, these models are trained on large databases of visual images used to create an original image. (MIT Technology Review, 2023)
Currently, text-to-image is arguably the most disruptive generative AI application within the design practice. Images created with models such as Midjourney, Dall-E, and StableDiffusion, have flooded the social media channels of the design world and beyond. However, the full implications of these applications still need to be defined.
Arguably the benefits of text-to-image in the design process can be divided into two categories:

1 - Divergence-exploration
The tool encourages the exploration of a broader solution space, creating links and chain reactions between ideas and stimulating dialogue with the tool itself. This might foster novelty and innovative solutions. Some interviewees mentioned using text-to-image to create mood boards and "get the ideas flowing."

2 - Fast visualization
The tools enable fast visualization of future scenarios and previously clearly defined concepts, improving internal and external communication with stakeholders.
These two benefits are directly related to the act of visualizing. While in the second, the designer already has a clear idea of what needs to be visualized, and the machine has the only task of rendering this idea. In the first case, the tool is used almost as a sparring partner in the creative process.
Two elements might come into play, aiding the creation process: the speed of visualizing ideas that can significantly increase the number of iterations in searching for an idea and the level of randomness or serendipity offered by the generative system. Therefore, in a way, the source of ideas is not anymore only the designer's brain ideating, but it is the designer's brain stimulated and guided by a system that responds to the designer's input (prompt). The designer can choose if follow a thread or not, but without any doubt, the level of serendipity increases during the creation process. The effects of this should still be evaluated in depth.

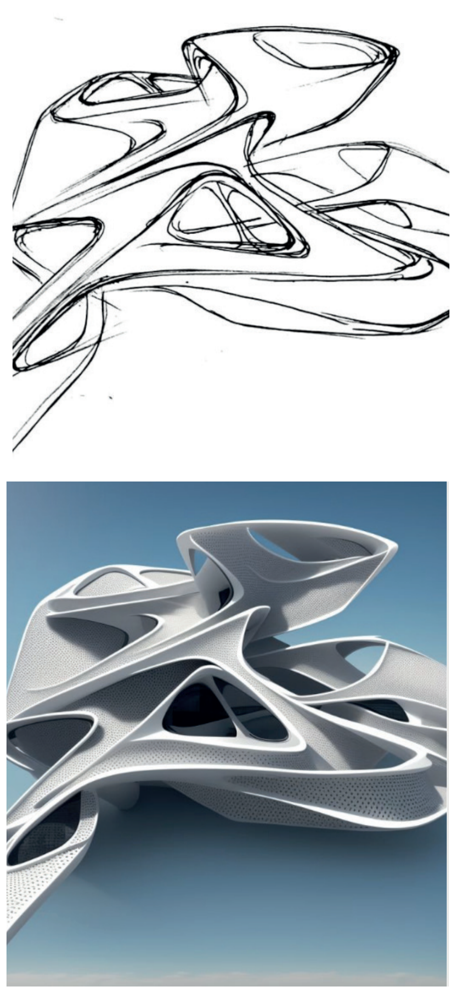


Figure 31: Sketch-to-render, Tedeschi (2023)

AI in 3D Shape Optimization
Isgrò et al. (2022) consider 3D shape optimization as an AI application in the ideation phase. This is a controversial topic because it needs to be clarified to what extent 3D shape optimization applications use AI, and at the same time, shape optimization is undoubtedly applied also in later phases of the design process and not only during the ideation phase. In another paper (Mountstephens & Teo,2020) on Generative 3D design, only one example was cited for using AI systems (Dhokia et al., 2017); the examples are described in the previous section 2.6.6.1 in the paragraph about Swarm intelligence. In addition, software companies often use the word "AI" without disclosing how much AI is used and contributes to the software. Some software uses AI to generate 3D content, such as PointE from openAI or GET3D from Nvidia. However, this 3D content has yet to be used for engineering.
Duann Scott discusses some of the limits of using AI in the optimization of 3D geometry by interviewing Rebekka Vaarum Woldseth and Ole Sigmund, authors of the paper "On the use of artificial neural networks in topology optimization (2022)."
One key reason for the scarcity of AI applications valuable to industrial design engineering is the lack of data sets to train models. While traditional optimization models seek solutions outside the dataset, a problem with using AI in topological optimization might be that artificial neural networks might not successfully find improved solutions beyond the initial dataset. (Scott, 2022)
Another problem of using AI to optimize a 3D model might be that errors in the modeling process can be propagated. With an AI black box model, it can be challenging to identify such errors if they are not immediately apparent, making it even more challenging to determine if a solution is optimized correctly. To ensure the efficiency and validity of an AI-generated result, it might be necessary to conduct post-analysis or post-optimization with well-established algorithms. (Scott, 2022)

AI adoption in industrial design
While generative AI offers great potential to enhance efficiency in industrial design, however it also poses challenges. Traditional product prototyping and drawing processes will be significantly altered when generative AI tools instantly generate numerous alternatives of design content. This eliminates time-intensive processes that involve manually plugging specifications into the design process. As a result, companies need to carefully review their design and operational processes and be open to substantial changes to effectively incorporate generative AI. (MIT Technology Review, 2023)
For MIT tech review (2023), the integration of generative AI models into manufacturing and industrial development processes is expected to increase in the next three to five years. Initially, industrial companies will use these models to automate repetitive tasks involved in creating products. In the next ten years, these models might allow companies to create products and services more efficiently and with increased resilience. With better and more precise designs, the amount of materials and energy used may decrease,

which could lead to more sustainable operations. (MIT Technology Review, 2023)
Industrial design companies are focused on solving specific design problems. Therefore, their generative AI models should rely on precisely curated image datasets and additional data in various formats closely related to the firm's production requirements and criteria. (MIT Technology Review, 2023)
However, for these efforts to be successful, developers must first define the problem accurately and then gather and structure the training datasets based on their own expertise, experience, and intellectual property.
MIT tech review (2023), points out that Diffusion models, consisting of a single neural network, are considered more stable and easier to train and scale up than Generative Adversarial Networks (GANs).

Generative AI's implication on creativity and future scenarios
Though AI in design is sometimes viewed as a threat to creativity, it can be considered another potent tool in the designer's arsenal/toolbox. While AI can automate certain processes, it still requires human intervention to create genuinely engaging or valuable outcomes. In many ways, AI can be compared to photography, which disrupted the art world over a century ago. (American Scientist, 2019) Generative AI will soon be seen as a tool that augments the work of innovative designers rather than replacing it. (MIT Technology Review, 2023)

"PEOPLE THINK THAT AI IS A REPLACEMENT OR EQUAL TO HUMAN INTELLIGENCE, AND IT IS NOT; YOU STILL NEED IDEATION AND SKETCHING. IT'S STILL A DESIGN PROCESS. OUR INTUITION COUNTS A LOT. STILL US, BUT AUGMENTED. THE BEST WAY TO WORK WITH AI AND ML IS TO USE TOOLS LIKE RUNWAY TO EXPAND YOUR CREATIVITY RATHER THAN CONSIDER THEM REPLACEMENTS FOR OUR CREATIVE ACTS. WE HAVE TO USE THESE TOOLS TO AID OUR HUMAN CREATIVITY AND MAKE HUMAN LIFE BETTER." (GÜN AS CITED IN VALENZUELA (2021))

Humans possess visual creativity and the ability to make open-ended associations; AI is limited by predefined patterns. However, AI has the potential to augment human visual creativity by generating new visual content. It is incorrect to define AI as creative, considering that humans are both pattern makers and breakers, while computers excel only at pattern recognition. (Gün, 2023)

" GENERATIVE AI WILL MAKE ARCHITECTURE AND INDUSTRIAL DESIGN WORK MORE CREATIVE, NOT LESS." (MIT TECHNOLOGY REVIEW, 2023)

De Cremer et al. (2023), in an article for Harvard Business Review, suggest three not mutually exclusive future scenarios concerning the impact of Generative AI on creativity:
The first scenario suggests that AI will augment human creativity, allowing creators to work more efficiently and produce ideas faster. This could lead to increased productivity and a rise in the number of people engaging in creative work. Generative AI tools can assist novices and facilitate rapid innovation through natural language interfaces. Arguably this could be seen as a form f democratization of creative work.
The second scenario raises concerns about algorithmically generated content crowding out authentic human creativity. It highlights the risks of an abundance of low-quality content, copyright issues, and the loss of shared experiences. Curated content would become more valuable, leading to market concentration and a limited number of established artists dominating the industry.
The third scenario suggests a "techlash" against algorithmically generated content, with a premium placed on authentic human creativity. Humans would have an advantage in terms of accuracy and contextual awareness. Strengthening the governance of information spaces would be necessary to counter the downside risks of generative AI.
All of these scenarios share a common factor: the significant role of human creativity. While there are positive aspects, such as enhancement and accessibility, there are also negative consequences, like copyright problems and potential job loss. De Cremer et al. (2023) stresses the importance of preparing for generative AI disruption by "investing in your ontology," in other words organizing, digitizing, and structuring proprietary knowledge.

Conclusions
In conclusion, generative AI has made significant advancements and is a topic with inherent complexity that extends beyond computational design but has an inextricable connection with it.
Generative AI, particularly in the form of text-to-image generators, has emerged as a powerful tool within the design process. It can enhance efficiency, and creativity in design. By creating original content based on natural language instructions, generative AI algorithms enable designers to explore a broader solution space and stimulate dialogue and innovation. They also accelerate the visualization of future scenarios and concepts, allowing for faster design process iteration and better communication with stakeholders.
Generative AI is still limited in creating industrial design engineering-worth 3D content.
While generative AI offers immense potential, it also presents challenges. Traditional design processes will be significantly altered. This necessitates a careful review and potential restructuring of the current design and operational processes for successful integration. It is important to note that while AI can automate certain processes, it does not replace human creativity but rather augments it.

2.5 CONCLUSIONS ON THEORETICAL CONCEPTS AND GENERATIVE METHODS

THE TERM 'COMPUTATIONAL DESIGN (CD)' IS SOMEWHAT ELUSIVE, PRESENTING A VAST ARRAY OF **DEFINITIONS** DETAILED IN SECTION 2.2. HOWEVER, ALL DEFINITIONS STRESS THE SIGNIFICANCE OF UTILIZING COMPUTATIONAL TOOLS TO BROADEN THE SOLUTION LANDSCAPE,FOSTERING CREATIVITY AND UNCOVER NEW AND BETTER-PERFORMING OUTCOMES.

REALIZING THESE BENEFITS CALLS FOR A **PARADIGM SHIFT.** CD TYPICALLY NECESSITATES THE CREATION OF A COMPUTATIONAL **SYSTEM** REPRESENTING THE PRODUCT AND ITS POSSIBLE VARIATIONS INSTEAD OF FOCUSING SOLELY ON DESIGNING THE INDIVIDUAL ARTIFACT. THIS APPROACH DEMANDS A MINDSET ROOTED IN THE **THEORETICAL CONCEPTS** DESCRIBED IN SECTION 2.3. **EVOLUTIONAY COMPUTATION** (2.3.4) HELPS TO IN UNDERSTANDING THE IDEA OF "EVOLVING" A DESIGN DESCRIBING THE REASONS BEHIND THE NOVELTY OF CERTAIN SOLUTIONS. THE **FORM FINDING** APPROACH (2.3.5) CAN BE INSTRUMENTAL IN CREATING A MENTAL FRAMEWORK TO IDENTIFY MEANINGFUL PARAMETERS AND GOALS FOR DESIGN PROJECT.

AMONG THE **GENERATIVE METHODS** ANALYZED IN SECTION 2.4, **GENETIC ALGORITHMS (GA)** ARE PARTICULARLY NOTEWORTHY. THEY EMULATE THE LOGIC OF NATURAL EVOLUTION, ALLOWING FOR THE EFFECTIVE RESOLUTION OF MULTI-DIMENSIONAL OPTIMIZATION PROBLEMS AND EXPLORATION OF A VAST DESIGN SPACE, AS NAGY ET AL. (2017) OUTLINED.
FURTHERMORE, THIS CHAPTER EXAMINES THE ROLE OF **GENERATIVE AI** IN PRODUCING IMAGES (SECTION 2.4.2). THIS PROCESS CAN EXPEDITE THE VISUALIZATION OF CONCEPTS AND FUTURE SCENARIOS, SUPPORTING THE IDEATION PHASE AND FASTER COMMUNICATION WITH STAKEHOLDERS.

Image from the author produced with Midjourney

3 COMPUTATIONAL DESIGN IMPLICATIONS FOR THE DESIGN PROCESS AND OPPORTUNITIES IN INDUSTRIAL DESIGN

This chapter outlines the implications of Computational Design (CD) in Industrial Design (ID). The first part (3.2-3.5) discusses the approach's effects on the design process, the relevant skills, and the shift in the designer's role. The second part (3.6) focuses on the opportunities enabled by CD and how it positively impact industrial products.

Image produced with Midjourney

3.1 METHODOLOGY: CD EXPERTS INTERVIEW

Objective
The literature research provided an understanding of the theoretical aspects of Computational Design (CD). However, most of the literature focused on cases developed in an academic environment. Interviews with CD experts were deemed necessary to understand CD skills, opportunities, and tools, from an industry standpoint. The main objective of the interviews was to understand the expert's point of view and to capture some of their experience. The interviews aimed to investigate further the following four research questions regarding the potential of CD in industrial design:

RQ1.2: WHAT ARE THE IMPLICATIONS OF CD FOR THE **DESIGN PROCESS** AND THE ROLE OF THE DESIGNER?

RQ 1.3: WHAT ARE THE **OPPORTUNITIES** THAT CD CREATES IN THE DESIGN OF INDUSTRIAL PRODUCTS?

Participants
The initial criterion for participant selection was to include designers who explicitly stated the use of CD as the main element of their practice in designing industrial products. Once the first criterion was met, participants were chosen based on the following criteria:
- Academic experience.
- Contribution to the promotion of intellectual discourse on CD in industrial design.
- Industry of origin to ensure heterogeneity between consultancy and in-house design teams.

Three experts were interviewed:

Onur Yüce Gün (New Balance): Through his social media channel and university lectures, he explains the role of CD and AI in the design of industrial products. He has a Ph.D. in design and computation from MIT and is the computational design director at New Balance.

Evan Greenberg (ModeLab): Evan studied and worked at the Architectural Association Emergent Technologies and Design graduate program. He is Head of Emergent Technologies at Modelab, a design studio focusing on CD.

Figure 32: Interview anlalysis with Condense

CD Expert 2: With an industrial design background, he is leading a computational design group in a multinational company, which focuses on revolutionizing various industries through Computational Design. Their goal is to help clients take advantage of the potential of mass customization, meta-materials, generative design, and design automation without investing significant resources or time in upskilling their staff. (Scott, 2023)

Interview Questions
Due to the topic's sometimes abstract and theoretical nature, a qualitative research method was chosen. The interview script included (Appendix C), among others, the following key questions:

- What are the primary benefits of CD when applied to industrial design?
- How do you apply CD throughout your process? What is your approach for a typical project?
- What are the software tools that are most frequently used in your practice?
- In which product categories (e.g., healthcare, sport, consumer goods, professional tools) can CD bring more benefits?
- What new expertise and skills are needed?

The last part of the interviews was dedicated to gaining feedback on some of the artifacts developed by the author and presented in Chapter 5.

The interviews were conducted individually via Zoom because all the participants were based in the US. Each interview lasted approximately 60 minutes, and the script was semi-structured and flexible to accommodate the natural flow of the discussions with the participants.

Methods of Analysis
First, the data from each participant were analyzed separately using Condense (Figure 32), which allowed for an initial coding of the interview results; the relevant and most interesting quotes were collected in statement cards on Miro (Sanders & Stappers, 2013). The cards were clustered to form various themes (Corbin & Strauss, 1990). The process of categorizing and clustering the statement cards contributed to structuring the information obtained from the interviews into macro themes.

Main Themes
The interviews have been instrumental in the deepening of topics encountered during the literature research, such as design optimization and automation. These approaches have been established as integral parts of the experts' daily work. Additionally, new aspects, such as the mindset and skills required in CD or the software utilized by experts, have been understood through the interviews. The results will be summarized in the following text.

What are the main benefits of CD applied to Industrial Design?

The approach has the potential to revolutionize the process of designing industrial products from the point of view of efficiency and creativity while enabling the creation of new product features such as ultra-personalized products or architected materials. Furthermore, the ability to develop specific systems tailored to design problems has been emphasized, with the complex problems being broken down into manageable steps and specific algorithms for exploration immediately conceptualized. It is important to note that the distinction between breaking down a problem into smaller components and simplifying it has been stressed by experts. CD empowers the embrace and maintenance of complexity.

How do you apply CD throughout your process? What is your approach for a typical project?

Experts have explained how CD can be used throughout the design process.
Computational tools have been integrated into every phase, from the initial exploration using generative AI, shape grammars, and procedural modeling to the final stages involving optimization tools like evolutionary solvers. However traditional methods like sketching, prototyping, and user testing remain fundamental to the experts' process.
CD has also the potential to change the design process output.
The deliverable to a customer can be, in addition to the traditional geometry, an engine or a configurator that generates variations of a product.

What are the tools you use the most during your practice?

On the software side, Grasshopper has been highlighted for its flexibility. Additionally, software typical of the film and gaming industries, such as Houdini and Unity, has been commonly used. The selection of this category of software is based on its versatility and its potential for creating bespoke solutions for diverse design challenges, including customized plug-ins.

In which product categories CD can bring more benefits?

The interviewees agreed that, currently, CD is beneficial for product categories such as shoes, prosthetics, and products that require complex geometries or specific performances. Nonetheless, they highlighted that there are no limits to the product categories that can benefit from the use of CD.
The promise of ultra-personalization, with its potential for reducing overproduction and mitigating unsold stock, has been particularly highlighted from a sustainability standpoint.

Which new expertise/skills are needed?

System thinking was a prominent topic among the skills being discussed. This skill is fundamental in defining the computational systems necessary to explore design problems.
Equally crucial is the ability to apply software development methodologies to physical product design, bridging the gap between code and desired physical solutions. Additionally, the adoption of agile processes has been considered pivotal in embracing the dynamic nature of CD.

Considerations on interviews
One key element of the interview was the confidence in CD's potential and its future growth.
The investment of time by some experts in educating colleagues and clients about CD has underscored the need for CD training in the industrial design industry.

The standout benefit of CD is its capacity to expand the design space, offering designers numerous solutions, some of which are wholly unexpected – these, from one expert, are referred to as "Wild cards." This not only fuels the creative process but also enhances the value proposition to customers. Moreover, CD accelerates the design process through automation, returning precious time to both designers and clients. The level of control over product geometry, referred to as "intricacy" by one expert has been considered key in achieving specific product properties.

On the limitations side, an expert has noted that an excess of solutions can create noise in the selection process, necessitating improved lenses and filters when examining the solution space. Another expert mentioned that "sometimes computational design or additive manufacturing is simply not the right solution, you have to be honest with yourself and move forward fast."
In conclusion, the interviews were used to understand the tools used during a CD process, the necessary skills, and in combination with literature research to define the benefits of the CD for the design process (section 3.4) and opportunities in ID (section 3.7).

3.2 EFFECTS OF COMPUTATIONAL DESIGN IN THE DESIGN PROCESS IN INDUSTRIAL DESIGN

This section will discuss the possible change in the mental framework and in the approach adopted by designers in a Computational Design Process.

As expressed in the previous sections of the report and confirmed by Saadi and Yang (2023), one of the significant impacts of CD in ID is the change in the mental framework while approaching a design problem, with the designer aiming to create a system to generate various design solutions.

This approach would imply using technical requirements and product specifications early in the design process. (Saadi & Yang, 2023) When designers define their objectives, parameters, and constraints so early in the DP, they enter a constraint-driven design process. (Saadi & Yang, 2023). Arguably, these constraints could be associated with the internal and external forces mentioned by Menges & Ahlquist (2011) in the form-finding framework (Section 2.3.3). Saadi and Yang (2023) describe that during a constraint-driven design process, designers focus on abstracting the design problem and improving the definitions of its boundary conditions between iterations, shifting the focus of the iteration process from the product's physical features to the generative system's parameters. This analysis effort could increase awareness of the design problem and decrease the need for prior ideas about the final form of the design. (Saadi & Yang, 2023)(Menges & Ahlquist, 2011)

The constraint-driven design process described by Saadi and Yang (2023) could have significant implications for the design process. Traditionally there is a substantial distinction in the DP between conceptual and detailed design stages, with the possibility of solving the majority of technical requirements only in later stages of the design process. (Mountstephens & Teo, 2020)
CD allows the integration of technical requirements in the early phase of the process, reducing the number of iterations or, in more extreme cases, directly blending the phases of the design process. (Mountstephens & Teo, 2020)
The constraint-driven approach (Figure 33) might also come with drawbacks, for instance, an excessive focus on technical requirements and performance, leading to less attention directed to the subjective criteria of the design problem. (Saadi & Yang, 2023)

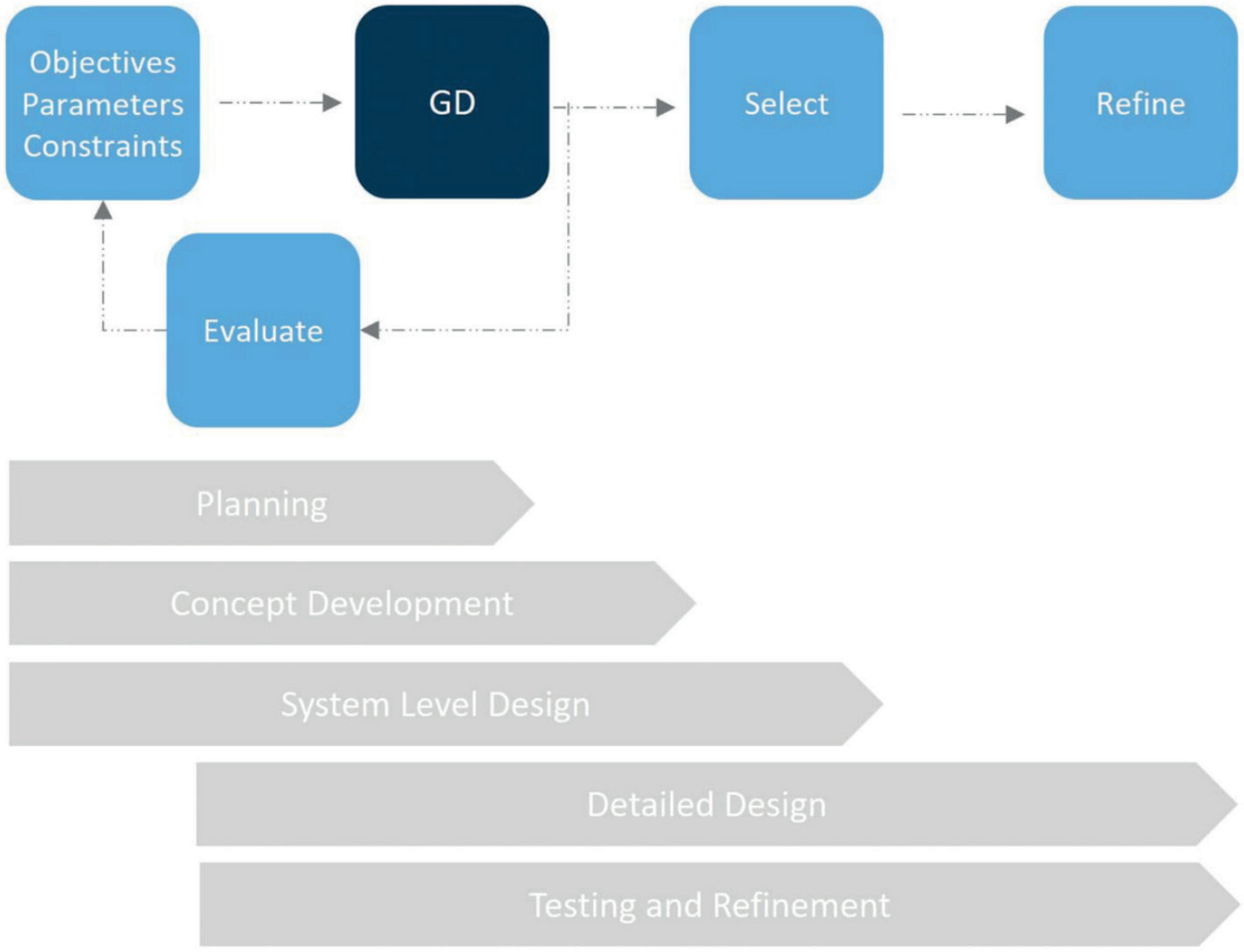


Figure 33: From Saadi and Yang (2023): Overlap of generative design (GD) process (top) and a more traditional design process

It is essential to consider that while using computational strategies, holistically approaching the project is fundamental, and using generative methods should be accompanied by traditional tools, such as drawings and physical models. (Car, 2017)

"IN THE REALM OF INDUSTRIAL DESIGN, MOCKUPS REMAIN CRUCIAL, AS DOES THE TESTING OF PRODUCTS. IT'S ESSENTIAL TO CONDUCT PERCEPTION, FIELD, AND EXPERIENCE TESTS AMONG OTHERS. YET, WHEN YOU MERGE COMPUTATIONAL THINKING, CRAFTING, AND SIMULATIONS WITH USER FEEDBACK, I BELIEVE IT LEADS TO SUPERIOR PRODUCT QUALITY."
CD EXPERT INTERVIEW 3: ONUR YÜCE GÜN, DIRECTOR OF CD AT NEW BALANCE

Conclusions

In conclusion, adopting CD in industrial design necessitates a significant shift in the designer's mindset, focusing on creating a system for generating multiple design solutions. This change prompts early engagement with technical requirements and product specifications, introducing a constraint-driven design process. While this new approach may improve understanding of the design problem and integrate technical requirements earlier in the process, it may overemphasize technical aspects at the expense of subjective criteria. Furthermore, traditional design methods and tools, such as mock-ups, tests, and user feedback, remain vital.

3.3 THE SHIFT OF THE DESIGNER'S ROLE IN A COMPUTATIONAL DESIGN PARADIGM

One of the recurrent themes in researching CD concerns the approach's impacts on the designer's role.
CD can strongly influence the overall design process, from initial exploration to the final design, while also affecting the designer's cognitive processes. (Song et al., 2020)
Mountstephens and Teo (2020) propose that the role of the designers in CD leans more towards the evaluation of design options than their creation. Arguably, both the definition of the design space through parameters and the evaluation of design options is innate in the nature of the design job; CD adds the interaction with the generative system. This passage from McCormack, (2004) discussing the designer's role in computational design deserves full-length quotation:

"IN TRADITIONAL DESIGN, THE ROLE OF THE DESIGNER IS TO EXPLORE A SOLUTION SPACE. THERE IS A DIRECT RELATIONSHIP BETWEEN THE DESIGNER'S INTENTIONS AND THAT OF THE DESIGNED ARTIFACT. IN CONTRAST, DESIGN USING GENERATIVE METHODS INVOLVES THE CREATION AND MODIFICATION OF RULES OR SYSTEMS THAT INTERACT TO GENERATE THE FINISHED DESIGN AUTONOMOUSLY. HENCE, THE DESIGNER DOES NOT DIRECTLY MANIPULATE THE PRODUCED ARTIFACT, BUT RATHER THE RULES AND SYSTEMS INVOLVED IN THE ARTIFACT'S PRODUCTION. THE DESIGN PROCESS BECOMES ONE OF META-DESIGN, WHERE A FINISHED DESIGN IS THE RESULT OF THE EMERGENT PROPERTIES OF THE INTERACTING SYSTEM. THE 'ART' OF DESIGNING IN THIS MODE IS IN MASTERING THE RELATION BETWEEN PROCESS SPECIFICATION, ENVIRONMENT, AND GENERATED ARTIFACT. SINCE THIS IS AN ART, THERE IS NO FORMALIZED OR INSTRUCTION-BASED METHOD THAT CAN BE USED TO GUIDE THIS RELATIONSHIP. THE ROLE OF THE HUMAN DESIGNER REMAINS, AS WITH CONVENTIONAL DESIGN, CENTRAL TO THE DESIGN PROCESS. "(MCCORMACK, 2004)

Creativity remains a vital part of the process, and it is used in the definition of parameters and in the use of computational methods to meet technical requirements but also to influence the design aesthetic and subjective qualities. (Saadi & Yang, 2023)
Arguably, the CD approach opens up new possibilities to express human creativity.

"THE PRODUCT COMPUTATIONALLY OPTIMIZED FOR TECHNICAL REQUIREMENTS IS JUST A STARTING POINT TO OTHER FORMS OF DESIGN" CD EXPERT INTERVIEW 1: EVAN GREENBERG, HEAD OF EMERGENT TECHNOLOGIES AT MODELAB

There is no straightforward solution in the design process, and human judgment and user testing are crucial, especially for subjective requirements. As mentioned previously, design problems are multi-dimensional (Nagy, 2017). The tradeoffs necessary to arrive at the best design solution – an optimal one is not yet possible- still require human evaluation. In this context, computational tools are another –powerful- tool to further explore the design space in the designer's toolbox. (Mountstephens & Teo, 2020)

Conclusions

To summarize, designers now have a more advanced role in the design process. They are responsible for controlling the generative design process, where the final design results from the combination of the designer's imagination with the generative capabilities of computer tools. (Leach (2009) Caetano et al. (2020)

3.4 THE SKILLS NEEDED TO USE COMPUTATIONAL DESIGN

In order to incorporate CD into industrial design practice, it is crucial to identify the necessary skills for designers to implement this approach effectively. To determine these skills, an analysis of job openings in CD and interviews with practitioners were performed. Some of the skills that emerged during the research are already covered in the curriculum of industrial design students, while others are currently not commonly taught in their education.

Hard skills

Three job openings from Oxman, Apple, and New Balance were analyzed to evaluate the skills requested by new hires in CD.

The skills outlined in the CD job openings reflect the multifaceted nature of the field and the demand for a diverse skill set. The desired qualifications emphasize a combination of creative and technical proficiencies. A strong portfolio showcasing out-of-the-box thinking and a keen eye for design and creative fundamentals such as composition is often highlighted as a prerequisite, indicating the importance of aesthetic sensibility and usability knowledge in CD. Proficiency in specific software, such as Grasshopper and Rhino, is preferred, suggesting their widespread use in the industry. The requirement of being highly adaptable and offering creative solutions for ambiguous problems highlights the need for problem-solving skills and flexibility in addressing diverse design challenges.

Knowledge of tools such as SideFX Houdini, Blender, or Cinema 4D is often requested. Moreover, familiarity with real-time tools like Touch Designer, Unreal Engine, or Unity is considered advantageous, as it suggests the increasing relevance of interactive and immersive experiences in this field. These software were also mentioned during the interviews from the perspective of delivering to the client a product configurator instead of the traditional product geometry.

"AS WE WORK WITH A COMPANY, EVENTUALLY THEY ARE GOING TO WANT ACCESS TO BE ABLE TO CREATE THEIR OWN GEOMETRY, AND THEN THAT WILL BE AN ENGINE, WHICH WOULD BE A GRASSHOPPER FILE IN SOME INSTANCES, HOUDINI FILE, OR IT MIGHT RUN IN LIKE UNREAL OR UNITY, IT MIGHT BE SOMETHING THAT'S PACKAGED LIKE A GAME. BASICALLY, WE ARE LEVERAGING ALL OF THE PIPELINES OF GAMING AND FILM TO DO INDUSTRIAL DESIGN AND ENGINEERING." CD EXPERT INTERVIEW 2

To be successful in CD, it is crucial to have a solid understanding of programming languages, particularly Python. Moreover, knowing computational geometry, digital fabrication, advanced linear algebra, multivariable calculus, or related fields showcases CD's research-based aspect.

As data-driven design approaches become more important, designers must possess the skills to integrate and comprehend large data sets within computational models effectively. They should also be proficient in managing complex data and files and manipulating design variables. These abilities are crucial for working with and organizing substantial amounts of design-related data.

Soft skills (SK)
The practitioners emphasize the distinction between a computational designer and a technician and the difference between designing through computation and implementing code. This differentiation underscores the multifaceted nature of computational design. It highlights the need for a series of soft design skills and mindsets and their meaning in the context of CD for effective engagement in this field.

SK1: Curiosity and being process oriented
A curious mindset is fundamental to seeing the world differently and having a genuine interest in how technology could influence how we design things and positively impact society. Computational designers, like every designer, should perceive the world through a unique lens, considering not only the product or work-related aspects but also the broader implications and interconnectedness of their designs. This perspective demonstrates the need for computational designers to think holistically and consider the larger context in which their work exists.
Interestingly, one practitioner shares a personal journey that began with experiments involving materials rather than immediately diving into coding. By exploring how materials behave and interact, he gained insights into the problem space from a computational perspective. This approach allowed him to approach problems differently, considering the cause-and-effect relationships between material properties and desired outcomes. This experience highlights the value of a strong foundation in physical experimentation and material understanding for computational designers.
This unfolds a perspective in approaching problem-solving differently, emphasizing the importance of understanding the problem space before diving into coding or technical tools. Once the problem space is understood, applying the necessary tools and building a solution becomes more accessible.

"THE PRIMARY SKILL IS CURIOSITY, AND THAT SHOULD BE EVERY STUDENT, BUT THE REALITY IS THAT IT IS A NEW WORLD FOR PEOPLE WHO ARE NOT INVOLVED. IT IS JUST A VERY NEW WAY OF THINKING ABOUT THE WORLD. I SAY THE WORLD BECAUSE IT IS MORE THAN JUST THINKING ABOUT THE PRODUCT. I SEE THE WORLD DIFFERENTLY BECAUSE OF WHAT I HAVE BEEN DOING AT WORK FOR SO LONG. YOU BROUGHT UP OUR HISTORY, WHERE WE LOOK, AND WHERE WE CAME FROM... OUR JOURNEY. AND YOU MENTIONED FREI OTTO AND FULLER. WHEN I WAS A STUDENT, I DID NOT START CODING. I WAS DOING EXPERIMENTS WITH MATERIALS. UNDERSTANDING HOW A SHEET OF LYCRA STRETCHES, HOW WOOD BENDS, AND THESE KINDS OF THINGS, YOU CREATE THE BASICS TO UNDERSTAND COMPUTATIONAL DESIGN.
THE MAIN POINT IS UNDERSTANDING THE PROBLEM SPACE. BECAUSE I UNDERSTOOD THAT WHEN YOU DO THIS, IF YOU BEND IT X MILLIMETERS MORE OR PUSH IT A LITTLE MORE THAN THIS, THIS HAPPENS, RIGHT? AND THEN, WELL, WHAT IF I HAVE THREE PARAMETERS? WHAT IS THE OUTCOME? IT'S A MINDSET. LEARN, LEARN. I WAS LEARNING ABOUT GENETICS, AND I WAS LIKE, WELL, WHY THE HELL AM I LEARNING ABOUT GENETICS? I DON'T WANT TO BE A BIOLOGIST. HOWEVER, IT ALLOWED ME TO UNDERSTAND HOW INSTRUCTIONS ARE WRITTEN, HOW THINGS INTERACT, AND HOW WHAT YOU KNOW RESULTS IN A PHYSICAL FORM. AND THEN ONCE YOU HAVE THAT FOUNDATION, YOU CAN DIVE INTO THE TOOLS, AND IT'S LIKE, OK, COOL, I KNOW HOW TO THINK ABOUT THIS. NOW I JUST NEED TO BUILD IT." CD EXPERT INTERVIEW 1: EVAN GREENBERG, HEAD OF EMERGENT TECHNOLOGIES AT MODELAB

While multiple interviewees mentioned the need to be process-oriented, also Oxman, in its career page for computational designers, cites the requirement of being process-driven to take a generative approach to design. Adopting this thinking is necessary to "facilitate mediation and dialog, opening opportunities for non-obvious interactions and combined systems that unite physical, digital, and biological elements."

SK2: System thinking and critical thinking

"TAKE THAT YOU HAVE TO TEACH A COMPUTER TO DO YOUR JOB FOR YOU AUTOMATICALLY. IT'S ANOTHER LEVEL OF COMPLEXITY AND SYSTEMS THINKING THAT'S REALLY INTERESTING." CD EXPERT INTERVIEW 2

The interviewees emphasized the importance of systems thinking in computational design. They distinguish between designing a single artifact and designing a system that can generate multiple possibilities. The ability to think through a systems approach is critical and offers significant value in computational design. This implies that computational designers should possess a holistic understanding of complex systems, enabling them to consider the interdependencies and emergent properties within their designs.

"CRITICAL THINKING IS CRITICAL, TO QUESTION EVERYTHING. HOWEVER, BEING ABLE TO THINK ABOUT PROBLEMS THROUGH A SYSTEMS THINKING APPROACH IS ALSO CRITICAL. THIS RETURNS TO THE DIFFERENCE I WAS TALKING ABOUT. YOU CAN BUILD A SINGLE MODEL IN RHINO, RIGHT? THUS, YOU BUILD THE THING, THE ARTIFACT. HOWEVER, IF YOU DESIGN A SYSTEM, THAT SYSTEM CAN NOW GENERATE MANY POSSIBILITIES. AND THERE IS A BIG DIFFERENCE THERE, AND THAT IS HUGE VALUE, RIGHT? SO I WOULD SAY IF I WAS LOOKING FOR SOMEBODY TO WORK WITH OR SOMEONE WAS LOOKING TO HIRE ME, YOU KNOW, I WOULD WANT TO BE ABLE TO THINK THROUGH A SYSTEMS APPROACH... THERE IS BEAUTY IN IMPLEMENTATION, BUT IF I CAN DESIGN AN ALGORITHM BECAUSE I UNDERSTAND HOW THE SYSTEM WORKS, I DON'T NEED TO BE ABLE TO IMPLEMENT IT." CD EXPERT INTERVIEW 1: EVAN GREENBERG, HEAD OF EMERGENT TECHNOLOGIES AT MODELAB

SK3: Software paradigm and agile process
The term software paradigm could be associated with the practice of approaching the design of a physical product with practices and frameworks used in software development. This term appeared multiple times during the project's interview with experts, and some software companies use it for marketing their proposed "paradigm shift" in the design of physical products.

"SO THAT'S ALL THERE. LIKE FOR ME, IT'S LIKE TURNING PHYSICAL INTO A DIGITAL CONTEXT" CD EXPERT INTERVIEW 2

One of the skills that emerges from the interviews is the ability to adopt an agile process. The practitioners express their inclination towards using agile methodologies, which emphasize the need for iterative and flexible approaches to problem-solving.

"I'VE BEEN LEARNING HOW TO USE MORE OF AN AGILE PROCESS" CD EXPERT INTERVIEW 2

Conclusions
In conclusion, the interviews shed light on the skills and mindsets necessary for success in computational design. These include, in addition to basic knowlede of computer science concepts, proficiency in agile processes, a curious mindset, an understanding of materials and physical experimentation, and the ability to think through a systems approach. By cultivating these skills, computational designers can effectively navigate the complexities of their field and generate innovative and impactful designs.

3.5
THE POSSIBLE ADVANTAGES OF ADOPTING COMPUTATIONAL DESIGN IN THE DESIGN PROCESS

In this section, it will be discussed how Computational Design (CD) can enhance two activities recurrent throughout the design process in Industrial Design (ID):

Divergence: exploring a design space to generate various ideas, creating choices. (Thoring & Müller, 2011)

Convergence: converging toward a solution that meets specific requirements, making choices toward a design goal. (Thoring & Müller, 2011)

We can think of the design process as a fractal with the act of diverging and converging, repeating at different scales and magnitudes:

"DESIGNING IS LIKE A FRACTAL: ZOOMING IN OR OUT RESULTS IN A SIMILAR IMAGE. DESIGNING IS AN ITERATIVE PROCESS, WHERE YOU SOMETIMES MUST TAKE A FEW STEPS BACK TO GO A STEP FORWARD LATER ON" (ROOZENBURG & EEKELS, 1995)

The design process is complex and entagled. However, the themes of divergence and convergence are often recurrent. (Goldschmidt, 2016)

The role of Computational design in Divergence and Convergence
During expert interviews, the following question was asked:

"From my understanding, the main value of most CD tools is divergence and creating many solutions to explore a wider solution space. What is the role of CD in divergence and convergence?"

From the discussion emerged that CD is beneficial for both divergence and convergence in the design process.

"COMPUTATIONAL THINKING AIDS IN BOTH DIVERGING AND CONVERGING PROCESSES."
CD EXPERT INTERVIEW 3: ONUR YÜCE GÜN, CD DIRECTOR AT NEW BALANCE

In divergence, CD helps explore a wider solution space, creating many solutions and allowing fast exploration of variants on a design while generating new solutions. It stimulates novel ideas through solutions that might be unexpected or unimagined or exploring all the possible solutions of a specific optimization problem.

"WE ARE ABLE TO SEE A FULL DESIGN SPACE. SOMETIMES SEE THE UNIMAGINED AND DISCOVER THINGS YOU DID NOT KNOW EXISTED. OR OTHER TIME JUST IMAGINING SOMETHING AND DOING IT WITH THE RIGHT AMOUNT OF COMPLEXITY"
CD EXPERT INTERVIEW 1: EVAN GREENBERG, HEAD OF EMERGENT TECHNOLOGIES AT MODELAB

However, an excessive abundance of possibilities can interfere with the design process. While diverging CD can help in thinking in terms of constraints, as described by Saadi and Yang (2023).

"IN THE PROCESS OF DIVERGING, KNOWING POTENTIAL DIRECTIONS DEFINING PARAMETERS FOR SEARCHING OPTIMAL DESIGN SOLUTIONS. HOWEVER, EVEN WHEN TRYING TO BROADEN ONE'S SCOPE, DIVERGENCE HAS ITS LIMITS IN COMPUTATIONAL DESIGN. WITHOUT CONSTRAINTS, DESIGN BECOMES AN IMPOSSIBLE TASK, AND THUS YOU START WITH A BOUNDED DESIGN SPACE WHILE TRYING TO SEARCH FOR THE 'UNKNOWN!'. IT'S THE PARADOX OF DESIGN. WHILE SOME PARAMETERS CAN BE DEFINED COMPUTATIONALLY, OTHERS SIMPLY CANNOT. THAT, IN MY VIEW, IS THE BOUNDARY AND CHALLENGE OF COMPUTATIONAL DESIGN."
CD EXPERT INTERVIEW 3: ONUR YÜCE GÜN, CD DIRECTOR AT NEW BALANCE

In divergence, the interaction with parameters could stimulate the designer to look at a design problem analytically and pinpoint the crucial elements to interact with to arrive at the desired solution. (Saadi & Yang, 2023) Some examples of these parameters could be load cases in a topology optimization problem, identifying the necessary data and parameters in the design of an ultra-personalized product, or a less mathematical fashion identifying the suitable prompts to get the image desired to visualize with generative AI.

"IN COMPUTATIONAL DESIGN, IT'S KEY TO FOCUS ON A SPECIFIC AREA AND SEEK ITS ADVANTAGES. THIS APPROACH ALLOWS REFINING A DESIGN IDEA ITERATIVELY, ENHANCING IT WITH EACH STEP. THIS ITERATIVE IMPROVEMENT IS A PRIME BENEFIT OF COMPUTATION IN MY VIEW."
CD EXPERT INTERVIEW 3: ONUR YÜCE GÜN, CD DIRECTOR AT NEW BALANCE

A hypothesis of categorization for CD benefits for the design process

It is challenging to trace clear boundaries in defining the benefit that CD could bring to the design process. However, this thesis attempts to propose a categorization of these benefits through an analysis of CD contribution on three dimensions: efficiency during the process, exploration of novel ideas, and improved quality of the final product.

Benefit 1: Efficiency

An overarching benefit of the process is speed, thanks to the computing power of machines. (Caetano & Leitão, 2019)
The rapid development of technology is mainly driven by the speed of computers, which is significantly faster than that of humans in specific duties. This enables software to take on a wide range of tasks on our behalf, as many of these tasks would be too time-consuming for a person to complete within a reasonable timeframe. (Denning & Tedre, 2019, p. 214)
While humans can carry out some information processing tasks using algorithms, computers can accomplish assignments that are beyond human capability, making their impact significant in the current age (Denning & Tedre, 2019, p. 214)

In industrial design, the speed enabled by computation can generate geometry or images and quickly propagate changes and variations in design artifacts. Some of the benefits of CD related to efficiency and speed are:

- Incorporating and propagating changes in a quick and flexible manner (Caetano et al., 2020)
- Automating design procedures (Caetano et al., 2020)
- Parallelizing design tasks and efficiently managing large amounts of information (Caetano et al., 2020)
- Decrease the number of iterations needed thanks to digitally validated results and integration of objective engineering requirements into the hitherto subjective conceptual design. (Mountstephens & Teo, 2020)

All the experts interviewed during the project mentioned increased efficiency and speed as one of the main benefits of applying CD to the industrial design process.

"CD ALLOWS YOU TO DESIGN MUCH MORE AND DO IT MORE EFFICIENTLY, BUT YOU NEED THE APPROPRIATE OUTLET, SO COMPUTATIONAL DESIGN IN THE CONTEXT OF TRADITIONAL PRODUCTION CAN BE MORE LIMITED." CD EXPERT INTERVIEW 2

"THANKS TO DESIGN AUTOMATION, YOU CAN MOVE MUCH FASTER. SPEED AND MINIMIZING REWORK FROM A FUNCTIONAL PERSPECTIVE ARE REALLY IMPORTANT ASPECTS OF CD." CD EXPERT INTERVIEW 1: EVAN GREENBERG, HEAD OF EMERGENT TECHNOLOGIES AT MODELAB

In conclusion, the computational speed of machines significantly enhances the efficiency and efficacy of the design process, an aspect affirmed by several experts. Its profound impact is seen in various design tasks, from rapidly generating and altering geometric shapes and images to efficiently handling vast amounts of data. The computational design process brings high flexibility and responsiveness, allowing changes to be quickly incorporated and propagated. It also supports the automation of design procedures and reduces the need for repeated iterations by integrating objective engineering requirements early in the design stage. Design automation will be discussed in section 3.7.1.

Benefit 2: Exploration

The concept of divergence is closely intertwined with the idea of exploration. The exploration quality of CD could be associated with the quantity and novelty of the solutions the designer is exposed to that could help solve a specific design problem (or a future one). This capability could be enabled by the speed and automation of design tasks, which generate a vast number of solutions in a relatively short period. Additionally, the quality of exploration depends on the novelty exhibited by the generated solutions, which, depending on the generative algorithm and the designer's input,may be unprecedented and beyond human imagination. (Mountstephens & Teo, 2020)(Saadi & Yang, 2023)

"GENERATIVE DESIGN CONTRIBUTES TO FOSTERING CREATIVITY AND INNOVATION IN HUMAN DESIGNERS BY PRODUCING FORMS NEVER SEEN BEFORE...THE AUTOMATIC GENERATION OF THOUSANDS OF DIFFERENT DESIGN OPTIONS ALLOWS COMPREHENSIVE EXPLORATION OF DESIGN SPACES TOO LARGE FOR HUMANS TO EXPLORE MANUALLY" (MOUNTSTEPHENS & TEO, 2020)

Evan Greenberg, durin an interview, provided a quote that accurately depicts the explorative capabilities of CD:

"FOR SOME PROBLEMS EXPLORING THE 20% OF THE DESIGN SPACE MIGHT BE GOOD ENOUGH. HOWEVER, OFTEN EXPLORING THE ENTIRE DESIGN SPACE WITH CD COMES FOR FREE AND CAN THROW A COUPLE OF WILD CARDS."

CD EXPERT INTERVIEW 1: EVAN GREENBERG, HEAD OF EMERGENT TECHNOLOGIES AT MODELAB

The process of exploring in design starts with human intuition, and CD offers the means to try things out and investigate in a new dimension. This strategy boosts human creativity instead of substituting it. (Terzidis 2004).

Exploration might be fostered not only by the definition of parameters but also by human perception and tools such as Shape Grammars or Generative AI. During an expert interview conducted during the research, Onur Yüce Gün (CD lead at NewBalance) was asked by the author of this thesis about the nature of generative design beyond evolutionary solvers. Gün's response was:

"IN DIGITAL COMPUTATION, GENERATIVE DESIGN IS OFTEN ABOUT FINDING THE SOLUTION THAT MATCHES A SET 'FITNESS VALUE'—OUR TARGET. WHEN I PONDER GENERATIVE DESIGN, MY MIND DRIFTS TO SHAPE GRAMMARS, EPITOMIZED BY GEORGE STINY'S NOTION OF SQUARES, TRIANGLES, AND K'S. THEIR VAST GENERATIVE POWER ALLOWS OUR EYES TO PLAY THE ROLE OF 'SOLVER', LETTING US PERCEIVE AND INTERPRET THESE SHAPES WITHOUT BOUNDS. WHILE THERE'S NO EXACT 'FITNESS VALUE', THE GENERATIVE PROCESS IS BOUNDLESS, GOVERNED ONLY BY THE SHAPES PRESENTED AND OUR OWN IMAGINATION.
THE POTENTIAL IS LIMITLESS; THESE SHAPES SET MY IMAGINATION ALIGHT, ALLOWING ME TO DISCOVER COUNTLESS CREATIVE AVENUES. THIS GENERATIVE APPROACH ISN'T ABOUT SEARCHING FOR A PREDETERMINED END; IT'S ABOUT SERENDIPITY—STUMBLING UPON WHAT YOU WEREN'T EXPLICITLY SEEKING.
HOWEVER, MANY DIGITAL COMPUTATIONAL GENERATIVE METHODS TEND TO LIMIT CREATIVITY, SETTING THEIR SIGHTS ON A SOMEWHAT PREDEFINED RESULT, MAKING THE JOURNEY MORE ABOUT OPTIMIZATION. VIEWING IT PERCEPTUALLY, THOUGH, OFFERS A MORE EXPANSIVE TAKE ON GENERATIVE DESIGN."
CD EXPERT INTERVIEW 3: ONUR YÜCE GÜN, CD DIRECTOR AT NEW BALANCE

In conclusion, Computational Design enhances design exploration by generating novel and diverse solutions and extending human creativity.

Benefit 3: improved quality and performance

As Kyratsis et al. explain in the book Computational Design and Digital Manufacturing. (2023), at least for now, there is no univocal method to assess if a design solution is the best possible. Generative design could offer the possibility to better depict the logical sequence between the design problem and solution. This is possible through methodically structuring and mapping the design space, identifying requirements, and exploring design solutions mathematically generated to meet those requirements. This constraint-driven approach could lead to improved performance in product design (Saadi & Yang, 2023)

When it comes to technical performances, optimization, and simulation can be used to meet specific requirements by using computational power to search for and optimize solutions toward defined goals. Similarly, but with more difficulty, subjective design problems can be optimized by using computational methods to define what is aesthetically pleasing or comfortable (Mountstephens & Teo, 2020). Additionally, controlling the generated geometry through architected materials or advanced modeling tools like field-driven modeling can improve design outcomes and reduce the need to simplify design solutions. (Ntopology, 2022)

“COMPUTATIONAL DESIGN PROVIDES THE ABILITY TO MAINTAIN COMPLEXITY AND IMPROVE THE PRODUCT’S QUALITY. THERE IS A LIMIT TO WHAT A HUMAN CAN HANDLE.” CD EXPERT INTERVIEW 1: EVAN GREENBERG, HEAD OF EMERGENT TECHNOLOGIES AT MODELAB

In addition to this, CD might be precious to “fail fast and learn fast” between iterations, allowing, for instance, mixing simulation with physical testing while iterating:

“OFTEN, COMPUTATIONAL DESIGN OFFERS RAPID LEARNING. FOR INSTANCE, WHEN DELVING INTO 3D PRINTING, PROGRESSING TO A 4TH-GENERATION COMPONENT INVOLVES SEVERAL OPTIMIZATION PHASES. WITH COMPUTATION, THE ITERATION PROCESS IS EXPEDITED, AS IT ALLOWS THE SEAMLESS BLEND OF SIMULATION AND ACTUAL TESTING AT EACH STEP.” CD EXPERT INTERVIEW 3 CD EXPERT INTERVIEW 3: ONUR YÜCE GÜN, CD DIRECTOR AT NEW BALANCE

In conclusion, CD offers a methodical approach to identifying requirements and generating mathematically-driven solutions, resulting in improved performance in product design. Optimization, simulation, and advanced modeling tools offer ways to meet technical and aesthetic goals while maintaining complexity. Expert opinions highlight the role of CD in learning and improving rapidly through iterations, enabled by blending simulation with physical testing. Hence, CD not only streamlines the design process but also enhances the quality and performance of the final product.

Conclusions on CD benefits in Industrial Design

This section explored the benefits of Computational Design (CD) within the design process, specifically utilizing the divergence and convergence framework represented by the double diamond model. CD plays a vital role in the design process’s divergence and convergence phases. In divergence, CD helps explore a broad solution space and generate new ideas. During the convergence phase, CD aids in a more focused and analytical approach to the design problem, ultimately resulting in a specific solution.

The benefits of CD within this framework are categorized into three main dimensions: efficiency, exploration, and improved quality.

1. Efficiency: CD greatly enhances the speed and efficiency of the design process due to the computational power of machines, allowing for quick changes, automation of design procedures, efficient management of information, and reduced number of iterations.

2. Exploration: CD contributes to the exploration of novel solutions beyond human imagination, boosting creativity rather than replacing it. It allows designers to investigate new dimensions and possibilities, fostering a richer exploration of the design space.

3. Improved Quality: CD offers a methodical approach to the design process, leading to improved performance and quality of the final product. It allows for optimization and simulation to meet specific design requirements, advanced modeling for better design outcomes, and faster learning and improvement through iterations.
To sum up, the improved computational power of tools and the wide range of available CD methods have empowered designers to improve their design process by making it more efficient or pushing its conceptual boundaries. (Caetano & Leitão, 2019)

3.6 CD SOFTWARE TOOLS IN 3D DESIGN: “SANDBOXES” VS. OTHER SOFTWARE

According to the research, two main clusters of software are available for designing and generating 3D geometry. The first category includes traditional CAD software, which is designed for engineering applications and includes variable degrees of parametric and generative design capabilities. Examples of such software include Fusion 360 and Catia (Generative Design extension). Industrial design engineers are likely more familiar with this software category, as it has been widely used in the industry for a considerable time. However, this category’s strengths come at a cost, as they may be considered “walled gardens.” In other words, these software packages are compelling but limited in their capabilities. Consequently, when a design idea or goal falls outside the standard and intended capabilities of the software, it may be challenging to achieve the desired result. Essentially, the design output could be restricted by the use cases foreseen and envisioned by the software developers. For instance, if a designer needs to create a lattice structure with specific mechanical properties, finding the desired structure in the software’s library is ideal. However, if such a structure is not available, obtaining the required output could be difficult, if not impossible. This topic was discussed during experts interviews:

“YOU CAN DO SOME BASIC LATTICING IN SOME CAD SOFTWARE. BUT IF YOU WANT TO DO THIS, DATA-DRIVEN DENSITY MODELS OR CONFORMAL LATTICING YOU ARE NOT THERE YET [...]I REFER TO THIS CATEGORY OF SOFTWARE AS A BIT OF A WALLED GARDEN. BEAUTIFUL THINGS ARE GROWING IN THAT GARDEN, BUT IT HAS WALLS. IF YOU WANT A NEW FEATURE, IT HAS TO GO THROUGH THEIR PRODUCT DEVELOPMENT, AND THEN EVERYBODY IN THE ENTIRE INDUSTRY GETS IT AT THE SAME MOMENT YOU DO. SO YOU HAVE NO TECHNICAL ADVANTAGE FOR ASKING FOR IT. ” CD EXPERT INTERVIEW 2

The second software category comprises what some experts defined during interviews as “sandboxes.”

“IN CONTRAST TO “WALLED GARDENS” IF YOU ARE WORKING IN WHAT I CALL AN OPEN SANDBOX, YOU ARE JUST ON A BEACH. YOU CAN BUILD SANDCASTLES TO BOTH HORIZONS. NO ONE’S GOING TO STOP YOU. IT IS A VERY DIFFERENT CONTEXT” CD EXPERT INTERVIEW 2

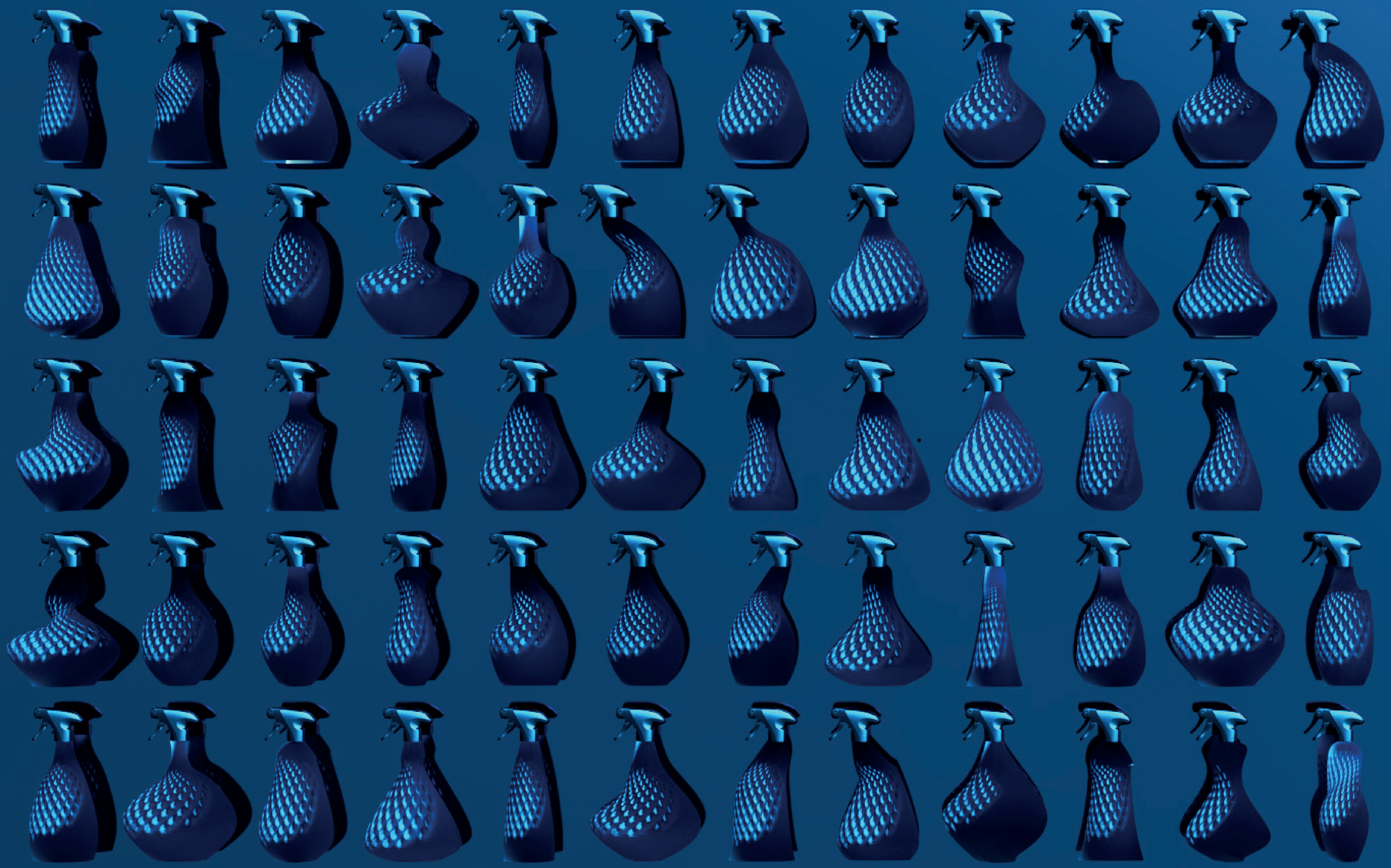
Sandboxes enable users to communicate directly with the software backend, usually via visual programming. This feature allows for greater flexibility and the possibility of building computational design systems tailored to the design problem. However, this flexibility comes at the price of a steeper learning curve, and the designer interacts primarily with node systems in visual programming and lines of code in direct scripting. As a result, familiarity with computational concepts, thinking, and programming is necessary. The learning curve could be reduced with new AI tools that help designers familiarize themselves with code. Nevertheless, such tools offer immense flexibility and the possibility of building customized solutions for design problems. Learning to use such tools should pay off in the long run due to their flexibility and computational power.
Therefore, these software packages can be platforms for users to build tailored solutions to their problems. Grasshopper is probably the most well-known software package in this category. In addition to its visual programming interface, which provides significant control over the geometry generated on the Rhino viewport, there are a couple of factors distinguishing the Grasshopper ecosystem. Firstly, there is a passionate and cohesive community)that mostly gathers on the Grasshopper forum (McNeel, n.d.). This community is a valuable resource that can help ease the software’s learning curve. Secondly, the software boasts numerous plug-ins available through the “food4rhino” website, which give the software Swiss Army knife qualities. These plug-ins allow users to find specific components and plug-ins tailored to their industry or desired applications.

“GRASSHOPPER IS INCREDIBLE FOR A COUPLE OF REASONS. IT IS BASICALLY OPEN SOURCE EVEN THOUGH YOU PAY FOR RHINO. IT’S WIDELY USED, AND PEOPLE USE IT LIKE YOU WOULD USE GITHUB FOR OTHER TYPES OF THINGS.
THEY ARE DOING PROJECTS, AND THEY’RE SHARING THEM WITH THE WORLD.” CD EXPERT INTERVIEW 2

Other software in this category can be considered Houdini and Blender. One expert recommended Houdini for its flexibility, stability, and capability of handling voxels.
It is worth noting that one aspect that should be considered when using software of the “sandbox” type is the packaging of the solution and the deliverable to the client. In this context, the open-source nature of software such as Grasshopper could be a problem. However, this topic requires further attention, as it was not prioritized in the research.

Conclusionos

In conclusion, the section highlights two types of 3D geometry design software: traditional CAD software with some degree of generative capabilities and more flexible systems defined as “sandboxes.” “Sandbox” software like Grasshopper, Houdini, and Blender offers customization and flexibility but with a steeper learning curve. The choice between these software types depends on the user’s specific needs, capabilities, and the project’s requirements.



3.7
COMPUTATIONAL DESIGN OPPORTUNITIES IN INDUSTRIAL DESIGN

Shapes and rendering created by the thesis 's author using Grasshopper and Biomorpher.
Spray trigger head 3D model from VanBerlo

This section aims to answer the following research questions:

RQ 1.3: WHAT ARE THE **OPPORTUNITIES** THAT CD CREATES IN THE DESIGN OF INDUSTRIAL PRODUCTS?

This final section of the chapter discusses the practical opportunities of utilizing Computational Design (CD) in Industrial Design (ID). The chapter's journey commenced with a broad, abstract analysis of theoretical concepts, gradually morphing into a more specific discussion as it transitioned into the realm of industrial design and ultimately focused on CD methods suitable for ID.
The discussion now culminates by spotlighting the tangible opportunities CD presents in ID. As outlined earlier in section 3.5, CD offer distinct benefits to the design process, such as quality enhancement, efficiency improvements, and expanded exploration possibilities.

However, these advantages may appear abstract initially, as they are described in section 3.5. To address this, the following section of the chapter illustrates the tangible impacts and benefits that can be obtained through the implementation of CD in the ID processes. This description provides a basic understanding of the CD's role in "augmenting" industrial design.

The opportunities presented in the following section are different topics encountered during the research, which aim to materialize and represent in a tangible fashion the benefits previously described with practical examples and concrete opportunities that could be almost immediately applied in the project to create value in the final product and expand the design process.
Some of these opportunities are more related to the design process, such as design automation or hyper production of images some are more related to the final product, such as optimization. It should be noted that it is too difficult to trace watertight definitions on these topics, which are often intertwined. For instance, design automation might be considered an enabler of mass customization, but these two topics will be explained in two separate sections.

It is important to note that this section does not aspire to provide an exhaustive overview of all possible CD opportunities in ID, nor does it aim to delineate definitive, watertight categories. It seeks to share the most promising prospects discovered during this research, thereby serving as a starting point for further exploration. During the research, some case studies were developed that allowed for the immediate creation of practical applications within the context of VanBerlo. These case studies can be found in the sections discussing configurators (3.7.3) optimization (3.7.4) and text to 3D utilizing ChatGPT (3.7.8). Among these, the top priority was assigned to developing a configurator to employ in future user research.

This aspect was given precedence due to its emergence during a focus group with VanBerlo. Before the focus group, the notion of a configurator uncovered in the research was primarily associated with mass customization. Interestingly, during the focus group, a participant suggested utilizing a configurator to empower individuals without a design background, enabling them to express their ideas on a project during a design research phase.
The product selected for the configurator is a trigger spray bottle (Figure 41). This product suits a user research method involving user and customer design input. Furthermore, preliminary experiments on optimization (as discussed in section 3.7.4) and text-to-3D conversion (outlined in sectio3.7.8) were also conducted on the same product.

3.7.1 DESIGN AUTOMATION

The idea of automation is closely linked to efficiency, as discussed in Section 3.5. It represents one of the main benefits of applying Computational design (CD), as highlighted in research by Caetano et al. (2020).
Furthermore, during experts' interviews, design automation emerged as a critical aspect of CD.

"AUTOMATION AND CUSTOMIZATION ARE MASSIVE ASPECTS IN COMPUTATIONAL DESIGN, AND WE SPEND MUCH OF OUR TIME IN THAT SPACE." CD EXPERT INTERVIEW 2

Autodesk defines design automation as follows:

"DESIGN AUTOMATION LETS YOU CAPTURE AND REUSE ENGINEERING KNOWLEDGE AND INTENT. AUTOMATION NOT ONLY HELPS REDUCE ERRORS AND TIME SPENT ON TEDIOUS, REPETITIVE MODELING TASKS BUT IT CAN ALSO BE SCALED TO STREAMLINE DOWNSTREAM DEVELOPMENT PROCESSES." (AUTODESK, 2021)
Similarly, nTop emphasizes the value of encapsulating and repurposing design knowledge through automation:

"DESIGN AUTOMATION ENABLES YOU TO CREATE PROCESSES, SYSTEMS, AND RULES THAT CAPTURE ENGINEERING KNOWLEDGE. AUTOMATION CAN ELIMINATE ERRORS, REDUCE THE TIME SPENT MANUALLY MODIFYING MODELS, AND ENHANCE THE QUALITY OF YOUR DESIGN OUTPUTS. SIMPLY PUT, AN AUTOMATION WORKFLOW IS A CONFIGURATOR OR TEMPLATE THAT RECEIVES CERTAIN PARAMETERS AS INPUTS, MODIFIES OR GENERATES GEOMETRY BASED ON PREDEFINED RULES, AND PRODUCES A NEW 3D MODEL AS OUTPUT." (NTOP, N.D.)

Emphasizing the value of encapsulating and repurposing design knowledge is critical. This principle facilitates the transference of knowledge from seasoned professionals and encourages skill development among newcomers. Preserving design knowledge is essential to circumvent repetitive labor and generate replicable design patterns, streamlining the design process and boosting productivity.

Figure 34: The HP Molded Fiber Advanced Tooling Solution

During experts interviews, automation emerged as a critical point for saving time and avoiding repetitive tasks:

"OUR GOAL IS TO STREAMLINE INTERNAL INFORMATION ORGANIZATION; EFFECTIVE PROJECT MANAGEMENT IS ABOUT WORKING EFFICIENTLY TO AVOID REDUNDANCY. BY ESTABLISHING ROBUST FRAMEWORKS AND AUTOMATING DESIGN TASKS, WE ELIMINATE THE NEED TO WORRY OVER OUR WORK METHODS, THEREBY ALLOWING US TO CONCENTRATE ON THE TASK AT HAND." CD EXPERT INTERVIEW 1: EVAN GREENBERG, HEAD OF EMERGENT TECHNOLOGIES AT MODELAB

"I WOULD PREFER TO INVEST TIME INITIALLY IN UNDERSTANDING HOW TO INSTRUCT A MACHINE TO DO A TASK, ENABLING IT TO CARRY OUT THE TASK A MILLION TIMES, POSSIBLY WITH VARIATIONS. THIS, TO ME, SEEMS MORE EFFICIENT THAN REPEATEDLY REPLICATING THE TASK MANUALLY." CD EXPERT INTERVIEW 2

Design automation can be achieved by breaking down certain steps of the process and making them repeatable, sometimes using algorithmic logic to create geometry automatically.
An example of how design automation can not only speed up the design process but also enable business opportunities born from a collaboration between the companies of two CD experts interviewed during this project: HP and Modelab. The project is an automated solution to automatically produce custom tooling sets to produce molded fiber packaging with high levels of precision and finishing.
The HP Molded Fiber Advanced Tooling Solution (Figure 34) allows manufacturers to broaden their tooling functionality. This broadening could lead to improvements in production efficiencies, the creation of new design possibilities, and a reduction in the time it takes to launch a product in the market. HP's complete service incorporates its own tooling technology and engineering knowledge. The potential benefits include reduced lead times and maintenance periods and the ability to execute short-run productions tailored to specific needs. (HP, 2021)
Through the project, the client can send the CAD file of the packaging, and after a review from HP experts, the 3D model for the tooling set can be produced in less than two weeks thanks to the automated design and 3D printing. (ModeLab, 2021)

WE HAVE AUTOMATED THE ENTIRE PROCESS FOR CAD DESIGN OF THE TOOLSETS. FOR INSTANCE, IF A SUPPLIER PROVIDES A COMPONENT - LET'S SAY, AN EGG TRAY THEY INTEND TO MANUFACTURE - THEY JUST HAVE TO PROVIDE THE MODEL OF THE PRODUCT. BASED ON THIS, OUR SYSTEM AUTOMATICALLY DESIGNS THE COMPLETE TOOLING STACK TO FIT INTO THE DESIGNATED MACHINERY. THIS PROCESS IS ACCOMPLISHED THROUGH MESH AND VOXEL MODELING INSTEAD OF TRADITIONAL PARASOLID CAD METHODOLOGIES." CD EXPERT INTERVIEW 2

In conclusion, automating design processes can offer numerous advantages, such as enhanced efficiency, reduced errors, and accelerated design iterations.

3.7.2 MASS CUSTOMIZATION

Mass customization, also known as ultra personalization, can be defined as the practice of tailoring physical products on a large scale to meet individual specifications or needs (ShapeDiver, 2021). The transformation in manufacturing capability driven by new processes, such as additive manufacturing, offers significant potential for product innovation and the opportunity to create bespoke designs tailored to individual specifications or needs (Price et al., 2022).

Through customizing products and services, mass customization offers customers a personalized experience that surpasses the value provided by standard offerings. (Torn & Vaneker, 2019).
Some of the possibilities enabled by mass customization are:
o Tweaking the aesthetic appearance to align with the user's taste and preferences.
o Geometric adaptations to meet specific user needs, such as ergonomic requirements, ensuring comfort and use. (HP, 2022)
o Feature adjustments based on the deployment environment and the context of use, increasing product functionality (TUDelft, 2022)

As emerged during expert interviews, mass customization combined with additive manufacturing could decrease unsold stock products, as it produces only what is needed and desired, thereby reducing waste and environmental impact.

"CUSTOMIZATION PLAYS A CRITICAL ROLE IN SUSTAINABILITY AS IT ENSURES PRODUCTION ALIGNS WITH SPECIFIC CONSUMER NEEDS. WHEN A PRODUCT IS MADE TO CATER TO AN INDIVIDUAL'S SPECIFIC REQUIREMENTS, IT'S HIGHLY LIKELY THAT THE PRODUCT WILL HAVE A LONGER LIFESPAN, REDUCING THE CHANCES OF IT BEING DISCARDED PREMATURELY. FURTHERMORE, WHEN PRODUCTS ARE MANUFACTURED ADDITIVELY AND 'JUST IN TIME,' IT NEGATES THE NECESSITY FOR MASS PRODUCTION. THIS APPROACH MINIMIZES THE PRODUCTION OF SURPLUS ITEMS THAT MAY POTENTIALLY SIT ON SHELVES, CONTRIBUTING TO WASTE IF NOT PURCHASED." CD EXPERT INTERVIEW 2

CD and, in some cases, 3D printing are the key enablers for mass customization. CD plays a crucial role because it enables the designer to create a system that can use the user data ergonomics or other metrics of use or the user preferences as inputs in the design

Figure 35: Bike saddle from Hyperganic

system to adjust the geometry or the product finishing according to the data. This is possible thanks partially automated propagation of changes.

Mass customization can be applied to a wide range of products, as emerged during the CD experts' interviews:

"OUR INTERDISCIPLINARY TEAM IS COMPOSED OF EXPERTS FROM VARIOUS FIELDS, INCLUDING FOOTWEAR, WHO HAVE EXTENSIVE EXPERIENCE IN LATTICE DESIGN, AND ANOTHER GROUP SPECIALIZING IN CUSTOMIZING GAMING PERIPHERALS SUCH AS KEY CAPS AND HEADSETS. WE ARE INTEGRATING THESE DIVERSE GROUPS INTO A UNIFIED TEAM.
AS FOR MY ROLE, IT PRIMARILY REVOLVES AROUND BODY FITMENT - GENERATING AUTOMATED GEOMETRY FROM SCANS OF BODY PARTS SUCH AS FACES, HANDS, OR FEET. THIS COMES INTO PLAY IN AREAS LIKE PROSTHETICS, ORTHOTICS, EYEWEAR, AND WEARABLES. IT IS INCREDIBLY FASCINATING TO APPLY THIS WIDE-RANGING CONTEXT AND EQUALLY INTRIGUING TO DESIGN FOR THESE DIVERSE APPLICATIONS." CD EXPERT INTERVIEW 2

Key technologies like 3D scanning and pressure sensors play significant roles in mass customization. 3D scanning is integral in capturing user-specific anthropometric data, driving the generation of personalized geometries. By creating pressure maps, pressure sensors highlight the user's body pressure points, helping generate customized geometries for optimal comfort. (TUDelft, 2022a)

Implementation and case studies
While conducting the research, software solutions with built-in capabilities to generate geometry according to 3D scans or pressure maps were limited. Instead, experts interviewed in this field often rely on "sandbox" tools - defined in section 3.6- to create ultra-personalization systems tailored to their needs.

Hyperganic (2021) explains a process leading to an ultra-personalized saddle (Figure 35):

They begin by determining the requirements of the final product and work backward to identify the necessary functions and assets to be captured. To create personalized saddle designs, they digitally create accurate representations of cyclists' bodies using sensors to generate pressure maps indicating their bone structures' precise mass and pressure intensities. They algorithmically design the thousands of struts that make up the saddle's lattice structures modulated according to the input pressure maps. They add a layer of uniform aesthetic lattices that conform to the curved surfaces of the saddle to fit the functional lattice. Finally, a unique rim is automatically produced to join the circumference of the lattice cells without glue.

ModeLab developed another example of mass customization for Smith, a manufacturer of ski goggles. Mode Lab collaborated with Smith to create **Imprint 3D Technology**. Utilizing a facial morphology scan through a phone app that charts the distinct features of an individual's face, Smith employs advanced 3D printing technology to produce custom-fitted goggles explicitly tailored to the user (Figure 37). The time frame from order to unboxing is two weeks. (ModeLab, 2021b)

A sui generis example of ultra personalization is **Carpal Skin** from Neri Oxman. It differentiates from other examples because, in addition to the ergonomic data, it uses mapping of patients' pain profiles:
Carpal Skin (Figure 36) is an experimental protective hand-covering prototype to counteract Carpal Tunnel Syndrome. This medical condition occurs when pressure is exerted on the wrist's median nerve, leading to discomfort such as hand numbness, muscle wasting, and weakness. The typical pre-surgical intervention involves wearing wrist splints at night.
Carpal Skin's methodology involves crafting a patient-specific pain chart—tracking both the severity and persistence of pain—and strategically positioning hard and soft materials to accommodate each patient's unique body structure and physiological demands, thereby providing customized restriction of motion. The inspiration behind the formation process of this glove is drawn from the patterns seen in animal skins, which display control in the range of stiffness. (Oxman, 2010)

Figure 36: Carpal Skin, Neri Oxman (2010)

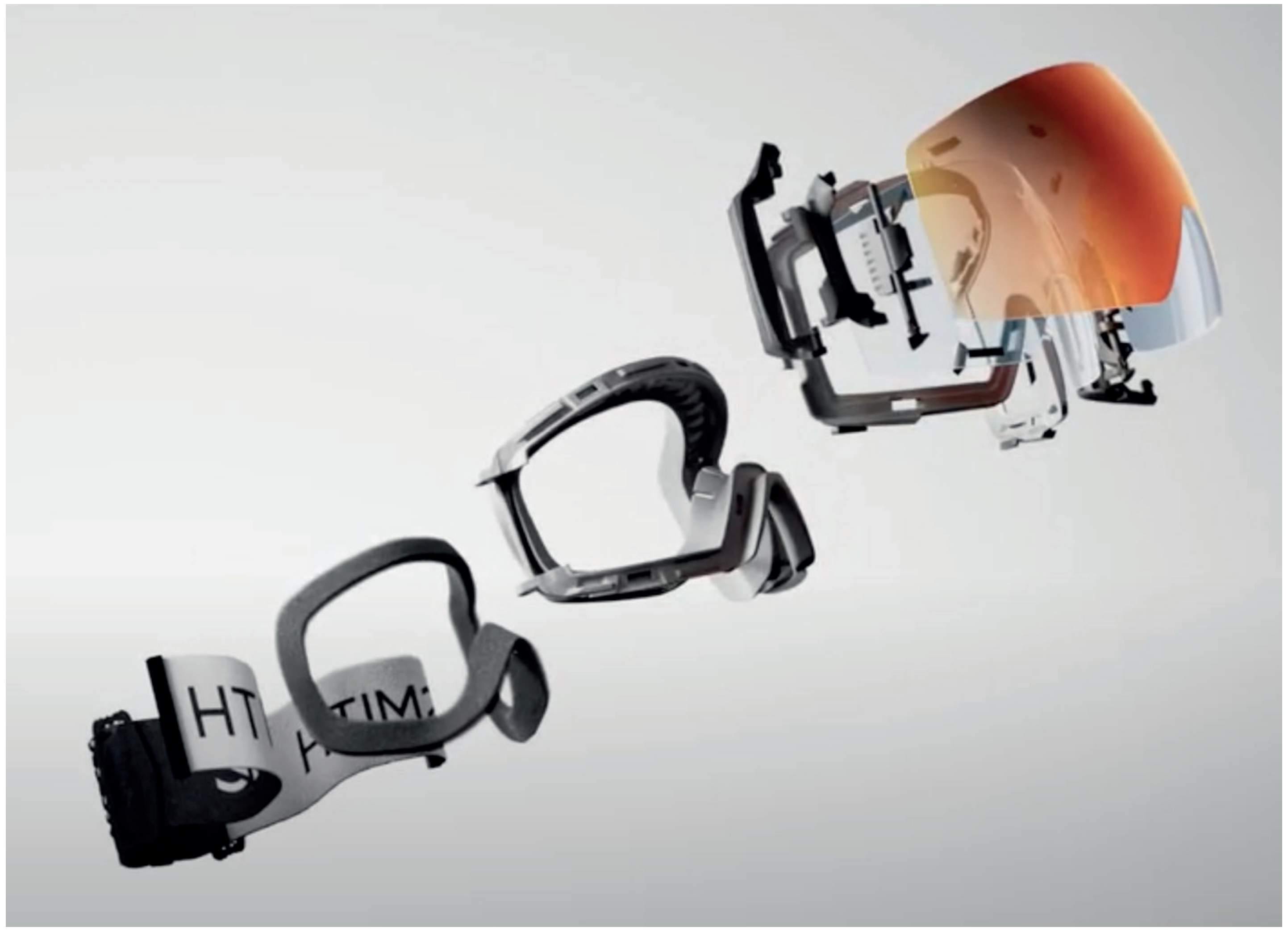


Figure 37: Custom-fitted goggles designed by Smith with software devlopment from ModeLab

3.7.3 CONFIGURATORS

As the concept of mass customization continues to grow, products are being broken down into customizable components to cater to the unique requirements of consumers. (Yang et al., 2008) Technology for product configuration has been developed to improve efficiency by minimizing lead time and product cycles. This automates the process of structuring a product. A product configuration system is a platform that can autonomously or collaboratively structure a product to fulfill the consumer's desires and technical specifications by utilizing these technologies. (Yang et al., 2008)
Typically, a configurator comprises a parametric model representing the product and parameters allowing for variations, along with a user interface (UI) whose refinement is crucial if used directly by the product's end-user.

"OUR ONLINE PRODUCT CONFIGURATOR HELPS SAVE ENGINEERING TIME, SPECIFICALLY BY REDUCING THE NUMBER OF DESIGN ITERATIONS GOING BACK AND FORTH BETWEEN THE CUSTOMER, SALES, AND ENGINEERING TEAMS."
RICH CRO, OPERATIONS MANAGER, CON-FORM GROUP FROM (AUTODESK, 2021)

An interesting case of a configurator that leverages AI to foster design exploration in the early phases of the design process is BLANK AI and was developed by PCH Innovations.
BLANK AI (Figure 39) goes beyond the functionality of other configurators because it is not based on a single parametric model but is trained on historical 3D designs and their associated meta-data to align the system with the context of the users' targeted design space. Following training, BLANK allows designers to create and modify distinctive and contextually appropriate 3D ideas within milliseconds. The generative algorithm of BLANK learns characteristics from the training data and uses them as semantic parametric controls to manipulate designs. Consequently, even inexperienced users can swiftly produce, modify, and explore various 3D design concepts in real time without editing intricate surface sketches or manipulating BReps. (PCH Innovations, 2022)

While KISKA developed for ADIDAS, a configurator (Figure 38) on the other side of the spectrum, allowing users to customize their shoes.

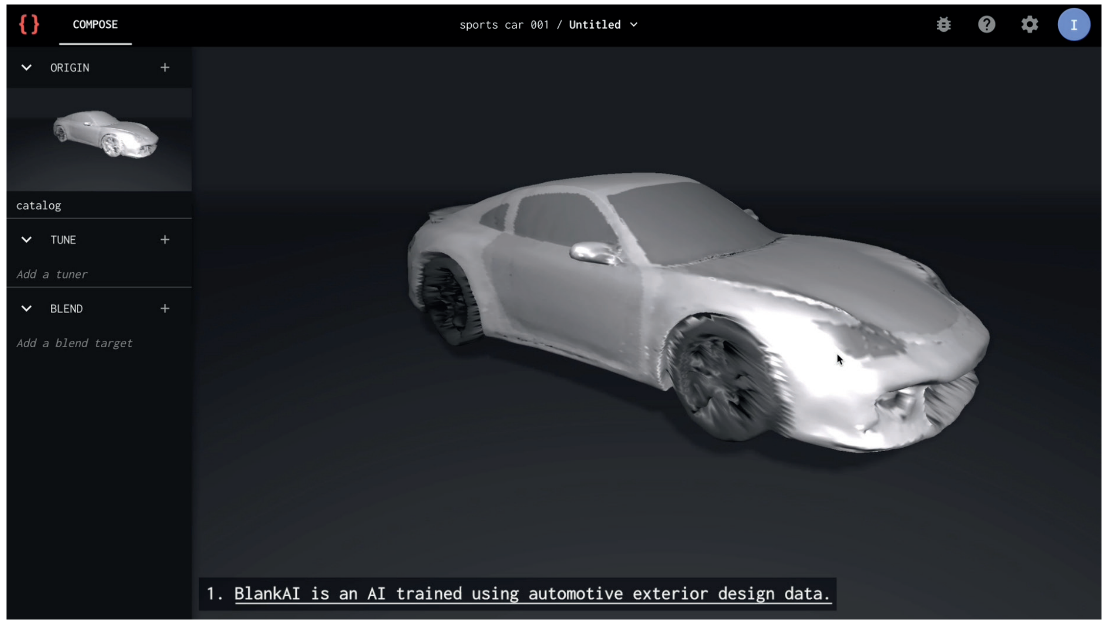
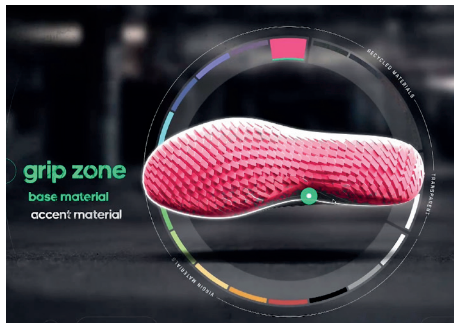


Figure 39: BLANK AI from PCH innovations (2022)

Figure 38: Shoe configurator KISKA (2019)



"IF YOU WANT A CONSUMER TO BE ABLE TO INTERFACE WITH IT. THAT WILL BE ANOTHER LEVEL ON TOP, WITH AN INDUSTRY-STANDARD USER INTERFACE.
SO, THE DELIVERABLE IS ANYWHERE IN THAT SPECTRUM (THE THREE LEVELS OF CONFIGURATORS).
[...] KNOWING AND EMPATHIZING WITH YOUR USER IS ESSENTIAL. I THINK IT ONLY GETS ELEVATED IN THIS CONTEXT.
YOU ARE TRYING TO BAKE THAT INTO A SYSTEM, BUT YOU NEED TO GIVE SOME CONTROL BACK TO THEM, OR ELSE THEY WOULD NOT EVEN USE YOUR PRODUCT." CD EXPERT INTERVIEW 2

Changes in product typology : from geometries to configurators
According to expert interviews conducted during the graduation project, Computational Design could shift the final deliverable of a design project from an artifact's geometry to a system generating controlled product variations based on client or user input. In this case, the deliverable could be a configurator.
According to experts' interview, there might be different levels of this deliverable.

"AS WE WORK WITH A COMPANY, EVENTUALLY THEY ARE GOING TO WANT ACCESS TO BE ABLE TO CREATE THEIR OWN GEOMETRY, AND THEN THAT WILL BE AN ENGINE, WHICH WOULD BE A GRASSHOPPER FILE IN SOME INSTANCES, HOUDINI FILE, OR IT MIGHT RUN IN LIKE UNREAL OR UNITY, IT MIGHT BE SOMETHING THAT'S PACKAGED LIKE A GAME. BASICALLY, WE ARE LEVERAGING ALL OF THE PIPELINES OF GAMING AND FILM TO DO INDUSTRIAL DESIGN AND ENGINEERING."
CD EXPERT INTERVIEW 2

Level 0:
The configurator is used internally to satisfy client requests for product variations. In this case, using a configurator benefits the design agency by avoiding re-work and keeping up client satisfaction and engagement with the ability to satisfy their request and reduce time-to-market quickly.

Level 1:
In this case, the configurator is delivered to the client, requiring some simplification. Clients might possess the technical knowledge to operate the configurator or could be trained to do so. In this case, the design agency benefits by offering a valuable service, while the client gains the ability to respond quickly to market changes and user needs.

"THEY (CLIENTS) MIGHT WANT TO BE ABLE TO DO THAT THEMSELVES AND THAT WILL REQUIRE THE CONFIGURATOR TO BE A DIFFERENT ORDER OF MAGNITUDE.
YOU MUST IMPROVE THE USER INTERFACE, AND THE SYSTEM MUST BE MUCH MORE RELIABLE." CD EXPERT INTERVIEW 2

Level 2:
In this last stage, the end-user uses the configurator, which might necessitate significant simplification and an advanced UI. This case is strictly related to mass customization, and the user input might include anthropometric data, aesthetic, or performance-related preferences. Benefits include comfort and specific appearance/performances for the user and sustainability through avoiding overproduction.

Solutions like ShapeDiver and Houdini may be utilized for configurators.

Configurator as a codesign tool
Configurators already allow end users to express their preferences and modify the aesthetic appearance or performance of the final design. However, they can also be used during the design process to facilitate quick design changes while interacting with the client or user. Ideally, the idea of making the user/client directly interact with the configurator would be particularly promising to reduce the number of feedback loops needed to meet KPIs in a project. This method could allow non-designers to have direct control over part of the design, expressing ideas that might be challenging to convey without design representation skills. This idea came spontaneously from a participant during the focus group at VanBerlo during this graduation project:

"CONFIGURATORS MIGHT BE USEFUL IN AN AGILE PROCESS, TO GIVE THE CLIENT THE TOOL TO DESIGN AND HAVE MORE CONTROL - EVEN NON-DESIGNERS WOULD BE ABLE TO IDEATE FOCUS GROUP PARTICIPANT 4

During the graduation project it was decided to experiment with building a configurator to demonstrate the power of configurators in a user research context. A product with strong semantic components determined in the early phases of the design process was chosen: a trigger bottle. (Figure 41)

During the user research phase, consumers are often asked to depict the product profile's shape as representing specific semantic characteristics or aesthetic preferences. However, this process may be impeded by some users' need for sketching or design representation skills.

This configurator case study aims to empower individuals, be they users or clients, by allowing them to manipulate given geometry without needing advanced design representation skills.

Configurator development
Initially, key features or parameters influencing the product's perception were identified. Five defining curves determine the bottle's shape and profile, each associated with specific parameters: base, waist, shoulder, neck, and head position. (Figure 44) These curves form the bottle shape via the loft command and delineate the bottle's silhouette.
A parametric model of the bottle was built using Grasshopper.

In this model, the curves are ellipses, with the topmost curve being a fixed circle. Alterations can be made to the major and minor radii on all curves. Adjustments can also be made to the height and rotation of the shoulder and neck curves.
By varying these parameters, a great range of bottle shapes can be created some examples are showed in Figure 40.

For diversifying the shapes beyond the basic ellipse, it would be relatively straightforward to adjust the definition inputs. One possible strategy could involve attaching any polygon or shape to a bounding rectangle, using the existing radii inputs to establish its principal dimensions.
Another notable feature of the configurator is the ability to apply a pattern to the bottle's surface (Figure 43).
A slider can be used to manipulate the pattern's distribution, controlling its expansion from a specific point. It would be an intriguing addition to have control over the point's position using a graph mapper within the configurator.

Building the configurator user interface
The final step involved creating an intuitive user interface for seamless interaction between the 3D geometry and the user. Grasshopper plug-ins like HumanUI or ShapeDiver facilitate this process, allowing the configurator to be uploaded to the cloud. HumanUI was chosen over ShapeDiver due to its free availability.
The construction of the User Interface (UI) was subsequently undertaken. Within the user interface (Figure 42), boxes represent the curves used to generate the bottle's surface. Inside each box, there are number sliders that can be used to manipulate the parameters of the curves. The interface includes a window that shows a 3D view of the product and a text box that displays the volume. This makes it easy to track how the manipulative actions within the configurator affect the volume.
With the configurator, non-designers can manipulate a 3D model in real-time, explore product variations, and save outputs for comparison and evaluation. Subsequently, design researchers might be able to analyze the models created by users to inform their research.
This method might help non-designers express their ideas and opinions and facilitate rapid exploration of shape variations, ultimately resulting in a 3D model that can enhance design research and the development of detailed designs.

Figure 41: Trigger bottle model provided by VanBerlo.

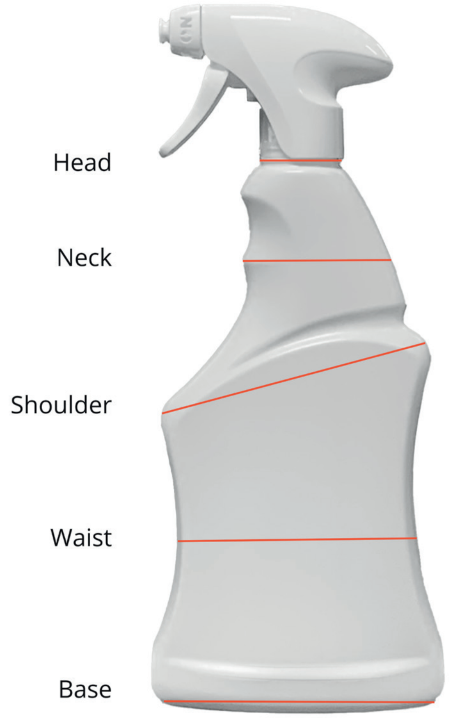


Figure 44: The key curves generating the bottle's shape in the configurator

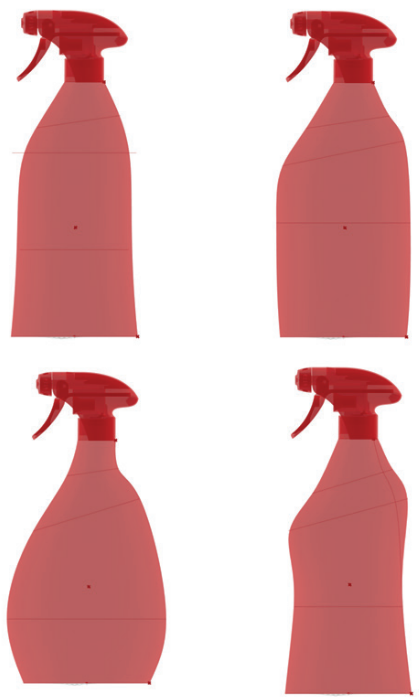


Figure 40: Some of the possible variations on the bottle shape generated with Grasshopper.

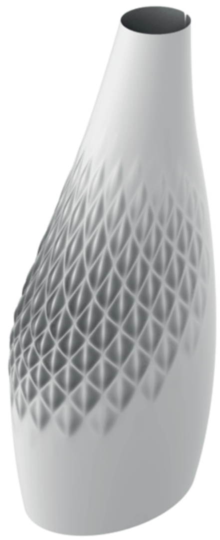


Figure 43: Pattern applied to the bottle's body, created following instructions from Tedeschi, A. (2014)

Figure 42: The configurator

3.7.4 GEOMETRY OPTIMIZATION

Optimization and multi-objective optimization are common practices and applications of computational design (CD). They are often related to genetic algorithms (GAs) - as discussed in section 2.4.1- but are not limited to them. The optimization goals depend on the project's requirements.

Technical performances
Typically, the main optimization goals in industrial design are physical properties, such as mechanical attributes. These properties can be digitally simulated and measured, providing specific and quantifiable optimization goals.
For instance, a common objective is to optimize mechanical properties by improving the stiffness-to-weight ratio or the specific Young's modulus, a process known as structural or topology optimization, discussed in section 2.2.1 In some cases, this approach is mistakenly referred to as generative design.

However, optimizing for virtually any physical properties, such as sound thermodynamic properties, aerodynamics, and more, is possible.

An example of optimization not based on mechanics is the optimization of heat exchangers. Heat sinks are vastly used in industrial design.
There are typically three primary design goals that engineers consider when designing a heat exchanger. The required heat transfer and the surface area wall thickness are the two main design parameters that determine the often-contradictory goals. The goals are to maximize heat transfer, minimize pressure drop, and minimize size. (nTop, 2022)
A case of thermal optimization was developed by Puntozero using Ntopology. Puntozero reimagined the cold plate of Dynamis PRC's electric race car, in Figure 46, for additive manufacturing, resulting in a 25% lighter, liquid-cooled heat sink with bioinspired flow guides, boosting the heat transfer surface area by 300%. They used nTop to create guides based on a warped gyroid lattice, improved fluid flow, and increased contact area with the aluminum heat sink. The external lattice was also optimized to reduce weight, material use, production costs and enhance heat dissipation. (nTop, 2022)

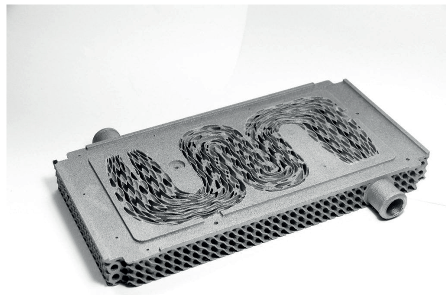


Figure 46: Liquid-cooled cold plate for automotive power electronics, designed by Puntozero using nTop.

Figure 47: Start of the bounding box optimization using Galapagos.

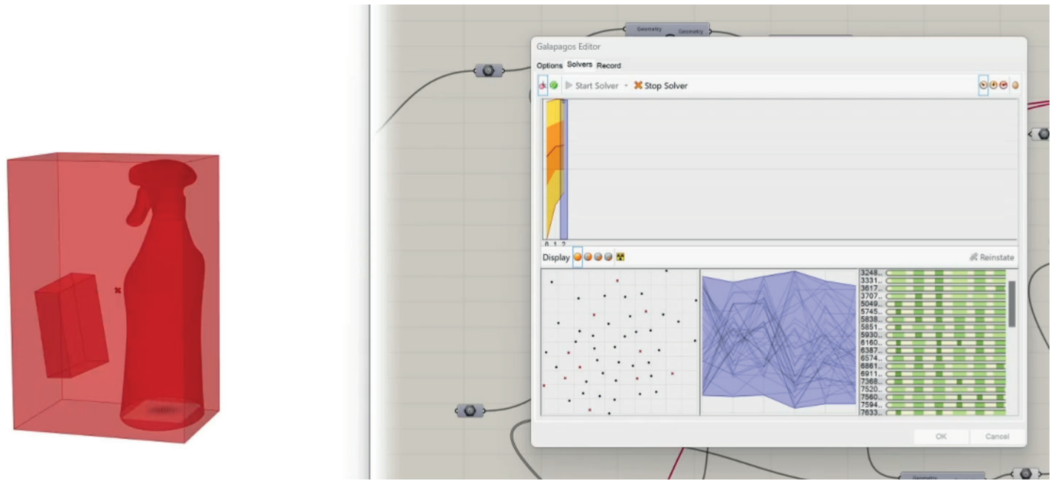
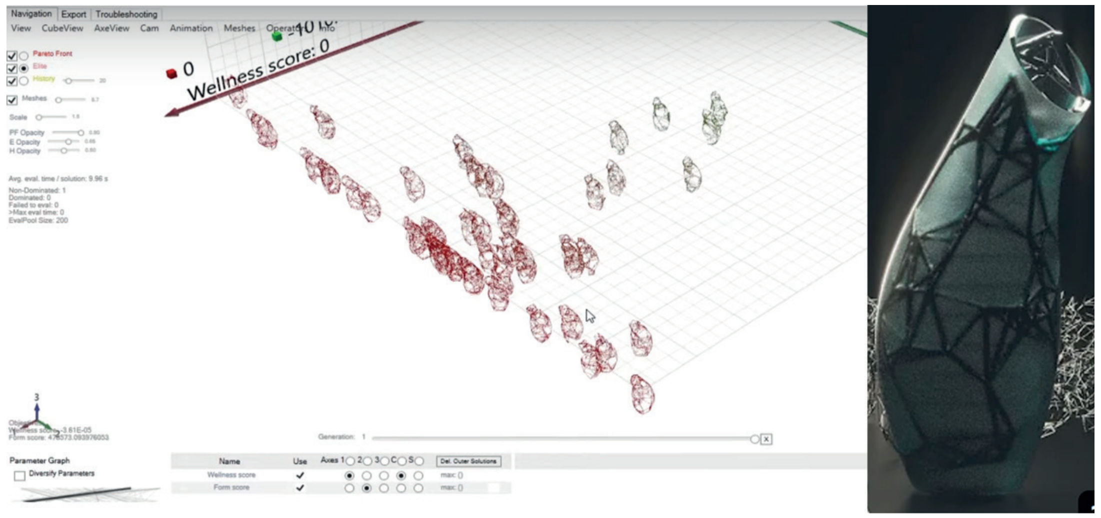


Figure 45: Shell optimization from Gediminas Kirdeikis



In architecture, buildings are often optimized or evolved by evolutionary solvers against environmental factors, such as daylight or wind analysis, energy consumption, soil sealing, and cost (Rohrmann, 2019).

It would be interesting to find similar recurrent optimization objectives -in addition to mechanical strength- in the industrial design practice and start to use multi-objective optimization and evolve product design(s). Some of these could be in the sustainability domain, for instance, using LCAs parameters or ease of disassembly as optimization goals. Considering the significance of this topic, it is discussed separately in section 3.7.5.

Development of a case study using optimization for objective requirements
The possibilities of using CD to optimize objective requirements are countless. In the context of this thesis, small experiments have been developed in the case study of the bottle introduced in section 3.7.3.

A simple example of using evolutionary solvers in the same use case of the configurator - the trigger bottle- is related to the product's shipping. Usually, the product is shipped with a couple of rechargers. To minimize emissions during transport, it is fundamental to ship as many products as possible on a given volume. For this reason, an evolutionary solver in Grasshopper -Galapagos- was used to find the optimal orientation of the trigger bottle and two refills to obtain a bounding box with minimal volume. Figure 47
A potential hypothesis for enhancing sustainability in bottle design could be strategically optimizing fold placement on the bottle's surface. This could amplify the bottle's resistance to compression, reducing the plastic required in its production. Given the high volume of bottle production, this approach could significantly improve overall sustainability.
To execute this strategy using Grasshopper, it is possible to use Finite Element Analysis (FEA) plug-ins such as Millipede, Kiwi, or Karamba. Optimization plug-ins like Octopus, Galapagos, or Wallacei can also be utilized for the best results.
FEA software provides the capability to calculate stress on the bottle's surface, defined as a shell in the software. In contrast, evolutionary solvers can be employed to identify the optimal positions for folds or various patterns.
Below is a brief description of a tutorial that can aid in achieving this objective:
This tutorial by Gediminas Kirdeikis leverages an evolutionary solver to create supporting beams for a shell structure (Figure 45). The case of the beams might pose challenges, in the bottle case, because the beams need to conform to the shell's surface. To adapt this approach to a bottle design, the script would need to be modified to generate curves on the surface rather than straight lines. These curves can then be converted into folds to reinforce the bottle.

Computational Optimization to explore subjective requirements
Using optimization to explore subjective requirements presents an exciting yet challenging dimension in computational design. These factors might be related to the aesthetic or experiential characteristics of the product.
Gün (2006) created something in this direction proposing a computational model for evaluating rendered images' tonal and compositional qualities.

One interesting application could be defining the key characteristics of a brand's identity and design DNA and then using a system to explore and generate multiple concepts within these aesthetic boundaries, resulting in a cohesive brand identity. Being the objective of the variations, subjective and perceptional, it might be difficult, but not impossible, to define it computationally. In any case, one could look at the designer's eye as the solver of an aesthetic optimization problem.

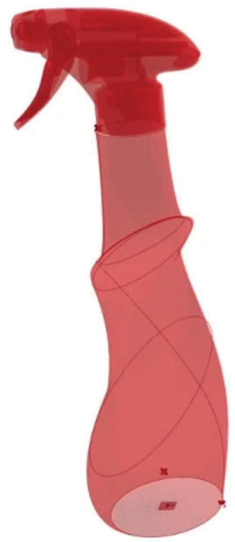
"ONCE YOU MASTER THE ART OF CONVERTING YOUR CONCEPTS INTO COMPUTATIONAL LANGUAGE, THE POTENTIAL FOR OPTIMIZATION IS VIRTUALLY LIMITLESS."
CD EXPERT INTERVIEW 3: ONUR YÜCE GÜN, CD DIRECTOR AT NEW BALANCE

Throughout this thesis, two small-scale experiments were conducted to investigate the potential of using evolutionary solvers for exploring design spaces according to subjective requirements.
The initial attempt involved defining a subjective requirement and transforming it into a quantifiable parameter. In this instance, the subjective requirement was defined as the 'dynamism' of the bottle case introduced in section 3.7.3 and was associated with a specific dimension of the bottle, as depicted in Figure 49.

An evolutionary solver -Octopus- was then employed to set up a two-objective optimization problem exploring the trade-offs between the bottle's volume and the parameter defined as 'dynamism.' The primary objective was to decrease the dimension in figure 49 which defined the dynamism of the bottle. The secondary objective, inversely related to the first, was to maximize the bottle's volume. The evolutionary solver explored the solution space between these two opposing objectives by adjusting the other parameters (detailed in section 3.7.3) that define the bottle's shape across successive generations.

Another experiment was conducted to explore subjective optimization using Biomorpher. This tool is notable for its capacity to generate numerous solutions akin to traditional evolutionary solvers. However, it also enables interactive involvement of the designer in the evolutionary process. As a result, it combines algorithmic efficiency with the designer's intuitive input, taking into account considerations that might not be easily defined in an optimization algorithm, such as subjective qualities.

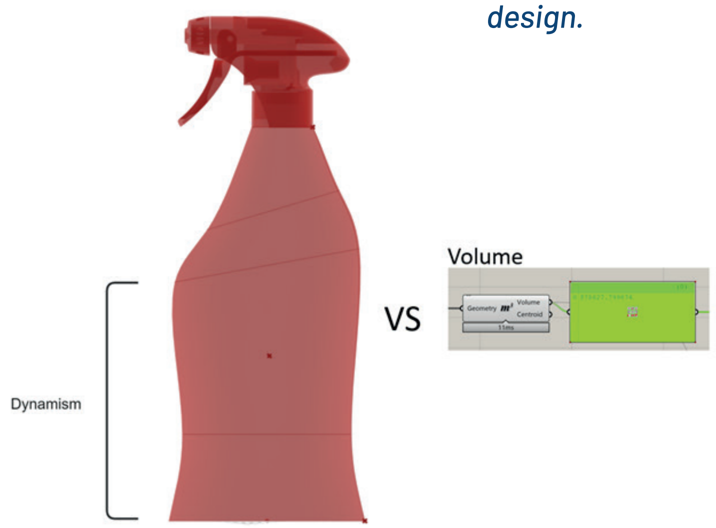
Figure 48: Tradeoff between Volume and Dynamism explored with Grasshopper and Octopus

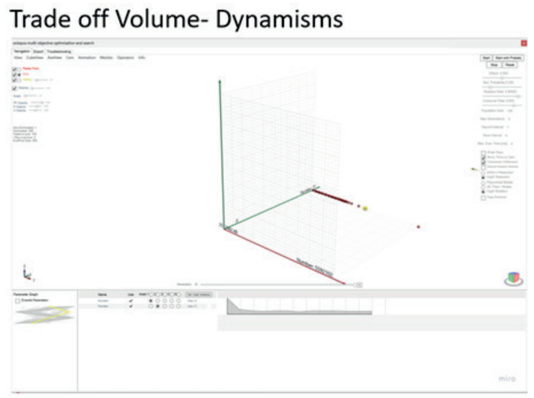


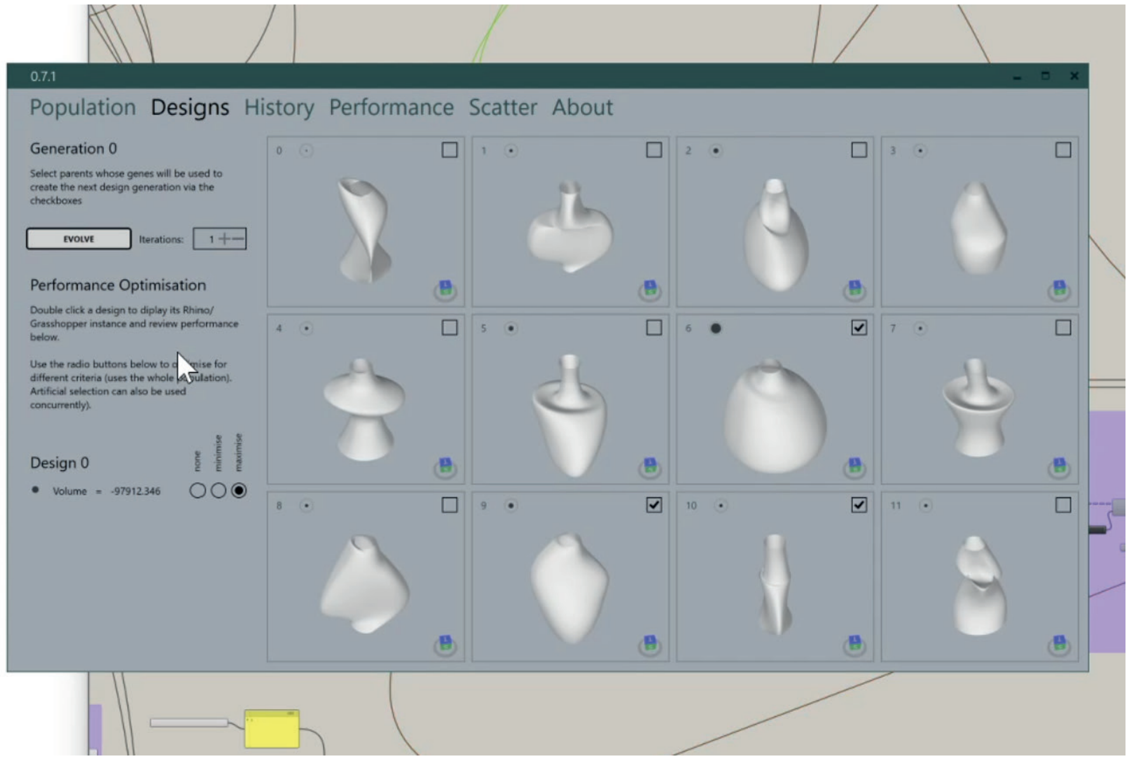
Biomorpher was used to explore evolutionary solvers from a perceptual perspective. The focus was on bottle design, allowing for the modification of all parameters to produce varied shapes and increase volume. With each subsequent generation, the designer can influence the form's evolution by selecting individuals that exhibit desirable (Figure 48) characteristics—attributes that might be challenging to define computationally, like aesthetics or user experience. These designer-selected individuals then influence the next generation.

In conclusion, these experiments have highlighted the potential of using optimization solvers to explore and innovate within the design space, particularly by integrating the designer's subjective input. This approach opens up new avenues for achieving a balance between functional efficiency and subjective qualities in product design.

Figure 49: Biomorpher interface during the selection of individuals that will have an increased fitness in the next generation.







3.7.5 COMPUTATIONAL DESIGN AND SUSTAINABILITY

This section explores the potential of Computational Design (CD) in fostering sustainable design opportunities. The research identifies three key opportunities for sustainability: Mass customization to mitigate overproduction, function integration strategies to reduce different materials usage, and optimization for enhancing the sustainability score of industrial products. These opportunities will be discussed in detail in the following sections.
Mass customization is a promising avenue for addressing overproduction. Section 3.7.2 delves this concept, highlighting how it can be employed to tailor products to individual needs, thereby minimizing waste and unnecessary production.

The concept of mass customization is vital because it focuses on meeting specific demands, enhancing both environmental sustainability and economic viability.

Function integration strategies offer another avenue for sustainable design. Section 3.7.6 provides an analysis of the strategy, emphasizing the ability to achieve multiple functions typically fulfilled by various materials by modifying a single material structure via architected materials. This approach can ultimately lead to the development of mono-material products, thereby increasing recyclability.

Furthermore, computational optimization techniques profoundly impact enhancing the sustainability score of industrial products. This section will thoroughly examine the significance of optimization and its implications for sustainable design.

Optimization
Throughout the research, it became evident that Computational Design holds great potential for sustainability. However, in the cases found during the research often, the link between computational optimization and sustainability was often indirect. For instance, optimizing the mechanical capabilities of a part can subsequently reduce material usage and transportation weight, as discussed in Section 2.4.1 on Topology optimization.

Implementing effective strategies for optimizing Circular Economy (CE) design can augment the outcomes of traditional design methods, decreasing waste and environmental footprints throughout the product's lifecycle. (Ortner et al., 2022)

The complexity involved in CE product design prompts the employment of multi-objective optimization (MOO), which can offer valuable assistance to designers in this field. MOO can help in multiple quantitative evaluations for various design alternatives and incorporate numerous potentially conflicting or redundant goals that can arise in CE design. (Ortner et al., 2022)

Computational Optimizaton for CE design Implementation: A case study from the literature
During the research conducted for this thesis, two primary studies employing computational techniques to optimize industrial products were identified.
Ren and Su (2020) employed a genetic algorithm (GA) in MATLAB to optimize a gearbox according to Life Cycle Assessment criteria. On the other hand, Ortner et al. (2022) utilized Grasshopper along with an open-source Python library to optimize a furniture item for Circular Economy (CE) criteria, specifically adhering to the 9R framework as defined by Potting et al. (2017).
The methodology proposed by Ortner et al. (2022) for computational optimization of product design with a focus on the circular economy comprises three overarching phases, which will be elaborated upon later. The forthcoming section aims to distill the technique employed in the study. This is intended to provide readers with a quick, comprehensive understanding of using Computational Design (CD) to optimize a product on sustainability parameters. Figure 50 represents a diagram created by the author of this thesis, representing the process employed by Ortner et al. (2022)

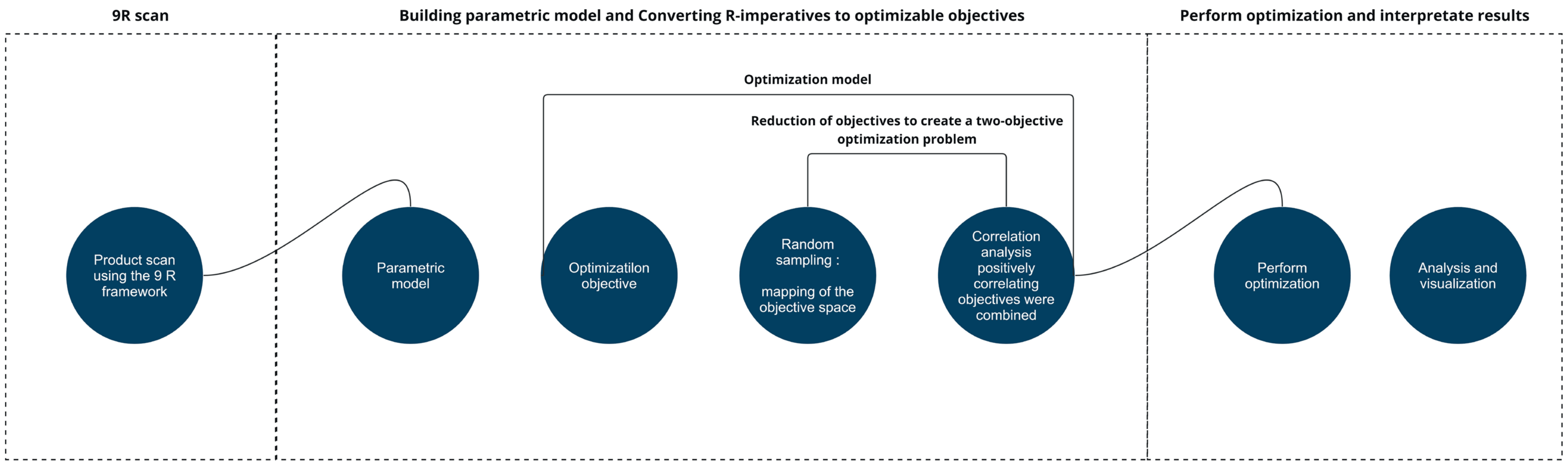


Figure 50: Diagram created by the thesis author representing the optimization process discussed by Ortner et al. (2022)

Step 1: Product scan using the 9R framework
The optimization from Ortner et al. (2022) is applied to a furniture product represented in Figure 51.

Initially, the product is examined by Ortner et al. (2022) using the 9R framework developed by Potting et al. (2017). The 9R framework encompasses Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. During this phase, pertinent design strategies for each 'R' principle are determined, as demonstrated in the second column of Figure 52.

Subsequently, the task is to pinpoint the circular design strategy that lends itself to computational optimization, as represented from the third column onwards in Figure 52. Ortner et al. (2022) establish a suitable computational optimization strategy based on two criteria:
1. The presence of a use-case that calls for optimizing a relevant objective.
2. A pre-established method for computationally evaluating this objective.
As a result of this process, the optimization objectives are specified in the fifth column of Figure 52. Strategies coloured in green are further developed as optimizable objectives in the case study by Ortner et al. (2022). In contrast, those highlighted in yellow are earmarked for future investigation.
The table presented by Ortner et al. (2022) in Figure 52 establishes a potential framework for understanding when and where a product can be computationally optimized for circular economy parameters.

The product scan from Ortner et al. (2022) will be summarized here as it provides a helpful example for the readers of conducting an analysis that can be applied to other designs.

R1 and R0: The initial two steps of the 9R framework, Refuse and Rethink, were found to have limited potential for computational optimization.
R2: The Reduce strategy, encompassing aspects like weight reduction of the product and minimization of manufacturing waste, was incorporated during the initial design process and further enhanced in the study. Three 'Reduce' strategies, under the R2 category, were computationally optimized in the methodology from Ortner et al. (2022):
1) Reduction in material usage proportional to functional volume (F1),
2) Diminishing material consumption as calculated by embodied carbon (EC) (F2).
3) Lowering production waste (F3).
Topology optimization may also benefit this goal, with possibilities outlined in Section 2.4.1.
R3-R7: R3 through R7 are grouped due to their shared aim: prolonging a product's lifespan (Potting et al., 2017). The fundamental strategy adopted was "robustness," referring to the reliability and durability criteria used in designing the furniture to endure multiple cycles of use. Other strategies showing potential for computational optimization were noted but not employed by Ortner et al. (2022). Areas where computational optimization could be beneficial, include modular product structure, disassembly and reassembly, and upgradability and adaptability.
R8-R9 Recycle, Recover: The final steps in the 9R framework, Recycle and Recover (R8-R9), center around the product's end of life and the reutilization of materials. Ortner et al. (2022) point out that automated material search can aid in selecting recyclable and low-toxicity materials.

Figure 51: Case study from Ortner et al. (2022) to perform computational optimization for circular economy design

Figure 52: Product scan to identify optimization opportunities utilizing the 9R framework from Ortner et al. (2022)

R-imperatives	Circular design strategies in case study	use-case for optimization	method of optimization	Optimization objectives applied to case study		Relevant methods in literature
R0 REFUSE R1 RETHINK	identify stakeholders/ functions for future use	☐	☐	☐		N.A
R2 REDUCE	reduction in weight	☑	☑	☑	Material Use [F2]	(Koo et al. 2017) (Luedeke et al. 2014) (Oliveira et al. 2016) (Zhou et al. 2009)
	reduction in volume	☑	☑	☑	Functional Volume Ratio [F1]	
	lower energy materials	☑	☑	☑	Material Use [F2]	
	renewable materials	☑	☑	☑	Material Use [F2]	
	lower carbon materials	☑	☑	☑	Material Use [F2]	
	cleaner materials	☑	☑	☐		
	minimal production waste	☑	☑	☑	Fabrication Waste [F3]	
R3 REUSE R4 REPAIR R5 REFURBISH R6 REMANUFACTURE R7 REPURPOSE	reliability & durability	☑	☑	☑	Robustness [F4]	(Fu et al. 2015) (Gehin, Zwolinski, and Brissaud 2008) (Peng Song 2017) (Preisinger and Heimrath 2014) (Senatore and Piker 2015)
	standardization & compatibility	☑	☐	☐		
	modular product structure	☑	☑	☐		
	dis- and reassembly	☑	☑	☐		
	classic design	☑	☐	☐		
	strong product-user relation	☑	☐	☐		
	upgradability & adaptability	☑	☑	☐		
R8 RECYCLE R9 RECOVER	recyclable materials	☑	☑	☑	EoL Cost [F5]	(Igarashi et al. 2016) (Saidani et al. 2019)
	low toxicity materials	☑	☑	☐		
	minimal downcycling	☑	☐	☐		

Step 2: Parametric and optimization model
The next phase involves transforming the circular design strategies into objectives for the optimization problem (fitness functions). These objectives form the foundation of an optimization model that applies a Genetic Algorithm and stores iterations, while a Parametric model is employed to generate geometries and assess functions. (Ortner et al., 2022)

Building the Parametric Model
A critical initial step in applying computational optimization to an industrial product involves creating a parametric model (Figure 55) that representing the product (Ortner et al., 2022). The principles of parametric design are elaborated in sections 2.2.1 and 2.3.2. Usually, the parametric model is constructed in Grasshopper for Rhino, a platform that provides numerous plug-ins for Multi-Objective Optimization (MOO) (TUDelft, 2022b).
The parametric model should be created with consideration for the input factors that need to be utilized in the optimization model. The variations on the product produced through the parametric model are then used as feedback within the optimization model for the Genetic Algorithm (GA) to yield optimized results. (Ortner et al., 2022)
In the case study presented by Ortner et al. (2022)., the model is engineered to generate two configurations: an assembled state and an unfolded version. The unfolded configuration enables testing for fabrication and storage optimization.

Defining the optimization objectives
The optimization goals identified during the product scan with the 9R framework are then converted into algorithms for assessing the parametric model's performance relative to the circularity objectives.
In the case study presented by Ortner et al. (2022), five objectives are established for the parametric model: functional volume ratio, material usage, fabrication waste, robustness, and end-of-life (EoL) cost. Each of these objectives is described via a fitness function in the provided pseudocode, all constructed as minimization problems. A sample fitness function outlined using pseudocode is demonstrated in Figure 54.
These fitness functions are evaluated in the case study from Ortner et al. (2022) as follows:
F1 Functional Volume Ratio (%): This is defined as the percentage of the total material volume utilized in a single instance of the design variant relative to the overall space volume, or "bounding box," occupied by this instance.
F2 Material Use (kgCO2e): This evaluation automates a restricted version of an environmental impact assessment by calculating the Global Warming Potential (GWP) for the materials used in the given design variant, expressed in kilograms of CO2 equivalent (kgCO2e).
F3 Fabrication Waste (kgCO2e): This definition takes shape in 3 steps: Step 1 clusters the geometries based on the material used. Step 2 duplicates each group of material geometries, applies a bin-packing algorithm, and yields the fewest bins required for each geometry. Step 3 computes the fitness value for F3 by summing up the GWP cost of the material wasted during fabrication.

Fitness Function 3, F3: Fabrication Waste (kgCO2e)

Inputs: **Folded Geometries:** $G=\{G_1, G_2, \ldots, G_K\}$
Material List: $M=\{M_1, M_2, \ldots M_J\}$
Carbon Factors: $C=\{C_1, C_2, \ldots C_J\}$
Bin Sizes: $B=\{B_1, B_2, \ldots B_J\}$
Quantity to fabricate: Q

1: Sets of geometries grouped by material,
$A = \{A_1, A_2, \ldots A_J\}$ s.t. $A_j = \{g \mid g \in G \wedge g.\text{material} = M_j\}$
2: Set of bins required per material, $L = \{\textbf{Call}\ \text{BinPack}\ (Q \times A_j, B_j) \mid j \in \{1, 2, \ldots J\}\}$
3: **Return** $F3 = \sum_{j=1}^{J} C_j \times (L_j \times \textbf{Call}\ \text{Volume}\ (B_j) - \textbf{Call}\ \text{Volume}\ (A_j))$

Figure 54: Pseudocode to define the optimization's fitness functions from Ortner et al. (2022)

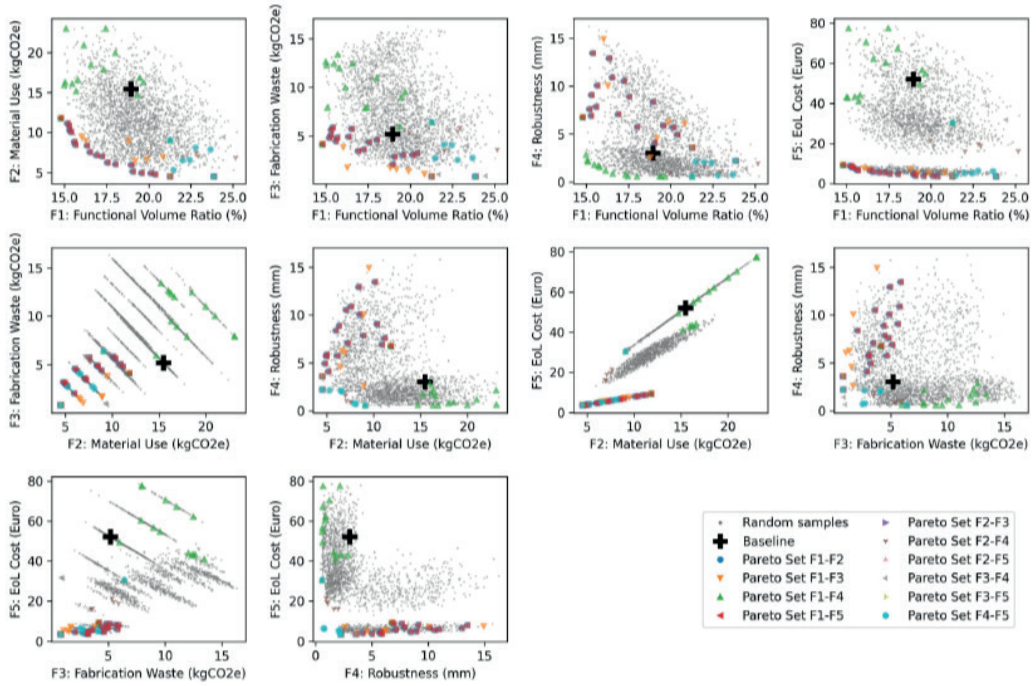


Figure 53: Random sampling plots from Ortner et al (2022)

F4 Robustness (mm): The fitness function generates a Finite Element Analysis (FEA) model by initially defining anchor points and load vectors on the design variant using Karamba software.
F5 End-of-Life Cost (€): The aim here is to minimize the product's value loss at the end of life (EoL cost) by accounting for the returned value from recycling, less the original value.

While these fitness functions are applied specifically to the case study developed by Ortner et al. (2022), the same process could potentially be applied to a broad range of products.

The subsequent stage in the objective reduction process involves conducting correlation analysis and consequent simplification of the objectives. Here, positively correlated objectives are merged, and the remaining ones are tactically transformed into constraints until a two-objective problem is formulated.
In the case study developed by Ortner et al. (2022), objectives relating to material use (F2), fabrication waste (F3), and End-of-Life cost (F5) are combined due to their positive correlation in the random sampling, creating a single objective: reduce + recycle index (F2 + F3 + F5).
The functional volume ratio (F1) and robustness (F4) conflict with all other objectives. Therefore, Robustness (F4) is transformed from an optimizable objective into a constraint. Below a certain displacement level, all solutions can be considered structurally functional. Consequently, the problem is condensed to a two-objective optimization problem, with the reduce + recycle index (F2 + F3 + F5) and functional volume ratio (F1) as the defined objectives.
Following the definition of the fitness functions detailed in the previous section, the next stage involves simplifying the multi-objective Circular Economy (CE) design problem into a two-objective optimization problem, extracting meaningful Pareto sets of design alternatives. (Ortner et al., 2022)
The initial step towards achieving this objective reduction is Random Sampling. This method involves evaluating random samples of the parametric model based on the earlier defined fitness functions. This technique enables an initial mapping of the design space, as illustrated in Figure 53. This process aids in identifying conflicting or redundant objectives.

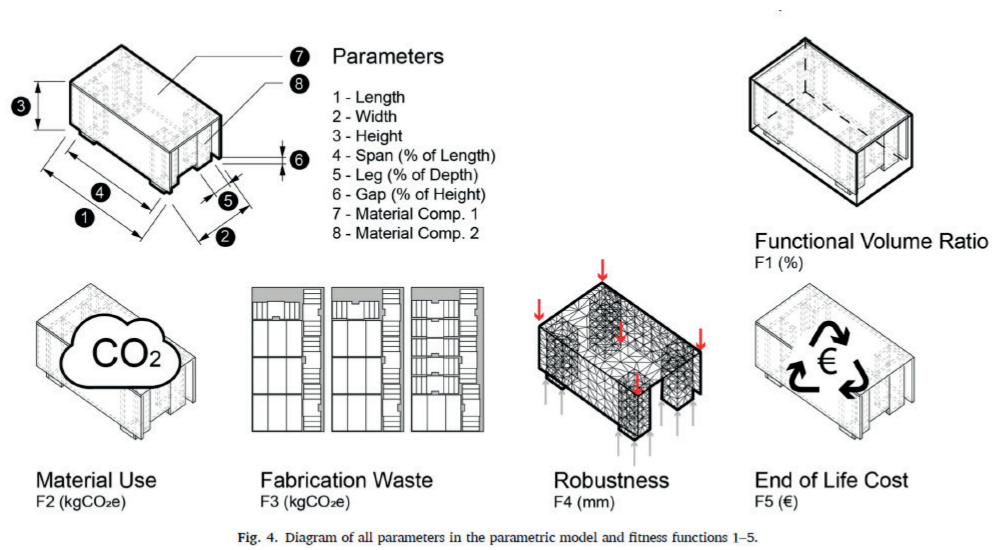


Figure 55: Parametric model and fitness functions from Ortner et al. (2022).

Step 3: Optimization and visualization

Optimization procedure

The following stage involves executing the optimization process. Various plug-ins for Multi-Objective Optimization (MOO), such as Octopus and Wallacei, are available in Grasshopper. In the case study presented by Ortner et al. (2022)., the Nondominated Sorting Genetic Algorithm II (NSGA2), a type of genetic algorithm (GA), was implemented using the open-source Python library, PYMOO (PYMOO, n.d.). GAs are described in section 2.4.1 of this thesis.

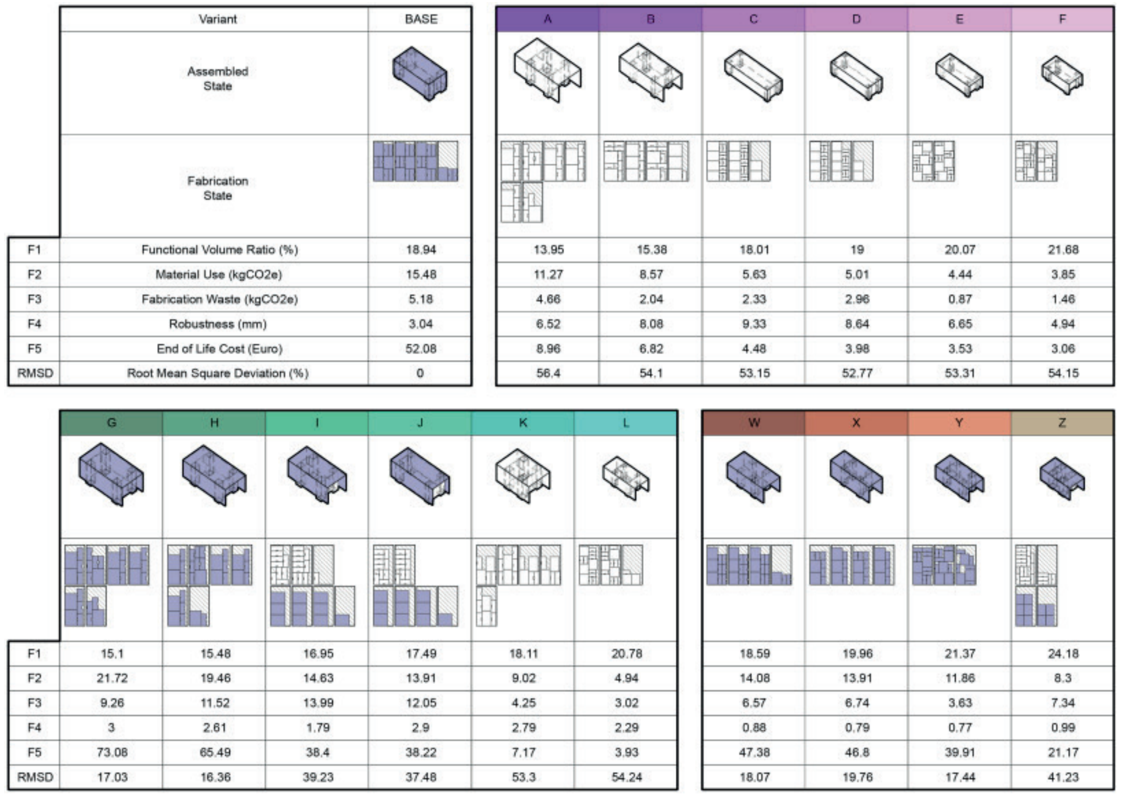
The procedure embodies the evolution of design variants across generations, incorporating opportunities for mutation and generation of offspring. Furthermore, it also includes ranking and discarding poorly performing or excessively similar individuals. The genetic algorithm facilitates a systematic design space exploration, leading towards improved solutions in each successive generation. (Ortner et al., 2022)

Analysis and visualization

During this phase, the first step involves visualizing the solution space using a scatter plot of Pareto-optimal design variants based on the two objectives defined earlier.

In the study by (Ortner et al., 2022), the dual objective optimization had the functional volume ratio (F1) and reduced + recycle index (F2 + F3 + F5) as objectives, with robustness (F4) transformed into a constraint. The scatter plot representing the resulting solution space is depicted in Figure 57.

Out of the 3300 design variants, Ortner et al. (2022) selected three subsets based on displacement values, representing robustness. These subsets are color-coded in Figure 57 as purple, green, and brown, with different materials symbolized by circles, squares, and diamonds. The selected variants are showcased in Figure 56, both in their assembled and disassembled states, alongside their performance across the five fitness functions. Further scrutiny of this table facilitates the selection of the optimal designs. For additional details, please refer to Ortner et al. (2022).



	Variant	BASE	A	B	C	D	E	F
	Assembled State							
	Fabrication State							
F1	Functional Volume Ratio (%)	18.94	13.95	15.38	18.01	19	20.07	21.68
F2	Material Use (kgCO2e)	15.48	11.27	8.57	5.63	5.01	4.44	3.85
F3	Fabrication Waste (kgCO2e)	5.18	4.66	2.04	2.33	2.96	0.87	1.46
F4	Robustness (mm)	3.04	6.52	8.08	9.33	8.64	6.65	4.94
F5	End of Life Cost (Euro)	52.08	8.96	6.82	4.48	3.98	3.53	3.06
RMSD	Root Mean Square Deviation (%)	0	56.4	54.1	53.15	52.77	53.31	54.15

	G	H	I	J	K	L	W	X	Y	Z
F1	15.1	15.48	16.95	17.49	18.11	20.78	18.59	19.96	21.37	24.18
F2	21.72	19.46	14.63	13.91	9.02	4.94	14.08	13.91	11.86	8.3
F3	9.26	11.52	13.99	12.05	4.25	3.02	6.57	6.74	3.63	7.34
F4	3	2.61	1.79	2.9	2.79	2.29	0.88	0.79	0.77	0.99
F5	73.08	65.49	38.4	38.22	7.17	3.93	47.38	46.8	39.91	21.17
RMSD	17.03	16.36	39.23	37.48	53.3	54.24	18.07	19.76	17.44	41.23

Figure 56: Selected variants from Ortner et al. (2022)

Conclusion

The process described by Ortner et al. (2022) was described in great detail because of its potential to have a positive impact on sustainability.

The case study conducted by Ortner et al. (2022) demonstrates the feasibility of integrating computational design into industrial design to enhance circularity performance. Despite the application of circularity strategies in the initial design, computational optimization showcased a substantial potential with a maximum single-objective improvement surpassing the baseline by 74%. Multi-objective optimization can be leveraged to navigate the trade-offs between conflicting circularity objectives, simultaneously exploring a broad solution space. However, It's crucial to note that such optimization requires a well-defined concept as a starting point for its application.

As highlighted by Ortner et al. (2022), computational optimization for Circular Economy (CE) product design is an emerging field requiring further research. The study presented is among the initial explorations in this domain. Future work should strive for broader applicability across various product domains. In order to encourage this exploration, this chapter attempts to distil and visualize in Figure 58 the process adopted by Ortner et al. (2022), with the aim of inspiring industrial designers to experiment with computational optimization techniques for designing more sustainable products.

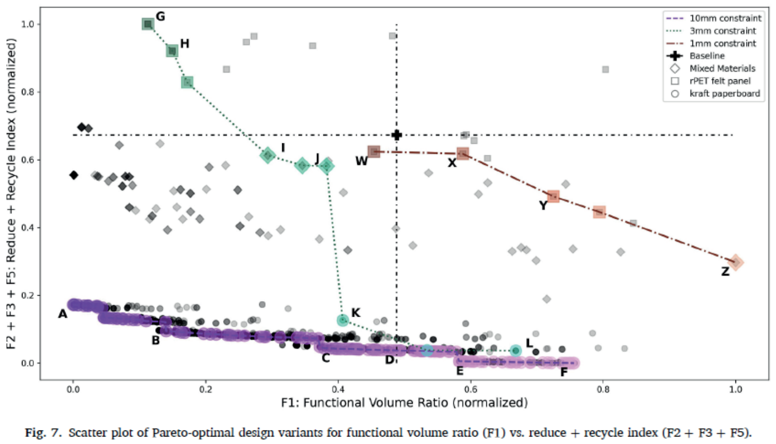
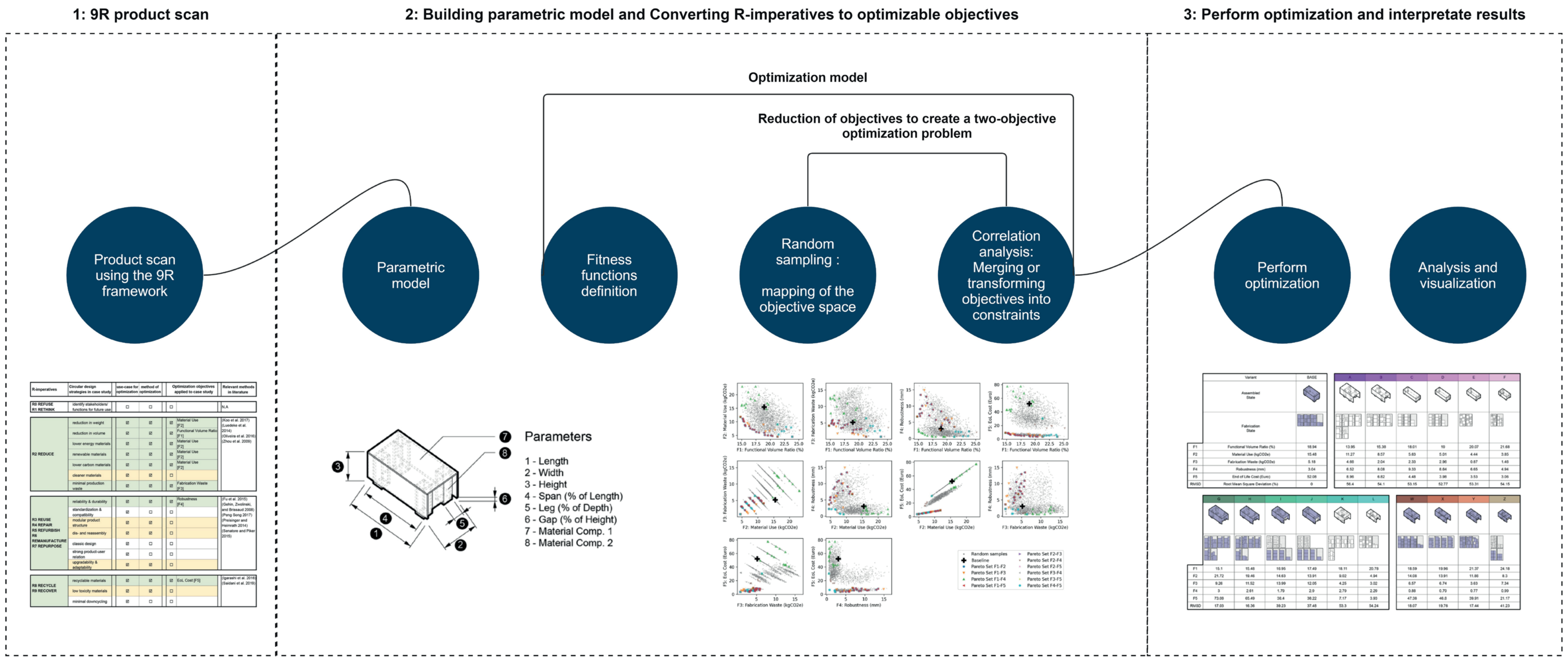


Figure 57: The scatter plot representing design space from Ortner et al. (2022).

Figure 58: Diagram created by the thesis author representing the optimization process discussed by Ortner et al. (2022) incorporating process figures from the paper



3.7.6 HYPER CONTROL ON GEOMETRY

CD allows having an outstanding level of control over geometry. This quality can be defined as hyper control on geometry. This advantage can be described as the level of control of a product's geometry, leading to intricacy and complexity, allowing the design of specific properties or behaviors of a product through its geometry. One expert mentioned control of geometry as one of the advantages of CD:

"ONE OF THE ADVANTAGES OF COMPUTATIONAL DESIGN IS THE LEVEL OF CONTROL YOU HAVE ON GEOMETRY. FOR INSTANCE, ON TEXTURING AND FINISHING OF PRODUCTS, YOU CAN GET THE RIGHT LEVEL OF FINISH AND THE INTRICACY YOU WANT."
CD EXPERT INTERVIEW 2

Architected materials can be considered as an effect of the Hyper control on geometry enabled by Computational Design.
Architected materials, also known as lattice structures, belong to a category of materials characterized by an engineered topology and geometry which can achieve tailored physical and mechanical properties. (Kladovasilakis et al., 2022)

The combination of architected materials and additive manufacturing allows designers to manipulate and design the inner volume of geometries. Usually, product design focuses on the outer surface of geometries, with the inner volume's physical properties dependent solely on the material property. This is primarily due to manufacturing constraints and the labor-intensive nature of designing intricate structures manually.
However, additive manufacturing, also known as 3D printing, can manage the geometry's internal space, opening up new opportunities for innovative shapes, design flexibility, and novel functionality and behavior (DFAM, 2022).

Function integration can be defined as the process of using architected materials to achieve mechanical properties in a product that typically are achieved using multiple materials but with a single material, and it is enabled by the control on geometry offered by CD. (Nature Architects, 2021)
The benefits of function integration in industrial design are vast. They range from creating products using fewer materials, which makes them easier to recycle, to designing compliant mechanisms. Nature Architects is a studio exploring this space, and they developed a series of products using this approach.
The first is a pair of headphones in which all the functions are achieved with a single material thanks to architected materials, giving life to a mono-material product Figure 60.
The second example is a 3D-printed arm with articulations engineered through architected materials, Figure 60.

Figure 60: Headphones designed by Nature Architects using function integration

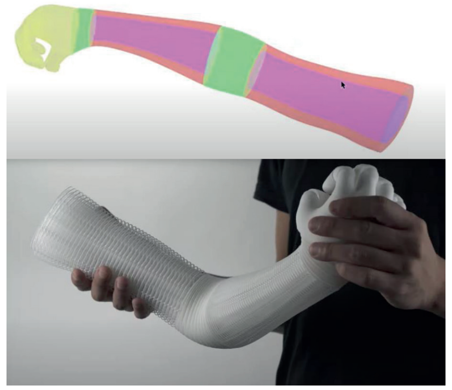


Figure 59: 3D printed arm designed by Nature Architects using function integration

Figure 61: ILABO SHOES, Arturo Tedeschi & Ross Lovegrove, 2015

Another possibility enabled by the geometry control offered by CD also creates opportunities for innovating products' aesthetics. Arturo Tedeschi has brought innovative transformation in product aesthetics using CD's high level of geometrical control.
Noteworthy among his creations are the Ilabo Shoes, designed in collaboration with Ross Lovegrove (Figure 61). The distinct feature of these shoes lies in their filaments, which were modeled using particle systems and attraction-repulsion logic. These unique geometries follow the foot's geometry, enhancing comfort and style. (Ilabo Shoes | Arturo Tedeschi, 2015)
Another noteworthy project under Tedeschi's belt is the Xev Yoyo, a city car Figure 62. Using the granular geometry control provided by CD, Tedeschi crafted intricate fading patterns, enhancing the car's overall visual appeal. (Tedeschi, 2018)

Figure 62: XEV Yoyo Arturo Tedeschi, (2018)

3.7.7
HYPER-PRODUCTION OF IMAGES USING MIDJOURNEY

The main opportunities enabled by Generative AI for hyper production of images are presented in section 2.4.2 However, during the graduation project, two small tests were carried out to reflect on the potential of this tool. The resulting images cannot be included in the report for confidentiality reasons. Therefore, this passage will focus on the insights gained from the experiments.

1-Text to image for brainstorming
Two designers used Midjourney (Midjourney, 2021)- a text-to-image application- to ideate in the very early stage of a project for a physical product; the brief was still somehow fuzzy.
The main takeaways are:
Obtaining compelling outcomes can be complex when the design challenge is still very abstract. If overly straightforward definitions are employed, for instance, using the brief as a prompt, the results may be predictable and sometimes unoriginal. Therefore, it might be necessary to first, reinterpret the design brief with a rough and abstract concept of what the solution may be in order to initiate a dialogue with the design tool.
It could be difficult to brainstorm within a group using the tool. It is probably easier to enter a "flow" state of conversation with the tool working alone because of speed and the lack of external judgment. It is important to mention that the designers were new to using the application. With practice, a team of designers could potentially achieve better results than an individual because there would be a wider range of ideas to input into the system.

2-Visualizing future scenarios for a client.
Midjourney was used to visualize future business opportunities for a client in the consumer goods sector.
The test was successful and demonstrated how having a clear idea of the concept and with the correct prompts, it is possible to obtain stunning and communicative images in a matter of minutes.

3.7.8
TEXT TO 3D

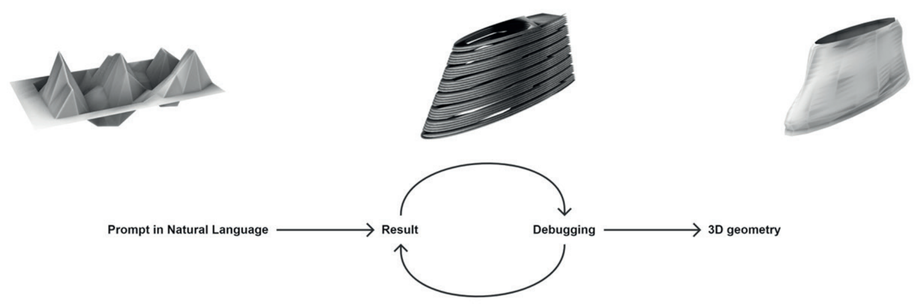


Figure 64: Process from text to 3D with some examples of outputs for a pattern on the bottle's neck

The graduation project also included experiments utilizing ChatGPT, with the specific objective of generating 3D geometry from textual prompts. Each experiment was conducted on the bottle case study introduced in section 3.7.3. The goal was to generate a pattern to enhance the bottle's grip.
The process began with requesting a GHPython script from the chatbot, asking for "a pattern to improve grip on a surface." This script was intended to design a pattern that could augment the grip on a surface, as depicted in Figure 63. Subsequently, the provided script from ChatGPT was integrated into a GHPython component in Grasshopper before applying it to the bottle's surface. The code produced several errors. In order to correct these errors, the faulty code was reinserted into ChatGPT, specifying the type of error encountered while compiling the code in Grasshopper. After several iterations of this process, the code started to work, giving life to the outcome illustrated in Figure 63.
The next challenge involved the creation of patterns more intricate than the circular one showcased in Figure 63. After a request for a more complex pattern, the chatbot created code for generating a pattern influenced by Perlin noise. The code failed to yield satisfactory results, as evidenced by some of the outputs in Figure 64.
The interaction with the chatbot is fascinating because it allows the user to pinpoint specific errors and get help from ChatGPT to solve them. This extends to not only code-related errors but also adjustments required in the code due to external factors, such as aligning the pattern with the surface normals rather than the Rhino viewport coordinates.
While ChatGPT's capabilities are currently somewhat restricted for this application, the rapid advancements in this field hint at substantial potential. Generating 3D geometry using text prompts could profoundly influence the design world. It may lower the skill threshold required for generating intricate geometry or drastically expedite the creation of 3D models.

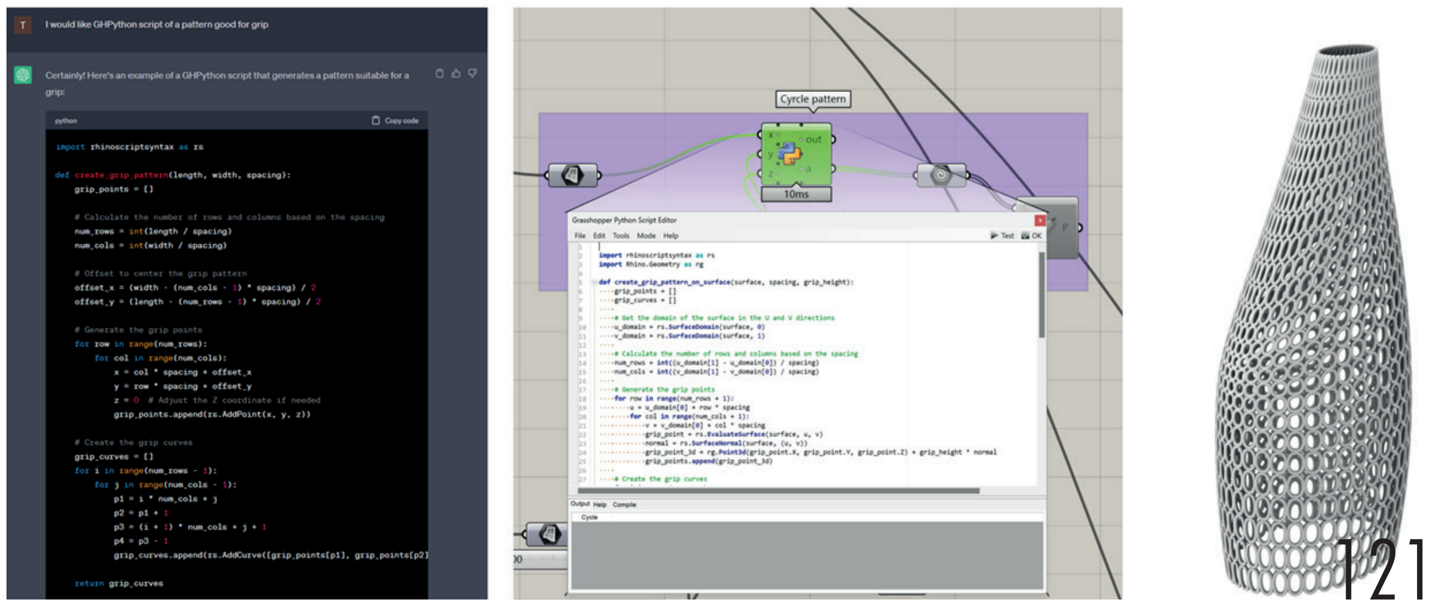


Figure 63: From text prompt in chat GPT to 3D geometry using GHPython

3.7.9
CONCLUSIONS ON CD OPPORTUNITIES IN INDUSTRIAL DESIGN

This section delineated potential opportunities that could positively influence the future of industrial design via the integration of Computational Design.

Among these potentials, design automation can notably enhance efficiency during the design process. Mass customization presents the possibility of providing products customized to individual user preferences. Configurators, can be utilized for mass customization and during the design process for exploring product variations and allowing non-designers to experiment with manipulating geometries. CD's hyper-control over geometry can enable the creation of architected materials. This potential could minimize the diversity of materials required in products and open up novel possibilities in product aesthetics by creating complex geometries that would be challenging to achieve using traditional methods.

The capabilities of CD extend to the realm of sustainable design. An in-depth analysis of multi-objective optimization based on circular economy parameters was conducted. A case study drawn from existing literature was used to develop a diagram demonstrating the multi-objective optimization process approach when applied to circular economy design.
During the graduation project, several small-scale experiments were conducted, all revolving around a trigger bottle. These included a configurator for user research, an optimization of the bottle based on a subjective parameter, and an experiment with an interactive genetic algorithm plug-in for Grasshopper: Biomorpher. Another experiment aimed to use chatGPT to create of 3D geometry from text prompts without satisfactory results.
Hopefully, this section discussing the opportunities of CD in Industrial Design will inspire other designers and encourage their exploration of the potential that CD brings to the industrial design profession.

3.8
CONCLUSIONS ON COMPUTATIONAL DESIGN IMPLICATIONS FOR THE DESIGN PROCESS AND OPPORTUNITIES IN INDUSTRIAL DESIGN

THIS CHAPTER DISCUSSED THE **EFFECTS** OF COMPUTATIONAL DESIGN (CD) **ON THE DESIGN PROCESS** AND THE **OPPORTUNITIES** ENABLED IN INDUSTRIAL DESIGN (ID).
A **CONSTRAINT-DRIVEN** APPROACH IS NECESSARY TO IDENTIFY PARAMETERS AND GOALS NEEDED TO DEFINE A COMPUTATIONAL SYSTEM, RESULTING IN A SHIFT OF THE **DESIGNER'S ROLE** THAT BECOMES AN EDITOR OF CONSTRAINTS AND THE "**CONDUCTOR**" OF THE GENERATIVE PROCESS.
THE ADVANTAGES OF CD IN THE DESIGN PROCESS ARE:

EXPLORATION: THANKS TO ITS GENERATIVE CAPABILITIES CD ENABLES THE DESIGNER TO EXPLORE A WIDER SOLUTION SPACE, ENCOUNTERING OFTEN UNEXPECTED SOLUTIONS CAPABLE OF STIMULATING CREATIVITY AND CREATING SYNERGY WITH THE DESIGNER'S INTUITION.

EFFICIENCY: THROUGH DESIGN AUTOMATION AND PARAMETRC DESIGN, DESIGNERS CAN CAPTURE AND REUSE DESIGN SOLUTIONS AND QUICKLY EXPLORE VARIATIONS OF A PRODUCT RESULTING IN FASTER ITERATIONS AND A REDUCED TIME-TO-MARKET.

QUALITY: THANKS TO COMPUTATIONAL OPTIMIZATION AND HYPER CONTROL ON GEOETRY DESIGNERS CAN CREATE BETTER-PERFORMING PRODUCTS BOTH FROM A TECHNICAL END EXPERIENTIAL POINT OF VIEW.

AMONG THE **SOFT SKILLS** NEEDED FOR CD, **SYSTEM THINKING** IS KEY TO CREATING THE COMPUTATIONAL SYSTEM TO EXPLORE THE DESIGN SPACE. CD EXPERTS OFTEN REFERRED TO A SHIFT IN MINDSET (**SOFTWARE PARADIGM**) IN APPROACHING THE DESIGN OF PHYSICAL PRODUCTS WITH MODALITIES OF SOFTWARE DEVELOPMENT. AN **AGILE PROCESS** CAN STREAMLINE PRODUCT DEVELOPMENT. QUICKLY IDENTIFYING THE CODE NECESSARY TO CREATE SPECIFIC GEOMETRY IS NECESSARY TO "**CODE AN OBJECT**" AND SOLVE DESIGN PROBLEMS.

CD EXPERTS IDENTIFY THEIR PREFERRED **SOFTWARE** FOR INDUSTRIAL PRODUCT DESIGN AS "**SANDBOX**" SOFTWARE (SECTION 3.6). THESE TOOLS, LIKE **GRASSHOPPER**, HOUDINI, AND BLENDER, INCORPORATE TRADITIONAL OR VISUAL PROGRAMMING TOOLS TO IMPLEMENT CD STRATEGIES TAILORED TO A SPECIFIC DESIGN PROBLEM.
THE CHAPTER ALSO PRESENTS A SERIES OF SMALL EXPERIMENTS (SECTION 3.7.3.- 3.7.4) CONDUCTED DURING THE PROJECT CONCERNING CREATING A CONFIGURATOR AND USING EVOLUTIONARY SOLVERS TO EXPLORE OBJECTIVE AND SUBJECTIVE REQUIREMENTS IN THE USE CASE OF A TRIGGER BOTTLE. ANOTHER TEST WAS CONDUCTED TO EVALUATE THE CAPABILITY OF USING CHATGPT IN COMBINATION WITH GRASSHOPPER TO CREATE 3D GEOMETRY FROM TEXT PROMPTS.
THE MAIN **OPPORTUNITIES** ENABLED BY CD IN THE INDUSTRIAL DESIGN PROFESSION ARE: **DESIGN AUTOMATION, MASS CUSTOMIZATION, CONFIGURATORS, HYPERCONTROL OVER GEOMETRY, AND MULTI-OBJECTIVE OPTIMIZATION APPLIED TO DESIGN FOR SUSTAINABILITY**.

VanBerlo part of Accenture headquarters in Eindhoven, image from VanBerlo Agency

PART 2
COMPUTATIONAL DESIGN ADOPTION IN INDUSTRIAL DESIGN

This part of the thesis focuses on the potential adoption of Computational Design (CD) in the Industrial Design (ID) world. A necessary condition for testing the waters of CD adoption is understanding the perspective of potential future users of the methodology: industrial designers. In the context of this thesis, the category is represented by the VanBerlo designers, who were involved through interviews and focus groups.
The first chapter (4) discusses the perspectives of ID practitioners on CD. The second chapter (5) proposes a series of preliminary strategies to facilitate CD adoption in a professional context.

4 INDUSTRIAL DESIGN PROFESSIONALS PERSPECTIVES ON COMPUTATIONAL DESIGN

This chapter aims to draw a picture of industrial design professionals' opinions and ideas on computational design (CD) and the challenges and opportunities related to its adoption in their daily practice. The research was conducted through interviews and a focus group in the design agency VanBerlo.

4.1 METHODS

This part of the research involved members of VanBerlo part of Accenture, to collect their perspectives on CD and test the waters for a possible integration of CD within the studio.

It is important to understand the agency's approach to projects and design process to find opportunities for CD to contribute. Therefore in the first interviews, questions about the VanBerlo design process were included.

RQ 2: WHAT IS THEIR **BASE KNOWLEDGE ABOUT CD**?
RQ 2.1: WHAT ARE THEIR **LEARNING HABITS** WHEN ACQUIRING A NEW SKILL?
RQ 2.2: WHERE DO THEY SEE **OPPORTUNITIES** IN INCORPORATING CD INTO THEIR PROCESSES?
RQ 2.3: WHAT ARE THE MAIN **BARRIERS** TO IMPLEMENTING CD IN INDUSTRIAL DESIGN?

This set of questions was investigated through a focus group and interviews. The following sections will describe the research methods -interviews and focus groups- used during the research, and the results will be presented and discussed.

4.1.1 INTERVIEWS

The first method to gaining insights on the VanBerlo design process was explorative interviews.
The main research questions behind the interviews was:
RQ: What is the structure of the VanBerlo design process?
The pool of participants was curated to be as heterogeneous as possible in terms of expertise and level of seniority: one designer, one engineer, one project manager, and two senior designers.
Two interviews were conducted online Via Microsoft Teams, while the others were conducted in person. All the interviews lasted approximately one hour.
The main goal of the interviews was to define the role of the design process at VanBerlo as a context for the project. The interviewees are the experts in their design process. The interviews aimed at understanding the VanBerlo approach and mindset toward design while discussing potential CD opportunities. The interviews were also used to gain feedback on the interactive list of case studies described in section 5.3.

Two unstructured interviews were performed as a pilot to discuss with participants their previous experience on CD and future possibilities.
Three semi-structured interviews were performed afterwards. The questions asked during these interviews are the following to better understand the VanBerlo design process:

- Can you walk me through typical project stages? What is the workflow?
- How much divergence and convergence are part of your process?
- What are the main activities in your process?
- What are the success markers for these activities?
- Could you identify the main outputs of each phase of the DP?

The interviewees tended to include answers to all the above questions when answering the first one.
CD design was always introduced after the questions on the VanBerlo design process to avoid interference with the definition of design activities at the studio.
After a presentation on selected CD case studies,

CD opportunities within the VanBerlo design process were discussed through the following questions.

- Where do you see this method/case study fit in the VB process?
- What functionalities would you like to see implemented into these tools?
- In your opinion, what are the limits of adopting this approach?

When interviewing designers and engineers, observing how they quickly begin searching for solutions and exploring ideas with minimal prompting is fascinating. Although this can make it challenging to stay on track during the interview, it is ultimately a great advantage as it generates new and exciting ideas.
The last set of questions aimed to receive feedback on the interactive list of case studies described in section 5.3; after going through its main features, the following questions were asked.

- What would you change?
- What would be the first information you would like to encounter?
- How would you search for information in this toolkit?
- Would you prefer a focus on tools or case studies?

Analysis.
The interviews were transcribed through the Microsoft Word transcribe function. First, the data from each participant were analyzed separately; the relevant and most interesting quotes were collected and clustered based on the three main objectives of the interviews: Understanding the VanBerlo design process, identifying opportunities on CD in the VanBerlo design process, and gaining inputs on the interactive list of case studies.

A small experiment was carried out to test the capability of chatGPT in extracting codes from interviews. The test was carried out on a single interview.
The following prompt (Kruikow, 2023), was used in chatGPT after scraping out all the sensible data from participants:

"You are a researcher. I will now upload an interview transcript, and you will do what is called qualitative coding - specifically, initial coding, also known as open coding. The text is an interview transcript; I do not want you to code the questions asked by the interviewer. I want the codes to be detailed and descriptive. I want you to apply codes to sentences or parts of sentences these codes were applied to. n other words, when I ask you to provide me example quotes for the codes that you create, I would like you to be able to do it. Here is the text to be coded:"
To gain additional insights, the following prompt (Kruikow, 2023) was used:
"Please develop more detailed codes. I would like the codes to be a bit more descriptive, and please separately list quotes that show all sentences or parts of sentences coded with each code."
The result can be seen in Figure 65.

Overall, the use of chatGPT gave some interesting insights and structure. However, some errors were made; for instance, sometimes, it included questions in the codes. Considering the limited number of interviews, this process was not applied to all the interviews.
The interviews gave access to in-depth and personal views on the VB design process and opinions on CD from the angle of different roles within the agency.

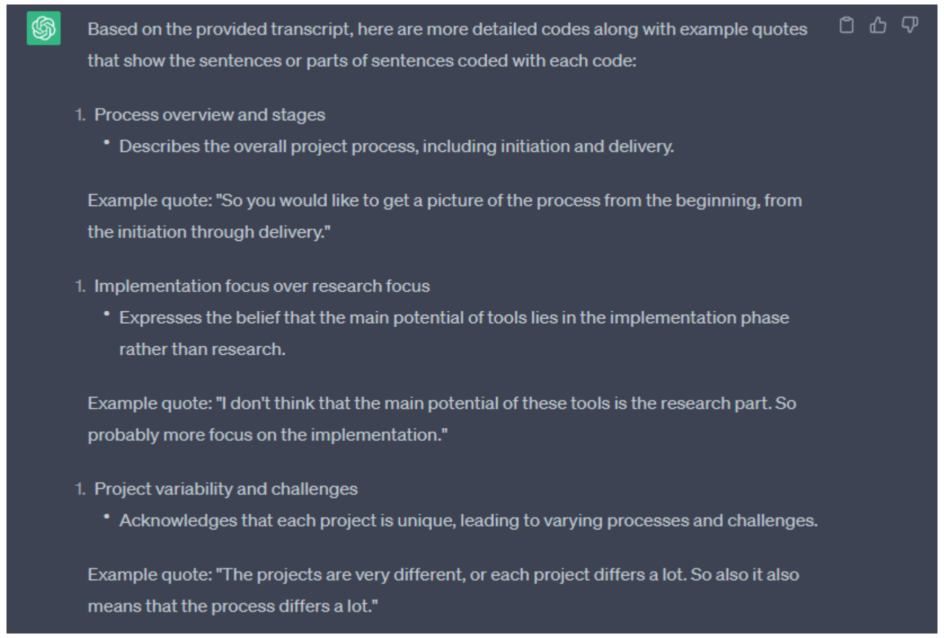


Figure 65: Interview coding using Chat GPT

4.1.2 FOCUS GROUP

After the interviews, it was decided to organize a focus group. This method was chosen because, through a social setting, it can create a critical and creative debate around the topic and be used to gain contextual information and gather recommendations toward the integration of CD at VanBerlo. (Zijlstra, 2020)

The focus group served to examine the general sentiment about CD and as a moment of discussion with studio members. The focus group aimed to answer the following research questions:

RQ 2: WHAT IS THEIR **BASE KNOWLEDGE ABOUT CD**?
RQ 2.1: WHAT ARE THEIR **LEARNING HABITS** WHEN ACQUIRING A NEW SKILL?
RQ 2.2: WHERE DO THEY SEE **OPPORTUNITIES** IN INCORPORATING CD INTO THEIR PROCESSES?
RQ 2.3: WHAT ARE THE MAIN **BARRIERS** TO IMPLEMENTING CD IN INDUSTRIAL DESIGN?

Preparation
A research canvas used by VanBerlo researchers was used to work toward relevant questions. The research canvas helped to transition from the research objective to critical questions and, in the end, to the definition of the focus group script that can be found in Appendix B. That ultimately led to the structure for the Miro board in Figure 66.

Execution
The session was hybrid; of the twelve participants, two were online, and ten were in person. Therefore, Miro was chosen as the main mean of interaction. The session lasted roughly 90 minutes; the group of participants was heterogeneous: different levels of seniority and multiple areas of expertise, designers, engineers, strategists, and one senior project manager. Every participant brought a unique perspective, ranging from product visualization to sustainability, software or mechanical engineering, project management, and more. The main goals were to gain a fundamental understanding of CD opportunities, generate ideas about overcoming obstacles, and explore different formats for learning more about CD. The last part was dedicated to gaining feedback on the prototype described in section 5.4 and will be discussed in that section.

Figure 66: The Miro board used for the focus group at VanBerlo

There were two 5-minute presentations. The first mainly focused on case studies and took place before the brainstorming on CD opportunities. The second presentation was a short introduction to the prototype described in Section 5.4.

Analysis

The focus group recording was analysed concurrently with the clustering (Figure 68) and analysis of the post-it on the Miro board. The functions of clustering and keyword finding on Miro helped in extracting trends and topics.

The first section of the focus group aimed to uncover participants' base knowledge of computational design and previous experience with CD tools. The results from this section were divided into seven clusters:

- Sentences aligned with the definitions that emerged during the research on CD described in section 2.1.
- Sentences that were already aimed at identifying possible opportunities.
- Definitions associated with topology optimization or the fulfillment of objective KPIs.
- Associations of CD with parametric design and Grasshopper.
- Comments highlighting the need for more clarity on the terminology related to CD.
- A comment highlighting the recent growth of the discipline.
- Sentences briefly describing the participant's previous experience with CD tools.

The second step of the focus group aimed to understand the skills recently learned by participants and the related learning method. All the inputs from participants were first divided into two main categories: skills learned and sources used for learning (Figure 67). The two categories were further broken down into subsections to identify which type of skills and learning methods were predominant.

The third phase consisted in identifying CD opportunities along the VB design process after a brief presentation on selected CD case studies. The post-its on Miro, representing opportunities, were already roughly positioned on the six phases of the VB design process. The input from participants was clustered into eleven categories (Figure 70):

- General suggestions about the process and improvement in efficiency.
- Related to market scan and understanding of overarching product features and trends in the market.
- Input on knowledge transferring from different fields.
- Ideation and inspiration, the category with the greatest number of inputs.
- Inputs on optimization.
- Inputs on validation.
- Inputs on sustainability.
- Inputs on CD potential to better integrate user and client feedback in the design process.
- Inputs that were comparing CD tools to having an additional team member.

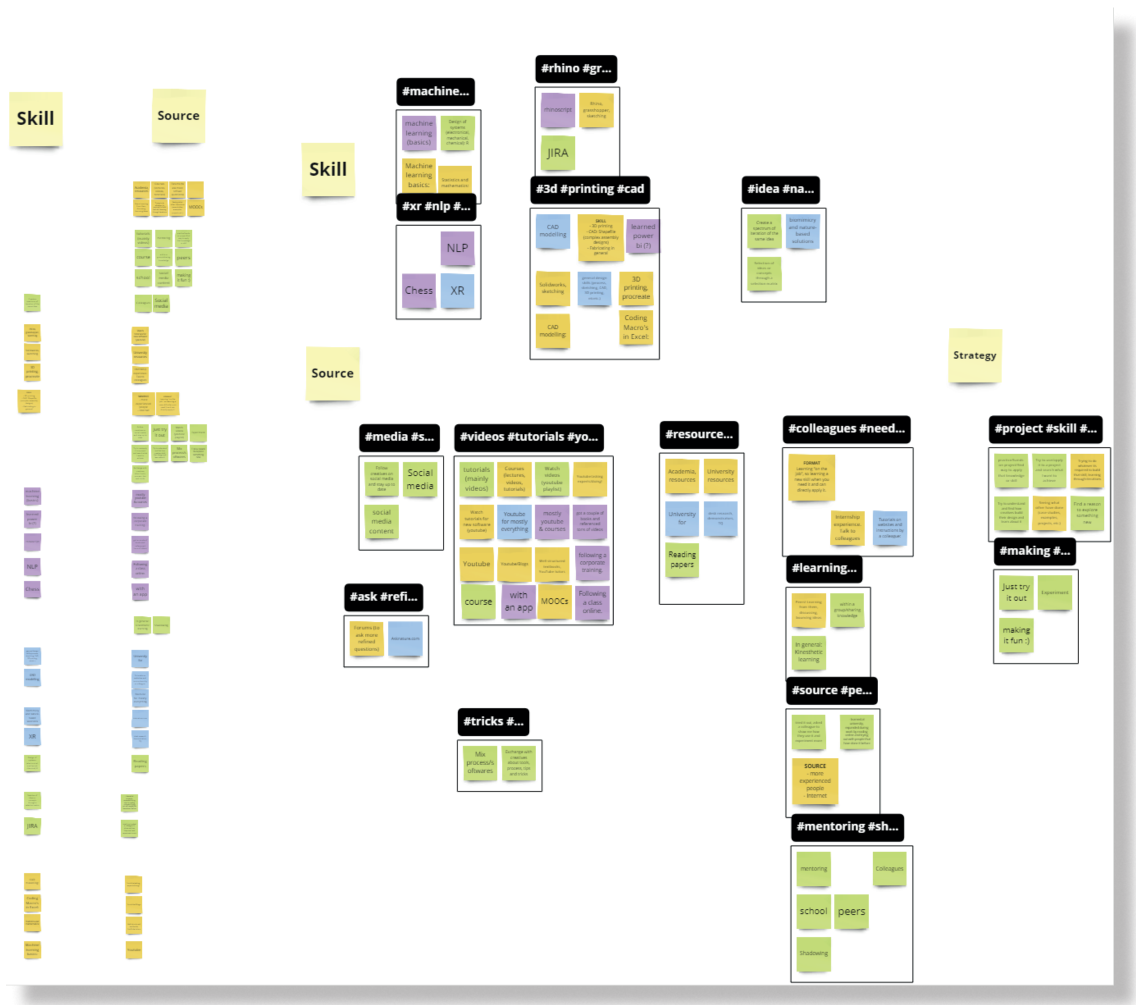


Figure 67: Clustering of the results: skills, sources, keywords.

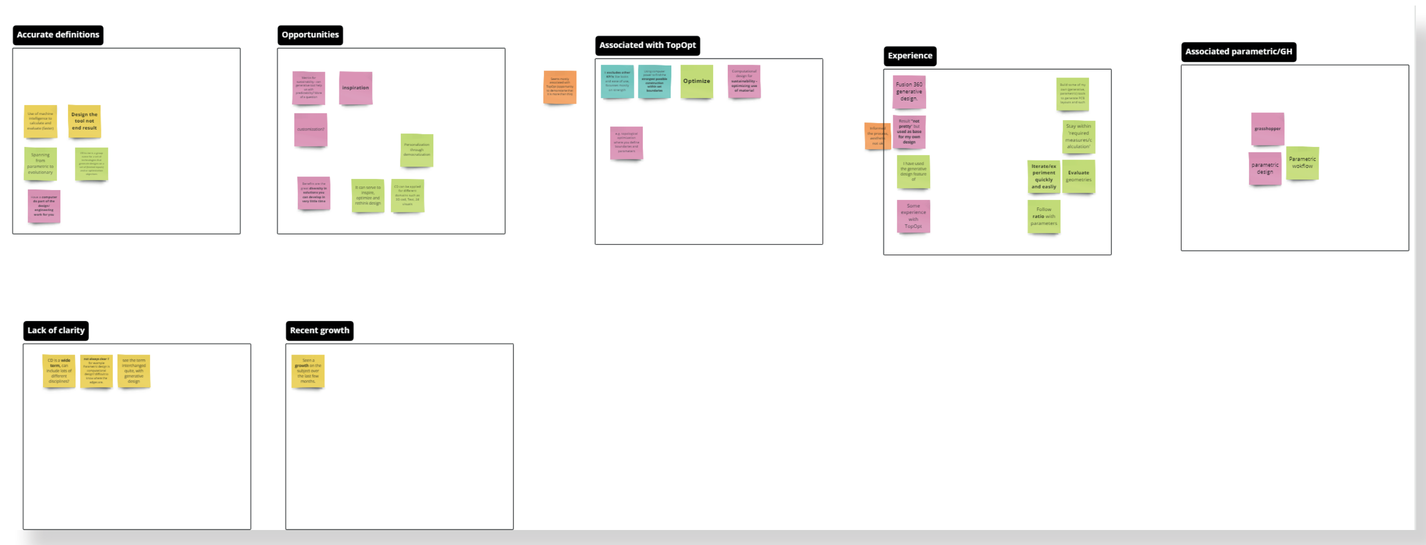


Figure 68: Clustering of the results: definitions and previous experience with CD.

• Input on forms finding and feedback loops.

The fourth step of the focus group aimed at brainstorming about perceived barriers and challenges to CD adoption. The results were clustered during the focus group (Figure 69). The clusters that emerged are:
• CD is perceived as a threat to human creativity.
• Concerns about the legal and IP aspects of Generative AI tools.
• Doubts about the choice of the right tools and the subsequent learning.
• Concerns about understanding the exact value that CD can bring to design problems.
• Doubts about excessive time investment in learning new skills and setting up CD systems.
• Limits of the using a CD approach e.g., mistakes based on the wrong definitions of input for a CD system.

In conclusion, the use of a focus group uncovered significant insights into the understanding and potential integration of CD at VanBerlo. The diverse participants provided unique perspectives on their base knowledge of CD, learning preferences, perceived value in their processes, and potential barriers to CD usage. The analysis highlighted a variety of potential opportunities for CD within the design process and identified key challenges for its adoption. The feedback on the prototype also offered valuable direction for refining and enhancing its effectiveness. This collective engagement enabled gathering substantial and valuable data, suggesting a path towards integrating CD into the daily processes of a design consultancy like VanBerlo and outlining the professionals' perspective on CD. Further training and a more precise definition of CD terminologies might be beneficial in overcoming the identified barriers and enhancing the successful implementation of CD.
The results that emerged from the analysis are described and discussed in the following section.

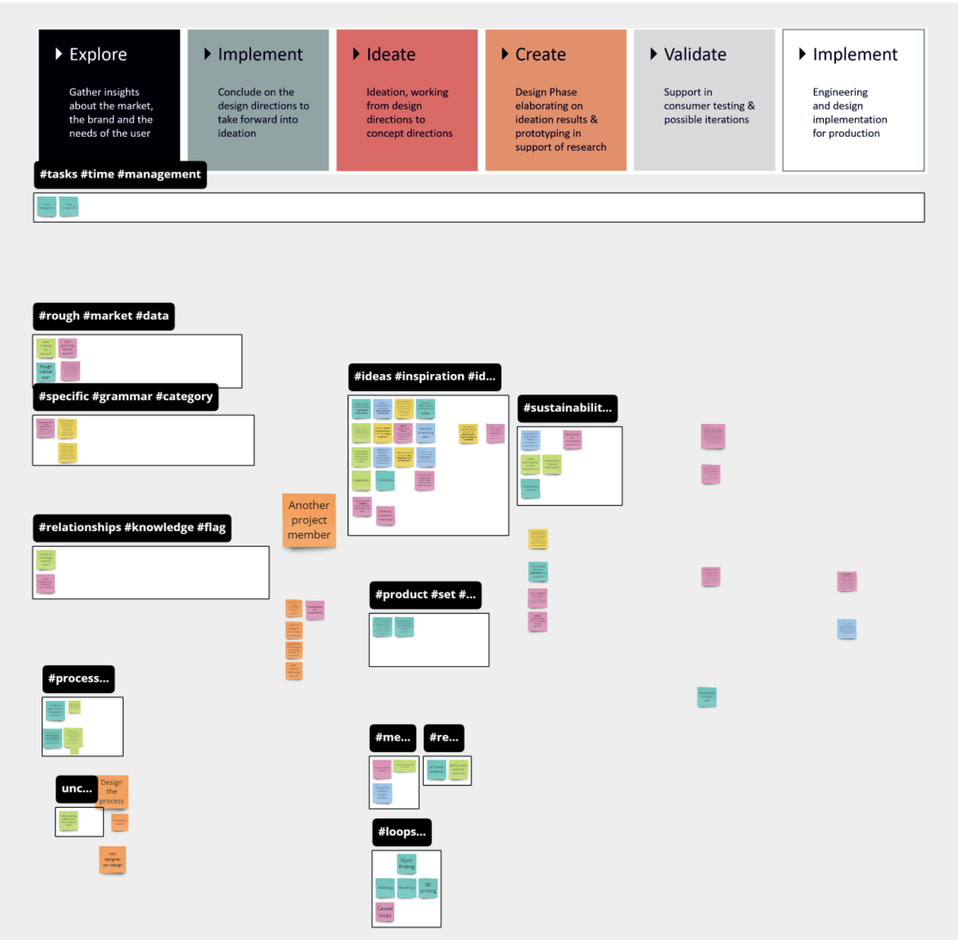
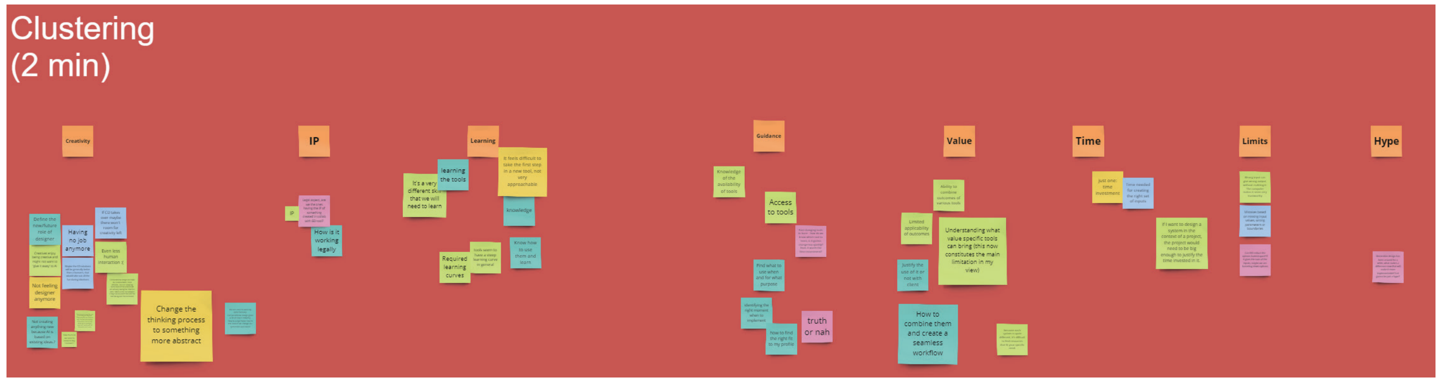


Figure 70: Clustering of the results: CD opportunities on the VanBerlo design process

Figure 69: Clustering of the results: Barriers and challenges in CD adoption



4.2 VANBERLO DESIGN PROCESS

This section aims to snap a picture of the recurrent themes that emerged during the research, which can help understand how VanBerlo approaches the process of designing products and services. Nevertheless, the process extracted from the research is a partial view of the process limited to the research that was carried out, and it does not have the ambition to accurately describe the VB design process, considering the variety of projects and people within the studio.

"WE ALWAYS LIKE TO HAVE A STRATEGIC APPROACH, WHICH MEANS YOU IDEALLY HAVE RESEARCH DESIGN RESEARCH BEFORE, DURING, AND AFTER A PROJECT. USUALLY, I LIKE TO QUICKLY DRAW THE DESIGN RESEARCH AND CONCEPT AND DESIGN TIMELINES, AND THESE CONSTANTLY DO SOMETHING TOGETHER." VANBERLO INTERVIEW 1

Every project usually starts with a client question. Understanding the client, their business needs, and their customer is fundamental to understanding the right direction to propose specific design efforts.

"A PROJECT STARTS WITH DEEPLY UNDERSTANDING THE CLIENT AND THEIR CUSTOMERS FIRST. SO, WHAT DO THEY NEED? WHAT IS THE POTENTIAL OF THE BUSINESS? WHAT KIND OF STATE IS THE CLIENT WITH THE PROJECT THEY ASKED US TO HELP WITH? IS IT BECAUSE THEY DO NOT HAVE THIS KNOWLEDGE IN-HOUSE, THEY DO NOT HAVE THE CAPABILITIES IN-HOUSE, OR ANOTHER REASON?" VANBERLO INTERVIEW 1

Sustainability and Inclusivity are integral to the VanBerlo mission and are treated as preconditions for a successful and meaningful project. For this reason, these values are investigated and prioritized from the beginning to ensure maximum impact in these areas.

"VALUES LIKE INCLUSIVITY AND SUSTAINABILITY NEED TO BE INTEGRATED EVEN BEFORE THE START OF A PROJECT, AND ARE PRECONDITIONS FOR A SUCCESSFUL PRODUCT AND BUSINESS." VANBERLO INTERVIEW 1

The interviewees emphasized the absence of a standardized approach or process for all projects. They underlined the need for flexibility and adaptability in project management, allowing for changes and iterations based on research, tests, and client insights. Each project is unique and presents its own set of challenges, demanding a tailored approach. VanBerlo offers a wide range of expertises, enabling them to create customized teams to address specific client needs.

"THE PROJECTS ARE VERY DIFFERENT, OR EACH PROJECT DIFFERS A LOT. SO IT ALSO MEANS THAT THE PROCESS DIFFERS A LOT. THERE IS A CERTAIN FLEXIBILITY AND CREATIVITY FROM A PROJECT MANAGEMENT STANDPOINT."VANBERLO INTERVIEW 2

Once there is a preliminary understanding of the client and user needs, the process involves customizing proposals and deliverables according to the client's specific requirements and project goals. The VanBerlo design process, consisting of Explore, Implement, Ideate, Create, Validate, and Implement, serves as the backbone of a proposal and the following design work. The process of divergence and convergence was confirmed as a recurrent activity during projects, and an interviewee, when asked about an opinion on the Double Diamond diagram, said:

"IN A NUTSHELL, THIS FLOW MAKES SENSE."

Another participant, while discussing the process, made a quick sketch of his view of a possible CD integration in the process (Figure 71)

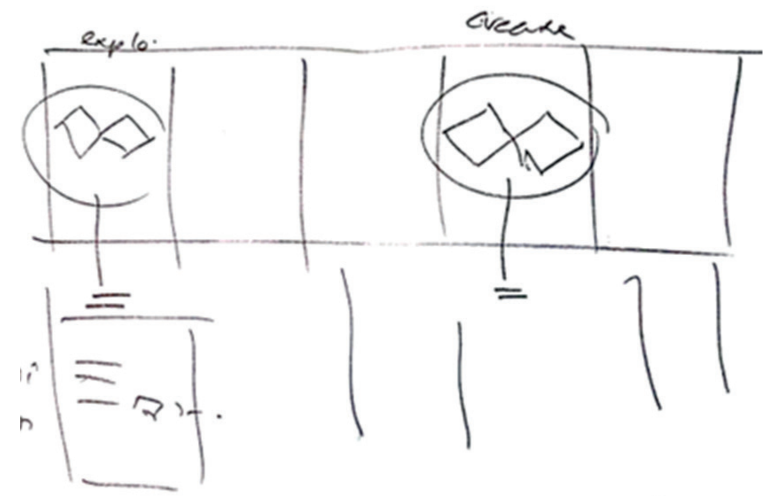


Figure 71: Quick sketch of an inteviewee representing how CD opportunities could be represented in relation to the VanBerlo process

A valuable tool for drafting an initial proposal is an internal method toolbox. This toolbox is divided into the phases of the VanBerlo design process, and each phase has a collection of design methods. The toolbox briefly describes the methods' goal, their implementation approach, maximum duration, and the experts within the studio who specialize in that particular method. The toolbox, offering an overview of methods, is widely used within the studio, and its use was discussed during the interviews.

"I THINK THAT IS A GOOD EXAMPLE OF AN OVERVIEW, GIVING ENOUGH INFORMATION WITHOUT BEING SUPER OVERWHELMING. YOU CAN GAIN A BASIC UNDERSTANDING OF A METHOD AND THEN KNOW WHOM TO CONTACT IF YOU WANT TO KNOW MORE. THAT IS MORE LIKE A BUILDING BLOCK. YOU HAVE PUZZLE PIECES, AND THEN YOU ARRANGE THEM AS IT WORKS BASED ON THE PROJECT CRITERIA." VANBERLO INTERVIEW 2

Research is always the starting point, and taking a strategic approach is fundamental in understanding the underlying reasons behind a client's question and determining where to act to achieve impact and value. The interviewees emphasized the importance of gathering insights through research to drive the project forward. They focused on identifying opportunities where their design work could make a meaningful difference in the future.
"As a designer, I'm expanding on the research side, so really trying to understand the question behind the question. Where can we push? Where shouldn't we push? Understanding what is the freedom that we have. Research, for instance, is also about understanding the opportunities where we can make a difference in the future and identifying those as a starting point for the next steps." VanBerlo interview 2

"SO, IN THIS VERY EARLY STAGE, IT IS SUPER IMPORTANT TO FIND THE RIGHT QUESTION. WHAT YOU SEE WITH CLIENTS IS THAT SOMETIMES THEY COME UP WITH A QUESTION, AND THEN IN THE END, THE QUESTION THEY ASK IS NOT THE KEY REASON FOR THE PROBLEM THEY ARE TRYING TO SOLVE OR WHAT THEY NEED. THUS, UNDERSTANDING THE UNDERLYING QUESTION IS SUPER IMPORTANT." VANBERLO INTERVIEW 2

After that a design direction is defined, the process continues in the ideation phase, whose goal is to transform the initial design direction into concept directions through ideation on the previously identified drivers and success criteria.

"THEN, ONCE WE HAVE SYNTHESIZED, WE MOVE INTO IDEATION. WE OFTEN START SKETCHING, BRAINSTORMING, SOMETIMES HAVING CLIENTS START THINKING TOGETHER, CREATING THEIR OWN RESEARCH SPACE, AND FAMILIARIZING WITH WHAT WE DO WHILE MOVING TOWARDS A SOLUTION TO THEIR PROBLEM." VANBERLO INTERVIEW 2

The ideation phase is followed by a creation phase, which aims to elaborate the ideation results into tangible results such as prototypes, renderings, or storyboards.

"NEXT, WE TYPICALLY MOVE ON TO THE "CREATE" PHASE, WHERE WE AIM TO MAKE OUR IDEAS MORE TANGIBLE. THIS CAN INVOLVE MERGING CONCEPTS, CREATING RENDERS, STORYBOARDS, PROTOTYPES, AND OTHER DELIVERABLES." VANBERLO INTERVIEW 2

These deliverables are used to support further research and testing that comes back in various stages of the projects to validate results, gain user feedback and inform design iterations.

"THEN WE USUALLY DO SOME ADDITIONAL RESEARCH IN BETWEEN, WE CREATE AND IMPLEMENT. SEVERAL RUNS, SOMETIMES JUST ONE, DEPENDING ON THE PROJECT. THERE IS ALWAYS SOME KIND OF RESEARCH TO GET FEEDBACK FROM CONSUMERS. THEN, WE MOVE INTO AN IMPLEMENTATION PHASE, WHERE WE TAKE THE CONSUMER FEEDBACK INTO ACCOUNT AND MOVE THAT INTO MORE REFINED CADS AND PROTOTYPES GOING TOWARDS ENGINEERING. THE INTERACTION WITH STAKEHOLDERS IS CONTINUOUS, TO UNDERSTAND WHAT IS FEASIBLE OR DESIRABLE FOR THEM." VANBERLO INTERVIEW 3

After concept validation and user testing, the process moves into the implementation phase, in which products are engineered; in this phase, the deliverables range from detailed CAD models to working prototypes.
VanBerlo is divided into three main capabilities: strategy, engineering, and design. However, representatives from each capability are often involved from the beginning of a project to ensure all possible design perspectives are considered from the early stages.
Also, clients and users are involved throughout the process to receive feedback and safeguard the project direction.
This description of the process highlights some recurrent themes. The participants emphasized the significance of understanding the client and their customers as a starting point for every project.
A deep understanding of the client's question allows the studio to propose a tailored project plan. The plan usually follows the phases of the VanBerlo design process that, based on the projects, are detailed by methods mainly extracted from an internal method toolbox. Flexibility and adaptability are preconditions of this approach.

Conclusion

The design process at VanBerlo showcases an inquisitive nature deeply rooted in research and validation. The iterative and feedback-driven approach allows for incremental improvement fueled by client, user, and prototype insights.
Iterating is indeed the key to the mindset at VanBerlo driven by a "fail fast to learn fast" approach. In this outlook, failure is encouraged as a way to succeed. An interviewee mentioned that CD could foster this mentality enabling failure in a controlled environment and speeding up iterations toward a final result.

"THESE TOOLS CAN REALLY SPEED UP THE ITERATIVE PROCESS. FOR MANY PEOPLE, NO MATTER IF IT IS IN BUSINESS OR DESIGN, FAILURE IS NOT SOMETHING ACCEPTED, BUT WE SHOULD CELEBRATE IT. I THINK THESE KINDS OF SYSTEMS MIGHT ENABLE PEOPLE TO FAIL FASTER, AND BECAUSE IT IS THE SYSTEM THAT MAKES THE MISTAKES AND THE FAILURES, IT IS LESS OF AN IMPACT ON OUR EGO, AND THIS COULD LEAD TO AN INCREASED NUMBER OF ITERATIONS IN LESS TIME. IT MIGHT LEAD TO BETTER DESIGN BECAUSE GOOD DESIGN REQUIRES GREAT FAILURES. " VANBERLO INTERVIEW 1

This perspective is fascinating because it explains what CD can bring to the sentence that can summarize the overall VB approach: "We shape the future by playing with it first."

"" PLAY" MEANS: "HEY, WE CAN TRY OUT THINGS WE CAN BUILD AND EXPLORE." WE DO NOT SAY LITERALLY, "WE CREATE THE FUTURE BY FAILING A LOT" THAT COULD SOUND NEGATIVE, SO WE PLAY A LOT WITH IT BUT PLAYING ALSO ALLOWS US TO FAIL AND SIMULTANEOUSLY EXPLORE AND TRY OUT. THROWING MANY THINGS IN THE (CD) SYSTEM AND SEE WHAT COMES OUT OF IT. I THINK THAT IS ALSO PLAYING." VANBERLO INTERVIEW 1

4.3 BASE KNOWLEDGE OF INDUSTRIAL DESIGN PROFESSIONALS ON COMPUTATIONAL DESIGN

During the focus group emrged that Computational Design (CD) is often associated with software like Grasshopper or specific CD applications, particularly topology optimisation, and with the satisfaction of objective requirements.
" CD EXCLUDES OTHER KPIS LIKE LOOKS AND EASE OF USE, FOCUSSES MOSTLY ON STRENGTH." FOCUS GROUP PARTICIPANT 6

This quote highlights the need to clarify that other KPIs in addition to strength can be included in the process. CD is often associated with tools, especially topology optimization and Grasshopper that are a part of it, but this view lacks the crucial idea of looking at CD as an approach to design more extensive than the sums of its tools, with effects in all the phases of the process and on the required mindset.
A participant recognized a lack of clarity in the disciplines included and on the terminology, (e.g. parametric. generative), and pointed out the subject's growth over the past months.
"CD IS A WIDE TERM. CAN IT INCLUDE DIFFERENT DISCIPLINES? IS NOT ALWAYS CLEAR IF, FOR EXAMPLE, PARAMETRIC DESIGN IS COMPUTATIONAL DESIGN? IS DIFFICULT TO KNOW WHERE THE EDGES ARE. I HAVE SEEN A GROWTH ON THE SUBJECT OVER THE LAST FEW MONTHS." FOCUS GROUP PARTICIPANT 8
This quote highlights the need for clarity in the definition and in the terminology around CD, this need is addressed in section x.
A couple of participants gave comprehensive definitions of CD. Especially relevant is the quote, "*Design the tool, not the end result*", or "*CD to me is a group name for a set of technologies that generate designs on a set of (limited inputs) and or optimization objectives*". These definitions showed an understanding of the comprehensive word of CD and the required switching of mentality associated with it.
Another participant highlighted a possible benefit of CD with a focus on efficiency:

"CD MGHT IMPLY HAVING A COMPUTER DO PART OF THE DESIGN/ ENGINEERING WORK FOR YOU" FOCUS GROUP PARTICIPANT 4

Some participants started to identify possible opportunities without being explicitly asked to do so. Some examples are metrics for sustainability, customization, inspiration, and optimization.

4.4 HABITS IN LEARNING NEW SKILLS

RQ2.1: WHAT ARE ID PROFESSIONALS' LEARNING HABITS WHEN LERNING A NEW SKILL?

During the focus group previously introduced, the participants were asked to add to a Miro board the most recent work-related skills learned and the source they used to learn them. This activity aimed to identify participants' preferences and learning habits and understand how future work on communicating CD could contribute to enriching a learning experience on CD.

The participants focused mainly on providing the source of information from which they learned a skill, sometimes without specifying the typology of information learned.

On the source side, the main categories are:

1. Social media, forums, and tutorials with a strong presence on youtube that almost all the participants cited.

3. Websites such as asknature.com (one participant)
4. University courses and papers

5. A big part of the Post-its refers to learning from peers/colleagues.

The main categories of skills learned:

1. Software (mainly CAD)
2. Other hard skills like machine learning basics or NLP
3. More abstract approaches like biomimicry.

The last group of post-its refers more to tactics to approach learning rather than a source.

- *Applying the skill in projects-use cases,*
- *find a reason to learn something new (motivation).*
- *Making learning fun and just experimenting.*

Books were only mentioned once, except for research papers that were mentioned multiple times; this unveils an inclination of the participants towards videos and websites. For this reason the last strategy in Chapter 5 takes the form of a digital guide.

Learning from colleagues/peers is an important point that emerges from the session; A digital guide on CD should have a section about colleagues who already have some CD expertise, particularly a group recently created at VanBerlo that focuses on Generative AI and Computational Design.
Applying knowledge in projects is another incentive to learn new skills.

4.5 COMPUTATIONAL DESIGN OPPORTUNITIES IN THE VANBERLO DESIGN PROCESS

RQ2.2: WHERE DO ID PROFESSIONALS SEE **OPPORTUNITIES** IN INCORPORATING CD INTO THEIR PROCESSES?

CD was introduced by presenting selected case studies during the interviews and the focus group. In the focus group, after this short presentation, participants were asked to write their ideas about CD opportunities on a Miro board with the phases of the VanBerlo design process (Figure 68).
This led to a discussion about CD and its opportunities at VanBerlo.

Participants exhibited a collective sense of enthusiasm and interest in the topic, recognizing the possibilities that CD could offer:

"THE OPPORTUNITIES ARE BOUNDLESS." FOCUS GROUP PARTICIPANT 1

"COULD WE EVEN USE IT TO DESIGN OUR PROCESS? ALSO, THERE WE HAVE BOUNDARIES AND PARAMETERS." FOCUS GROUP PARTICIPANT 3

In the **Explore** phase, participants thought of applications mainly related to understanding trends and extracting archetypes. The case of Alcaide-Marzal et al. (2020) on shape grammars -described in section 2.4.1 - was often taken as an example that "inverted" could bring to understanding typologies and visual languages of products. The case study started with a collection of archetypes to generate new shapes. The participants wondered if reverse engineering the method and extracting aesthetic vocabularies would be possible. The case study raised the same kind of thinking also during an interview:

"IT MIGHT BE INTERESTING TO UNDERSTAND THE MARKETS ZOOMING OUT AND UNDERSTANDING THE CATEGORY CUES. BECAUSE I THINK THIS IS MORE TO GENERATE STUFF. HOWEVER, WHAT IF YOU COULD DO IT THE OTHER WAY AROUND? FEEDING ENTRIES AND THEN RETURN TO THE CORE OF WHAT THE CATEGORY IS TRYING TO CONVEY." VANBERLO INTERVIEW 2

This goal could be hard to achieve using shape grammar. However, testing text-to-image generators for the same purpose could be interesting, considering that they are trained on massive datasets that could reflect general trends.
The board has a concentration of inputs in the "**ideate**" and in the "create" phases.
A participant mentioned the possibility of "using CD to quickly generate potential routes of a unique design intent."
While another one highlighted, that CD could lead to an increased definition of the design space.

For ideate, the main keywords are inspiration, exploration, idea generation, and happy accidents.
CD can aid the exploration of the design space by facilitating iterations. However, fully adopting CD tools is essential to continuously evaluate their impact on the process and the user's needs.

"IN THE IDEATION PHASE, THESE TOOLS CAN BE HELPFUL. UNDERSTANDING THE ESSENCE OF A DESIGN, ITS PURPOSE, AND ITS MESSAGE IS CRUCIAL. THESE TOOLS CAN TRULY ACCELERATE THE PROCESS BY FACILITATING ITERATIONS. THROUGH ITERATION, WE GAIN INSIGHTS INTO WHAT WORKS AND WHAT DOES NOT. DOES IT ADD VALUE OR NOT? OR DOES IT ADD TO THE EXPERIENCE OR NOT? OR DOES IT MAKE IT PRACTICAL OR NOT? YOU REALLY HAVE TO STRIVE FOR ERROR. THE MORE YOU FAIL, THE BETTER. BECAUSE THEN, YOU UNDERSTAND WHAT WORKS. SO I SEE THEM AS AN ENABLER OF CREATING MAYBE MULTIPLE NEW PERSPECTIVES. CREATING MORE PERSPECTIVES TO REFLECT, ITERATE AND DEVELOP. HOWEVER, AS THE DESIGNER OR CONDUCTOR, WE CHOOSE HOW AND WHEN TO UTILIZE THESE TOOLS. EVENTUALLY, WE SHOULD DISCERN THEIR VALUE BY EVALUATING THEIR IMPACT ON THE DESIGN PROCESS AND MEETING THE END USER'S NEEDS." VANBERLO INTERVIEW 1

Multiple participants made an analogy between generative tools and an additional project member, both from an exploration and a validation point of view.
"Have a sparing partner any time of day (or night)."

A participant mentioned that using tools like ChatGPT to co-ideate and refine design ideas would be interesting. While another one proposed the use of CD tools to scope a design brief better or test a design outcome.

"DEFINE, SCOPE, AND WRITE A BRIEF MAYBE. ENSURING WE HAVE EXCELLENT INGREDIENTS, A GOOD RECIPE, AND A GOOD OUTCOME. AFTER SETTING KPIS FOR A PRODUCT, TO SEE WHAT KIND OF SOLUTION FITS ALL KPIS - CAN YOU SET PRIORITIES FOR BOUNDARIES?" FOCUS GROUP PARTICIPANT 5

The tools could be used to overcome creative blocks and "see things beyond what has been created."

Text-to-image was often mentioned as a tool that could be useful to create storyboards and visualize ideas or subjective product features.

"WHAT IF WE COULD ASK MIDJOURNEY TO DESIGN A PERFUME BOTTLE THAT EXPRESSES THE IDEA OF PERFUME AND FRAGRANCE, FOR INSTANCE?" FOCUS GROUP PARTICIPANT 7

Text-to-image was also considered as a potential way to enable users and clients to visualize ideas during workshops.

"WHAT I SOMETIMES SEE IN WORKSHOPS IS THAT YOU HAVE PEOPLE JUST WRITING DOWN ON YOU HAVE SOME MAKING SOME NICE SKETCHES, AND THEN YOU WHEN YOU ARE GOING THROUGH EVERYTHING, YOU TEND TO GO MORE TOWARDS NICE SKETCHES THAN THE SMALL DESCRIPTIONS. USING TOOLS LIKE MIDJOURNEY MIGHT MAKE IT EASIER TO AVOID MISSING OUT ON SOME GOOD IDEAS BECAUSE THEY ARE E NOT VISUALLY REPRESENTED LIKE OTHERS. YOU NEED TO ENSURE THAT EVERYONE FEELS THEY CAN AND SHOULD CONTRIBUTE." VANBERLO INTERVIEW 2

Other tools, such as Grasshopper, were mentioned to explore a wide range of solutions rapidly and for form-finding approaches.

The main keywords in the "**create**" phase are optimization and sustainability.
Multiple users mentioned that the use of CD tools could be helpful to save time and **optimize** the design process, as well as to optimize and validate the design outcome. Using CD tools for sustainability purposes was a recurrent theme during the focus group:

"GATHER DATA TO PREDICT SUSTAINABILITY PERFORMANCES (SORT OF SIMULATION)." FOCUS GROUP PARTICIPANT 4

"OPTIMIZATION FOR SUSTAINABILITY PURPOSES?" FOCUS GROUP PARTICIPANT 9

Combining VanBerlo's expertise on **sustainability** with CD could bring interesting results, especially regarding using sustainability criteria as optimization goals. Sustainability and CD relationship is discussed in section 3.7.5.

ONE SIGNIFICANT AND NOVEL INPUT IS: "IN AN AGILE PROCESS, TO GIVE THE CLIENT THE TOOL TO DESIGN AND HAVE MORE CONTROL - EVEN NON-DESIGNERS WOULD BE ABLE TO IDEATE" FOCUS GROUP PARTICIPANT 4

This comment inspired the configurator case study developed during the graduation project and discussed in section 3.7.3.
Regarding the **validation** phase, it was proposed to use AI to test projects or build a virtual customer to judge a specific product.

"USING ASSOCIATION AND IMAGINARIUM TO TEST OUR DESIGNS (WHAT DOES THIS DESIGN EVOKE IN AN AI?)."
FOCUS GROUP PARTICIPANT 7
"AUTOMATION TO MAINTAIN PROCESS OVERVIEW AND FLAGGING CONTRADICTIONS." FOCUS GROUP PARTICIPANT 4
"MIGHT BE NICE TO LOOK INTO CONJOINT ANALYSIS. BUILDING A VIRTUAL CUSTOMER THAT 'JUDGES' YOUR PRODUCT BASED ON A SET OF GIVEN CRITERIA." FOCUS GROUP PARTICIPANT 8

Regarding domain-specific opportunities, within VanBerlo, an interviewee mentioned that there might be possibilities in every domain, considering the multifaceted nature of CD.

"I THINK YOU SHOULD BE ABLE TO USE IT FOR ANY DOMAIN BECAUSE THE CORE IDEA IS INPUTTING YOUR PROCESS. SO I DO NOT SEE A BIG DIFFERENCE IN TERMS OF POTENTIAL IN THE DIFFERENT DOMAINS." VANBERLO INTERVIEW 2

Conclusion

In conclusion, the introduction of Computational Design at VanBerlo sparked excitement, indicating vast opportunities for process improvement and potential applications. The participants identified many possibilities like trend understanding, extraction of archetypes, idea generation, design validation, geometry optimization, and sustainability as key areas where CD could be utilized. The opportunities for sustainability are promising ad for this reason were analyzed in depth and dicussed in section 3.7.5. One fascinating suggestion was client or user co-design through configurators, which could integrate user and client feedback more directly into the design process. This led to a small experiment presented in section 3.7.3. The multifaceted nature of CD sparked interest in industrial design professionals, suggesting opportunities across all domains and signifying a possible expansive future role for CD in the design process.

4.6 BARRIERS AND CHALLENGES IN CD ADOPTION

RQ 2.3: WHAT ARE THE MAIN **BARRIERS** TO IMPLEMENTING CD IN INDUSTRIAL DESIGN?

During the focus group, the possible barriers and challenges in adopting CD were brainstormed and clustered (Figure 69).
The first topic that arose during the focus group was related to creativity and the shift of the designer's role when adopting the CD approach.

"IS CD TAKING AWAY CREATIVITY AND PARTS OF THE PROCESS THAT DESIGNERS LIKE TO DO?" FOCUS GROUP PARTICIPANT 1

An interesting perspective that could answer this question come from an interviewee's reflection about the shift of the designer's role, which closely overlaps with the ideas found during the literature review:

"IT SEEMS LIKE THE DESIGNER'S ROLE SHIFTS MORE TOWARDS A CONDUCTOR ROLE THAT IT ALWAYS HAS BEEN BUT LET'S SAY LESS OF A CRAFTSMAN. AS A CONDUCTOR, YOU HAVE THE CHOICE TO UTILIZE THESE KINDS OF NEW OPPORTUNITIES, AND THEY ALSO BRING NEW FORMS OF CREATIVITY AND SOLUTIONS. SO, IT IS NOT CANNIBALIZING ON THE JOB ON OUR JOB AS DESIGNERS." VANBERLO INTERVIEW 1

The interviewee also highlights the need for a holistic approach, an integral part of the VanBerlo values, to effectively engage in a "conductor" role:

"SO A HOLISTIC APPROACH IS REQUIRED TO UNDERSTAND HOW IT (CD) BRINGS VALUE TO YOUR DESIGN PROCESS. BUT I THINK THE MORE WE UNDERSTAND THESE TOOLS. YEAH, THE EASIER IT BECOMES TO INTEGRATE THEM INTO OUR PROCESS." VANBERLO INTERVIEW 1

As was previously discussed in section 2.3, CD should be considered an addition to other tools, and the freedom to choose other tools remains. Arguably, the choice of tools depends on a balance between enjoying the creative activity to keep the motivation high and the efficiency and quality that the tools bring to the overall process. Some traditional creative activities, like sketching, are probably still without rivals, given the direct connection between ideas and signs without external filters. The discussion about CD and creativity is fascinating; however, it is difficult to find an objective and univocal answer that probably will be achieved with time when CD methods are further integrated into the design practice.
During the focus group, there were some concerns about "having no job anymore," but that was quickly addressed by a participant bringing up the opportunities identified in the previous section of the focus group, which could lead to plenty of business opportunities.
Some questions emerged about the legal aspect of generative tools.
"Legal aspect, are we the ones having the IP of something created in collab with GD tool?"
This concern is especially relevant to Generative AI, which uses large datasets.

Skills
The other major topic mentioned among the challenges in CD adoption is learning new skills.
An interesting remark from a participant was, "CD could change the thinking process to something more abstract." Focus group participant 6
This comment raises questions about the skills needed to adopt a CD approach discussed in section 3.4. The idea of system thinking needed to design the system and not only the artifact might be related to the change toward the more abstract process mentioned by the participant.

Knowledge about tools and methods.
During the focus group, a need for guidance in identifying and learning relevant tools emerged.

"FAST CHANGING TOOLS TO LEARN - HOW DO WE KNOW WHICH TOOL TO LEARN, IS IT GOING TO CHANGE TOO QUICKLY? DOES IT WORTH THE TIME INVESTMENT?" FOCUS GROUP PARTICIPANT 8

The **challenges** in this section can be divided into three clusters:

1. Learning the tool itself
In this cluster, participants' main concern is related to the learning curve.

"IT'S A VERY DIFFERENT SKILL THAT WE WILL NEED TO LEARN." FOCUS GROUP PARTICIPANT 9

"IT FEELS DIFFICULT TO TAKE THE FIRST STEP IN A NEW TOOL, NOT VERY APPROACHABLE." FOCUS GROUP PARTICIPANT 3

Some tools seem to require a different skill set from the one that the participants already have. This might be true for some hard skills like coding. However, as described in section 3.4, the CD experts mentioned as the most fundamental skills to engage with CD qualities that are already strongly present in the participant's background and that might only need to be adapted to a CD perspective: Curiosity, interest in technology, system, and critical thinking, and being process driven.

2. Knowledge and availability of the tool.
The participants mentioned that sometimes the quantity of the tools might be perceived as overwhelming, and it is difficult to find the relevant ones for the project or the personal profile.
"HOW TO FIND THE RIGHT FIT TO MY PROFILE, FIND WHAT TO USE WHEN AND FOR WHAT PURPOSE, IDENTIFYING THE RIGHT MOMENT WHEN TO IMPLEMENT." FOCUS GROUP PARTICIPANT 11

3. Value of the tools
"UNDERSTANDING WHAT VALUE SPECIFIC TOOLS CAN BRING (THIS NOW CONSTITUTES THE MAIN LIMITATION IN MY VIEW)." FOCUS GROUP PARTICIPANT 7
A crucial part of the project is guiding users toward the understanding of the benefits of CD and the choice of the right tool. The overarching benefits of CD for the design process are described in section 3.5. However, to be actionable in the future, this guidance must be structured with a direct link between the tool and the value created for the design process and in the final product, supported by references and case studies.

Another concern that emerged from the session is **time investment**:
• To learn the tools
• To justify the creation of a system in a project
• To define the right inputs

"IF I WANT TO DESIGN A SYSTEM IN THE CONTEXT OF A PROJECT, THE PROJECT WOULD NEED TO BE BIG ENOUGH TO JUSTIFY THE TIME INVESTED IN IT." FOCUS GROUP PARTICIPANT 4
An approach to solve this concern could be defining the value that a particular CD approach could bring to justify an estimated investment to explore it. At the same time, it should be considered that one of the main advantages all CD experts mentioned is time-saving and avoiding re-work.

Wrong output
The participants mentioned the possible problem of obtaining a wrong output if the input of the generative system is incorrect.
"Wrong input can give wrong output without realizing it. The computer makes it seem very trustworthy." Focus group participant 6
Understanding the limits and purpose of the tools is fundamental, and it should be part of every method presented in the digital guide. As emerged during a discussion about Topology Optimization, if a boundary condition is overlooked, the result might be fragile for load cases excluded from the initial definition of the system. For this reason, real-life testing and iterations should always be part of the process.
Another concern was that using CD could potentially lead to excluding other valid options.

"CAN GD REDUCE THE OPTIONS LOOKED UPON? IF IT GIVES THE SUM OF THE INPUTS, MAYBE WE ARE FUNNELING DOWN OPTIONS." FOCUS GROUP PARTICIPANT 8
As mentioned before, It is important to keep in mind that CD is an approach and a set of tools that should be an addition to the designer's toolkit, and of course, it is not the solution for every design problem. Section 3.7 on opportunities describes where CD could add more value to the industrial design practice. Furthermore, the "critical thinking" mentioned by experts should always be used to choose a specific tool for a design problem and to interpret the results obtained through CD systems carefully.

Hype
A participant suggested that a CD approach might be just a trend, asking what conditions should make it more implementable than before.
"GENERATIVE DESIGN HAS BEEN AROUND FOR A WHILE; WHAT MAKES A DIFFERENCE NOW THAT WILL MAKE IT MORE IMPLEMENTABLE? IS IT GONNA BE JUST HYPE?" FOCUS GROUP PARTICIPANT 8
While generative design tools are not entirely new, there is still a lack of literature on their application in ID (Mountstephens & Teo, 2020). This could indicate that the current times may not be mature enough for their full utilization. Software houses are augmenting their efforts in integrating CD systems into widely used tools and in training (Autodesk).
Arguably one of the main barriers to CD adoption is investing time in understanding the wideness of the topic and learning new skills. This needs a sound justification for the time investment. The software are becoming more accessible and 3D printing is enabling new ways of manufacturing complex geometry. The bottleneck for adoption might be of cultural nature: adopting CD tools requires further research, changes in mindset, and acquiring new skills. This could be a long-run investment in terms of time and money.

Conclusions
In conclusion, the focus group discussions shed light on the perceived challenges and barriers to adopting CD in industrial design. Key topics revolved around the shifting role of designers and the balance between creativity and efficiency that CD offers.
Notably, the learning curve associated with mastering new tools, keeping pace with rapidly evolving technologies, and understanding the intrinsic value of these tools emerged as significant concerns. Further, the fear of potential missteps in CD processes - resulting in flawed outputs - highlighted the importance of critical thinking and thorough system understanding.
Despite these challenges, the evolution of generative design tools signals promising opportunities for industrial design. The transformation may be seen as a long-term investment, necessitating a cultural shift, mindset change, and skill acquisition. However, with CD's potential to push design boundaries, this evolution appears to be a leap worth taking for the future of design.

4.7 CONCLUSIONS ON INDUSTRIAL DESIGN PROFESSIONALS' PERSPECTIVES ON COMPUTATIONAL DESIGN

This chapter aimed to address the following research inquiries:

RQ 2: WHAT IS THEIR **BASE KNOWLEDGE** ABOUT CD?
RQ 2.1: WHAT ARE THEIR **LEARNING HABITS** WHEN ACQUIRING A NEW SKILL?
RQ 2.2: WHERE DO THEY SEE **OPPORTUNITIES** IN INCORPORATING CD INTO THEIR PROCESSES?
RQ 2.3: WHAT ARE THE MAIN **BARRIERS** TO IMPLEMENTING CD IN INDUSTRIAL DESIGN?

The initial step of the research aimed to understand VanBerlo's design approach to provide a clearer context for the research. The design process at VanBerlo hinges on the flexibility provided by the diverse expertise within the studio and on research, which serves to comprehend the underlying motivations behind client queries. Misconceptions exist regarding computational design, as some practitioners link it solely to certain software programs. Regardless, participants expressed substantial interest in the subject, and several opportunities were recognized in the application of Computational design (CD) in industrial design. These include trend understanding, extraction of archetypes, idea generation, design validation, geometry optimization, and sustainability.
Among the prominent barriers to adopting a CD approach in industrial design is the time investment, which must be justified by the value that CD methodologies can bring to a project. Another challenge lies in navigating the array of tools available in the CD landscape; a proposed solution to this issue is discussed in 5.5.4.

VanBerlo part of Accenture Ypenburg office image from VanBerlo Agency

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FUTURE DEVELOPMENTS OF THE RESEARCH: RECOMMENDATIONS OF INITIAL STRATEGIES TO EXPLORE CD AND SUPPORT ITS USE IN ID

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5.1 INTRODUCTION

Two primary paths of investigation were pursued during this project: one focused on Computational Design (CD) and the other on outlining the industrial design professionals' perspective toward CD. The findings from these inquiries are discussed in the preceding chapters. This section proposes a way for these two research areas to converge and evolve into something beneficial to encourage the application of CD in industrial design.

The artifacts presented in this section aim to present some strategies to quickly communicate and ignite interest in CD's potential within the realm of industrial design, ultimately inspiring a deeper exploration and experimentation with the topic.

Throughout the project, several efforts were made to illustrate how knowledge about CD could be communicated and integrated into everyday industrial design practices. These efforts ran concurrently with the research, resulting in four key development points. The first two were developed during the investigation into CD: a diagram overlaying the main elements identified within CD on the double diamond model and an interactive list of case studies concerning CD applications in industrial design. The third outcome emerged after the experts' interview analysis, which attempted to visualize the complexity of CD through a network structure. The fourth and final work aimed at communicating CD to professionals followed a focus group at VanBerlo. This led to the development of use cases, a user journey, and a navigation structure to create an initial proposal for a digital guide on CD in ID. This could potentially serve as a starting point for this thesis's future development into an actionable digital guide.

It's important to note that these development points have not been thoroughly tested. The CD+DP diagram was discussed with CD experts and professionals at VanBerlo during interviews, and the CD network map was discussed during a focus group with VanBerlo professionals. The concept for the digital guide was created in a sprint towards the end of the project and has not received expert feedback nor tested with potential uses. Thus, it is a proposed starting point for future developments.

5.2 A DIAGRAM INTERSECTING CD ELEMENTS AND DESIGN PROCESS

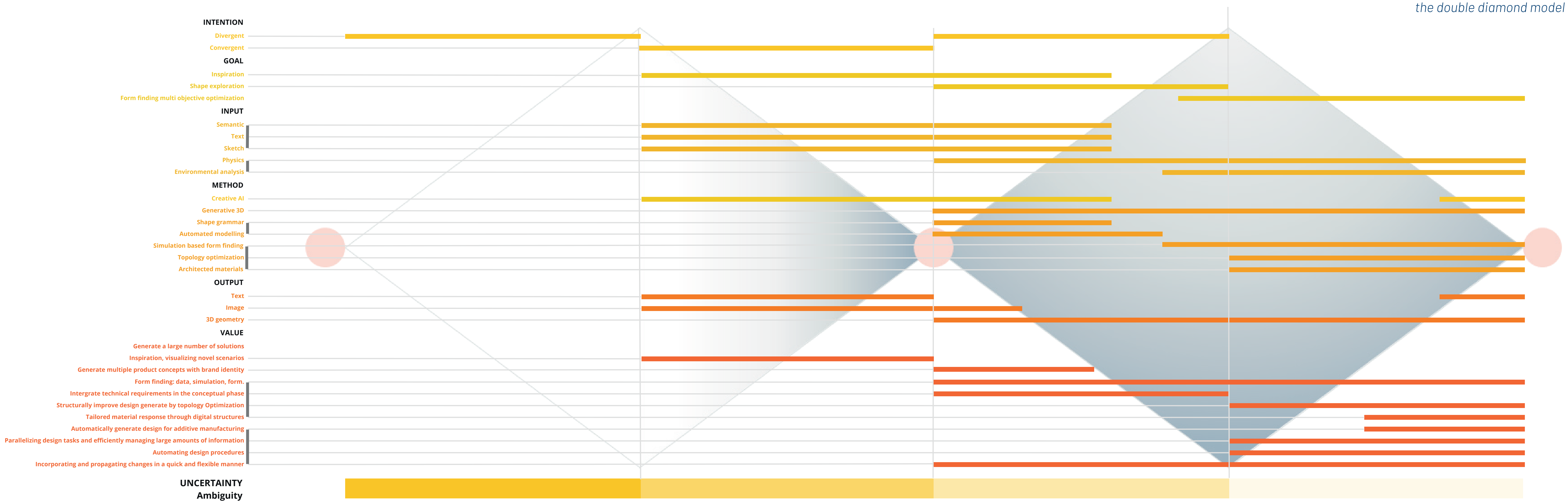
RQ 3: HOW TO VISUALIZE CD POSSIBILITIES AND THEIR INTERSECTION WITH THE DESIGN PROCESS?

Introduction
This thesis section introduces a diagram developed based on extensive literature research. The diagram, represented in Figure 72, aims to provide an overview of the key elements characterizing the computational design field, plotted against the Double Diamond Model (Design Council, 2023), a widely accepted model representing the design process.

The Double Diamond and CD elements
For readers unfamiliar with the double diamond model, it delineates the design process into four key phases: Discover, Define, Develop, and Deliver. Each phase of the design process is mapped out on the horizontal axis of the diagram in Figure 72.
The vertical axis represents the key generative methods encountered during the research, along with their associated inputs and outputs and the benefits derived from these methods. These generative methods primarily encompass two main groups: generative AI, typically associated with the earlier stages of the design process, and generative 3D, which usually becomes significant in the advanced stages of the process.
The intensifying blue gradient towards the right side of the diagram illustrates that most of the methods discovered during the research seem to find greater application in the final three stages of the double diamond. The horizontal lines denote areas where methods and related benefits might have potential within the design process.

Relationship between Input and Output
The relationship between input and output in generative methods is essential to this diagram. One spectrum of this relationship includes text and semantics, which tend to allow more interpretive space. On the other hand, there are environmental constraints and geometry, which necessitate well-defined facts and figures.
It is crucial to note the interplay between these factors and the level of uncertainty in the design process. For instance, generative AI methods seem to be more adept at handling greater uncertainty levels, contrasting with 3D generative methods, which might be more suited to meet specific technical requirements in product development.

Figure 72: CD elements plotted on the double diamond model



Value section and Expert Feedback

The value section at the bottom of the vertical axis is a significant aspect of the diagram, which illustrates the benefits or value derived from the generative methods. These are grouped into three categories: benefits tied to inspiration and aesthetics, advantages associated with optimizing objective requirements, and benefits related to improving efficiency and speed during the design process.

The feedback from computational design expert Onur Yüce Gün provided an important insight regarding this aspect. Gün emphasized that generating a wide array of solutions is not necessarily a desirable quality due to the potential increase in noise during the convergence process.

Classification and Future Considerations

In addition to the main categories that have a title, a change in text color and gray vertical lines denotes subgroups. Within the methods, there are two main groups: generative AI, typically associated with the earlier stages of the design process, and generative 3D, which usually plays a more significant role in the more advanced stages of the process.

Gray vertical lines delineate the other three categories. These categories represent benefits tied to inspiration and aesthetics, advantages associated with optimizing objective requirements, and a final category encompassing benefits related to improving efficiency and speed during the design process.

The elements characterizing the groups are not set in stone and are just an initial proposal of categorization from the author. This classification, however, may present some ambiguity, as pointed out by Gün. This ambiguity may be attributed to the inherent complexity of computational design methodologies and the overlapping boundaries between various generative methods.

"WHILE I APPRECIATE ITS INTERPRETIVE NATURE, THE CLASSIFICATION SEEMS A BIT UNCLEAR. THE 'VALUE' SEGMENT MIGHT LEAN MORE TOWARDS QUALITATIVE ASPECTS. I VALUE THIS CHART, BUT I BELIEVE IT HAS THE POTENTIAL TO GO FURTHER, LIKE SUGGESTING A ROADMAP FOR A QUALITY-CENTRIC COMPUTATIONAL DESIGN APPROACH." CD EXPERT INTERVIEW 3: ONUR YÜCE GÜN, CD DIRECTOR AT NEW BALANCE

Evan Greenberg of ModeLab suggested expanding on certain categories, such as procedural modeling, and exploring how computational design could increase efficiency in the process.

"I THINK IT MAKES SENSE, AND IT IS VERY COOL. HOWEVER, YOU COULD EXPAND ON THE CATEGORIES, FOR INSTANCE, ADDING PROCEDURAL MODELING AND EXPANDING ON THE INCREASED EFFICIENCY THAT CD COULD BRING."
CD EXPERT INTERVIEW 1: EVAN GREENBERG, HEAD OF EMERGENT TECHNOLOGIES AT MODELAB

Conclusions

The primary aim of this depiction is to serve as a tool for quickly identifying a generative method and discerning the potential contribution it can offer at a given phase of the design process. Another benefit of the visualization is that it offers an overview of CD in industrial design, drawing attention to the regions where most generative methods can be applied in the design process. Despite potential ambiguities, this diagram can serve as a foundation for further exploration into a more nuanced, quality-driven computational design process.

5.3 AN INTERACTIVE LIST OF CD CASE STUDIES IN ID

RQ 3.1: HOW TO GIVE AN IMMEDIATE SENSE OF CD POSSIBILITIES?

Enriching the Overview with Case Studies
In the previous section, a diagram was introduced that provides a general overview of computational design (CD) in industrial design (ID). While the diagram serves as a high-level introduction to CD, it may be beneficial to augment it with tangible examples that showcase the practical applications of CD strategies.
Incorporating case studies that feature industrial products designed using computational techniques may be valuable to achieve this. The selection of case studies as the central element of the work presented in this section derives from the hypothesis that they can aid users in understanding the core concepts of CD and in visualizing the real-world applications of these concepts.
As Onur Yüce Gün, during an interview, pointed out,

"THIS IS PROMISING. VIEWING THIS, I BELIEVE IT PROVIDES A RELATABLE INSIGHT FOR MANY. WHILE THERE'S ROOM FOR ENHANCEMENT, MERELY PRESENTING THIS OVERVIEW AIDS IN UNDERSTANDING THE SCOPE OF CD'S APPLICATIONS." - ONUR YÜCE GÜN, DIRECTOR OF CD AT NEW BALANCE.

Creating an Interactive List of Case Studies
An interactive list of case studies (Figure 73) was developed using Microsoft Lists to facilitate user interaction and continued updating. This easily updatable database includes filters based on categories from the vertical axis of the diagram presented in section 5.2. Users can thus quickly navigate through the case studies based on their specific interests or project requirements.
This tool can be handy during the preliminary phase of a project, where designers and project managers can explore industry case studies demonstrating how computational methods have been applied in industrial product design.

CD expert 2 during the interview appreciated the practicality of this tool, saying,
"WHAT YOU ARE BUILDING IS VERY SIMILAR TO WHAT WE ARE TRYING TO SHOW TO CLIENTS TO SAY, 'THIS IS WHAT IS POSSIBLE; THIS IS WHAT YOU CAN DO.' WHAT YOU BUILT MAKES SENSE, ESPECIALLY THE COMBINATION BETWEEN FILTERS AND CASE STUDIES." CD EXPERT INTERVIEW 2

Feedback from VanBerlo professionals
During the interviews with VanBerlo professionals introduced in Chapter 4, feedback was requested regarding the interactive list of case studies.
Overall, using case studies as a unit of the list was perceived as a positive approach. Case studies effectively demonstrate the benefits of a product or service in a tangible and relatable way. However, one interviewee recommended starting with an overview of available tools to determine their suitability for different needs.

"THE CASE STUDIES ARE REALLY GOOD FOR SUPPORTING THE IDEA OF USING CD. HOWEVER, IF PEOPLE ARE ALREADY CONVINCED, THEY WOULD RATHER SELECT AN AVAILABLE TOOL AND GET STARTED. THIS IS SOMETHING THAT WE ALSO MIGHT USE TO HAVE A BETTER LOOK AT IT IN TERMS OF INVESTMENT." VANBERLO INTERVIEW 1
"I THINK DEFINING WHICH TOOLS CAN BE USED FOR WHAT PURPOSES IS IMPORTANT. FROM A PRACTICAL STANDPOINT, WE SHOULD ALSO CONSIDER THE TOOLS' QUALITIES. DIFFERENT TOOLS MAY PERFORM SIMILAR FUNCTIONS BUT AT VARYING LEVELS OF QUALITY." VANBERLO INTERVIEW 2

These comments suggest that it would be helpful to include pricing information for various tools in the digital guide and their availability and effectiveness for different tasks.
Section 3.6 contains an analysis and comparison of CD tools for 3D modeling.
Flexibility emerges as an essential requirement when considering a tool.
An interviewee mentioned that there should be at least one tool that can be used at any moment in the process.

"I THINK THERE SHOULD BE A TOOL THAT YOU CAN USE AT ANY MOMENT." VANBERLO INTERVIEW 2

Such a tool could be considered Grasshopper as discussed in section 3.6.
A participant suggested that It could be helpful to identify areas where there is no existing solution, as this can inform the development process.

"I AM WONDERING WHETHER IT WOULD MAKE SENSE ALSO TO IDENTIFY WHERE YOU DO NOT HAVE A SOLUTION... THAT COULD ALSO BE INTERESTING TO KEEP AN EYE OUT ON THOSE THINGS." VANBERLO INTERVIEW 1

Instead of just being a database, users suggest making the tool more tangible and usable in projects to ensure sustained engagement.

"THE IDEA SHOULD BE TO ENSURE THAT PEOPLE KNOW THIS EXISTS SO THEY KNOW WHO TO CONTACT, WHAT IT DOES, ETC. BECAUSE IF YOU KNOW WHOM TO CONTACT, THEN YOU CAN LEARN MORE ABOUT IT. IF IT IS JUST A DATABASE FOR OBTAINING MORE INFORMATION ABOUT THE TOPIC, PEOPLE WILL EVENTUALLY FORGET IT. HOWEVER, IF IT IS SOMETHING TANGIBLE THAT YOU CAN USE IN YOUR PROJECT, THEN YOU ARE MORE LIKELY TO REVISIT IT." VANBERLO INTERVIEW 2

It is essential to make the interactive list or other future guides applicable to projects and direct users to experts who can provide insights on specific approaches.

"SO, WHICH TOOLS CAN BE USED FOR WHAT? AND FROM A PRACTICAL POINT OF VIEW, WHAT IS THE QUALITY OF THE TOOLS THEMSELVES? BECAUSE I CAN IMAGINE THAT DIFFERENT TOOLS PERFORM SIMILAR FUNCTIONS BUT AT DIFFERENT LEVELS OF QUALITY." VANBERLO INTERVIEW 2

Another interviewee suggested adding more parameters related to VanBerlo, such as domains or capabilities, to help users find relevant solutions for their needs. Additionally, finding specific use cases in current VanBerlo practices is suggested as a strategy to prioritize among various tools.

"I THINK IF YOU LOOK AT THE DIFFERENT DOMAINS, THAT'S THE EASIEST WAY TO DIFFERENTIATE. AND, OF COURSE, DEPENDING ON THE TYPE OF PROJECT, YOU HAVE STRATEGIST DESIGNERS AND ENGINEERS INVOLVED." VANBERLO INTERVIEW 1

"UNDERSTANDING WHERE WE ARE NOW AND WHAT WE CAN DO IN THE FUTURE MIGHT BE FUNDAMENTAL TO IDENTIFYING CD POTENTIAL. I SEE THE POTENTIAL OF USING AI OR COMPUTATIONAL DESIGN IN THE PRACTICE. THIS COULD ALSO HELP YOU PRIORITIZE WHICH TOOL TO EXAMINE IN DEPTH." VANBERLO INTERVIEW 1

In conclusion, the interviewee appreciated the interactivity of the list and mentioned that they would use it. The use of case studies was also appreciated; however, an interviewee suggested having tools as the central unit of the list. Specific software is preferred over generative methods, which is understandable considering that the latter is abstract and theoretical. However, the decision to focus on generative methods rather than software was driven by the goal of increasing the longevity of the database, as software options may change more rapidly. Another essential suggestion is to make the tool as applicable as possible in projects to encourage continued use.

All the suggestions steered the projects toward a more pragmatic approach that led to the definition of the cases "solve" and "plan" described in section 5.5.4.

Supplementing the general overview of computational design in industrial design with case studies provides a practical dimension that may help users more effectively understand and apply CD principles. By offering an interactive and continuously updatable tool, the aim is to foster a dynamic and user-driven learning resource for CD in ID.

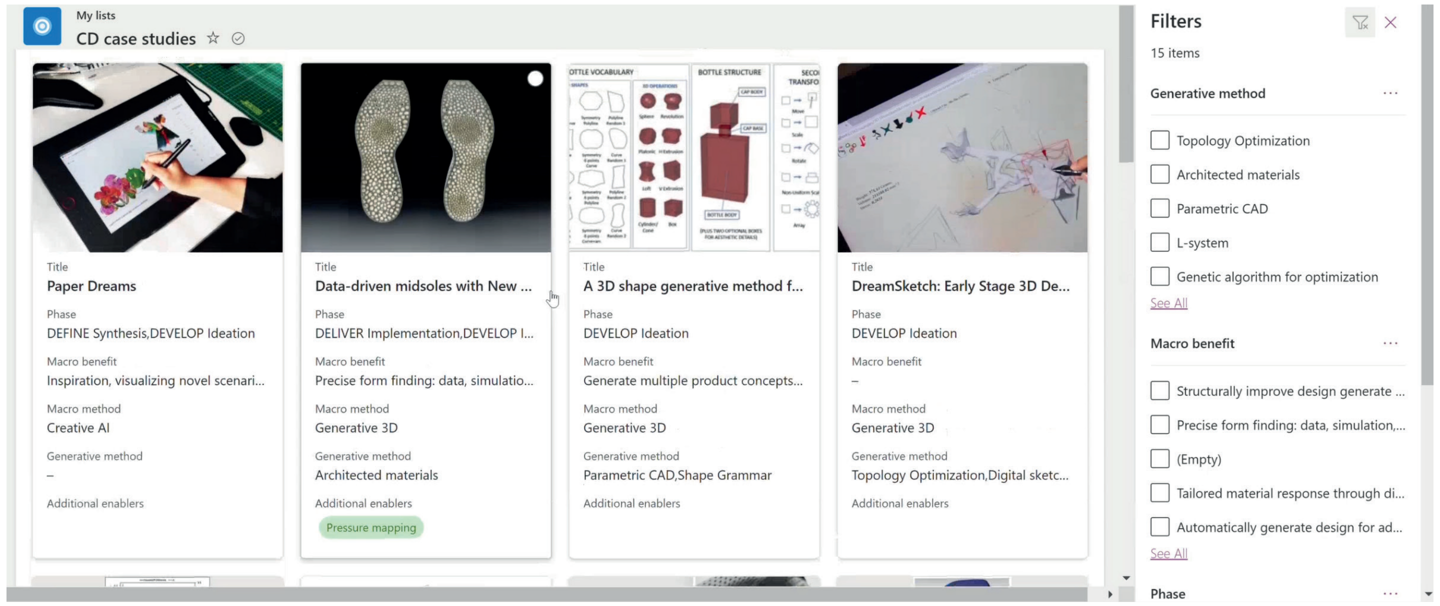


Figure 73: Screenshot of the interactive list of case studies

5.4 A NETWORK MAP OF CD CONCEPTS

RQ 3.3: HOW CAN CD POSSIBILITIES BE CATEGORIZED AND VISUALIZED, GIVING A SENSE OF THE ENTIRETY OF CD?

During conversations with industrial design professionals, discussed in chapter 4, it has emerged that there are some misunderstandings about Computational Design (CD), often confused with a specific software or application such as topology optimization. This report tackles these misconceptions in two ways. Firstly, an in-depth explanation of computational design and its sub-categories is provided in Chapter 2. Secondly, this section introduces a network map (Figure 74) to illustrate that CD is more than just software by showing the complex relationships among the key concepts that comprise it.
This map aims to provide an overview of the topic and its relationships, clearly referencing the links between theory, methods, tools, and the benefits they bring to the design process. Ideally, this map could be adapted to become an interactive version of the second chapter of this thesis. It also seeks to show the complex connections and ideas that make up the subject matter.

This map includes different levels. The first level shows the main topics related to CD, represented by nodes, and their connections, represented by edges. Each node includes sub-categories, which are also connected.

The first level of the map (Figure 74) will be described below.
The process node branches out into two macro-categories; the first concerns the framework from a theoretical standpoint, therefore, in general, how CD influences the design process from a theoretical point of view. The second cluster within the process concerns methods and tools that characterize a CD approach.
These methods and tools enable general benefits that characterize a computational approach to design: Design automation, Hyper control of geometry (lattices, field modeling, and more), and optimization in its various forms both for objective goals, usually the most widespread ones, and for subjective goals if there is the possibility to define them computationally.
These benefits of CD lead to two other categories. The first covers the benefits to the design process, which can be divided into efficiency, quality, or exploration, as explained in the section dealing with the benefits of CD in the design process. The second covers the benefits and features linked to the product, for example, in terms of sustainability, user experience, or value to the client business.
The diagram closes with a cluster concerning the effects that the CD has on the design outcome, which can be so radical as to change its typology from simple geometry to a configurator.

Feedback on the network map from VanBerlo professionals
The last phase of the focus group described in Chapter 4 was used to gain feedback during the focus group with industrial design professionals introduced in section 4.1.2 for the network map that was envisioned as the starting point for an interactive tool to explore CD. The process that led to using a network representation was explained, along with the reasoning behind it. The prototype was briefly displayed following the 5 seconds test method (Gronier, 2016). Subsequently, the participants used Miro to answer four questions:

1. Which message does this representation convey?
In general, the prototype managed to convey the idea of interconnectivity and vastness of CD:

"LOTS OF RESOURCES TO EXPLORE; I CAN TRUST I WILL FIND SOMETHING I CAN USE." PARTICIPANT 1
"LINK BETWEEN COMPLEX LANDSCAPE, A PLACE WHERE TO START" FOCUS GROUP PARTICIPANT 3

Trying to convey the concept of complexity and interconnectivity of the topic can have its disadvantages:

"SEEMS QUITE ABSTRACT TO ME. NOT SURE HOW TO USE IT." FOCUS GROUP PARTICIPANT 2
"NEED TIME TO EXPLORE." FOCUS GROUP PARTICIPANT 1

The reception of the message about complexity and interconnectivity went through. However, the representation might be disorienting and impractical if the goal is to find specific information quickly.
The word "trust" was a positive surprise and an inspiration: any future work must inspire trust to overcome and justify the time investment in exploring CD.
Another participant wrote:

"INTERCONNECTIVITY, SYSTEM THINKING IS NECESSARY." FOCUS GROUP PARTICIPANT 5

The representation conveyed the need for one of the primary skills mentioned by CD experts: system thinking. System thinking is discussed in sections 2.3.1 and 3.4.

2. How would you use this tool?
Explore, filter, broadening the scope. These keywords stand out regarding the possibilities of using the tool.

"TO EXPLORE OPPORTUNITIES FOR CD AND FILTER BASED ON MY NEEDS." FOCUS GROUP PARTICIPANT 4

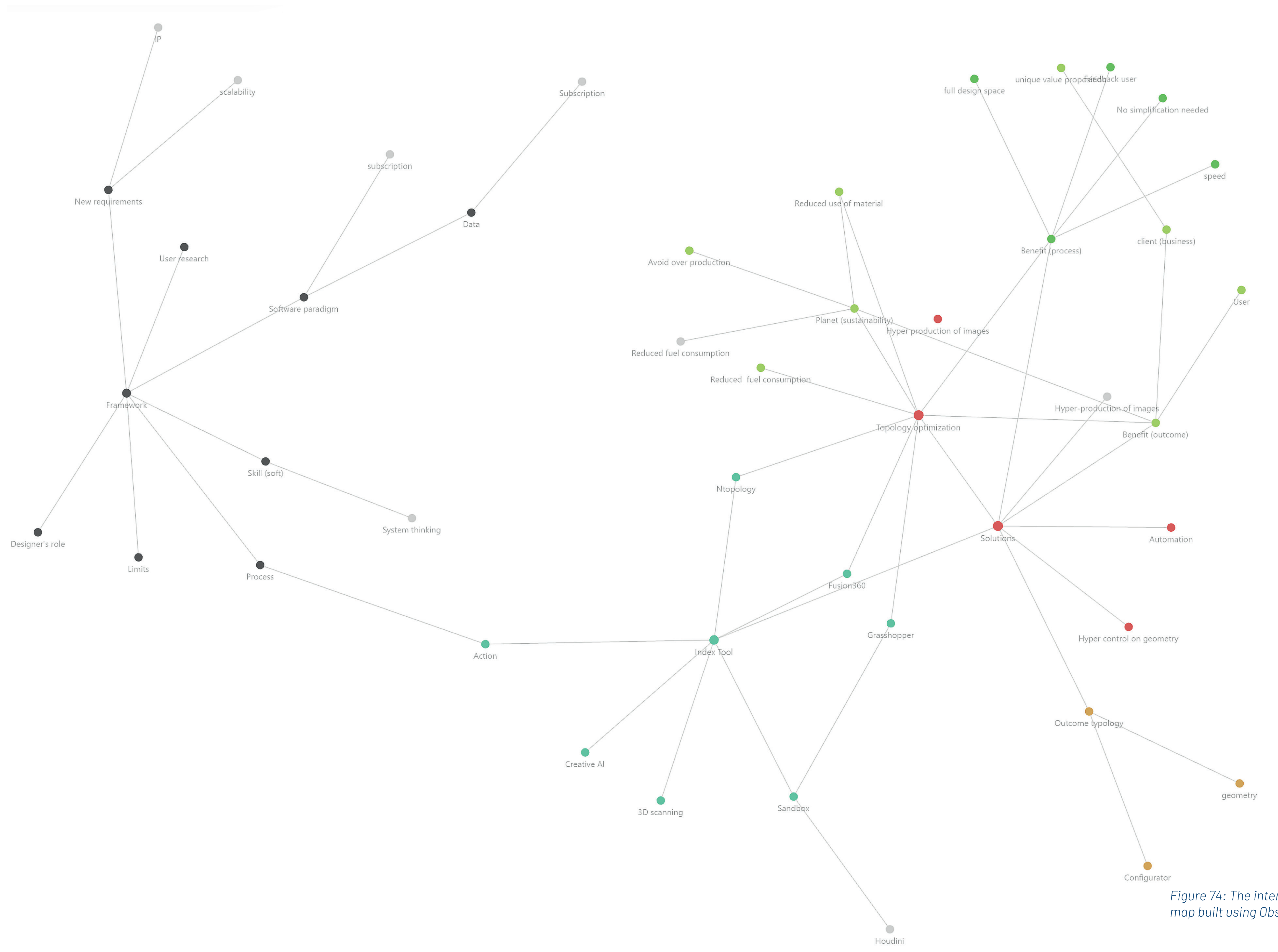


Figure 74: The interactive network map built using Obsidian

This sentence highlights the need to implement filters based on users' needs.

"AS THE TOOLBOX, GOING THERE WITH A SPECIFIC CHALLENGE, SEARCHING FOR A TOOL TO ANSWER THIS QUESTION." FOCUS GROUP PARTICIPANT 8

This comment shows the need to satisfy a pragmatic approach through in guide on CD and led to the creation of the use case "Solve" described in section 5.5.4.
The perspective about using the map as a planning tool led to the creation of the "Plan" use case described in section 5.5.4:

"AS A PLANNING TOOL, SO I CAN EXPLORE WHAT TOOLS I CAN USE DURING MY PROCESS." FOCUS GROUP PARTICIPANT 4

For the state in which the network map was presented, the aspects inviting exploration and scope broadening are prominent compared to the ones about planning and filtering.
A participant suggested implementing an archive feature in the design to keep track of the relevant tools for an individual or a team.

"MAYBE AS AN ARCHIVE OF TOOLS THAT I HAVE INTERACTED WITH?" FOCUS GROUP PARTICIPANT 8

In the case of future development of a digital guide, this aspect needs special attention from an implementation point of view - it brings another level of interaction, allowing the user to input content- if the tools are not already part of the guide. From a categorization point of view, to function as an archive, the digital guide should withstand input from the user.
The number of users might also influence the implementation of an archive function, and it would differ if the archive is for an individual, for the studio, or open to the public. A personal archive would be the easiest to implement and beneficial if someone wants to keep track of their tools. The second and third options leverage "contamination" from more people.

"MAYBE WITH MULTIPLE USERS UPDATING IT, YOU CAN FIND NOT A TOOL THAT YOU ASKED FOR BUT THE TOOL YOU NEEDED." FOCUS GROUP PARTICIPANT 10

3. What key features would you like to see in the guide?
In this section, a couple of inputs suggest features such as having topic-related suggestions but also to personalized needs e.g., sustainability

"A PRIORITIZATION OF SUGGESTED OPPORTUNITIES, WHICH BEST FIT MY NEEDS (SUSTAINABILITY)" FOCUS GROUP PARTICIPANT 9

A participant mentioned the desire to have a collection of relevant resources linked to tools and methods and know "the inputs needed for the expected output."
Therefore, Inputs-outputs to obtain a specific result and advantages-limitations and resources must be specified when presenting a CD strategy.

"HAVING TOOLS LINKED TO TASKS (FOR EXAMPLE RENDERING:...)." FOCUS GROUP PARTICIPANT 10

Another suggestion is adding experts to talk with in addition to "static" resources.
Multiple participants mentioned needing "Filters to cope with the topic's vastness."

4. What is the information you would like the encounter first?
An introduction/guide to the tool is the feature most requested:

"WHAT IS THE GOAL OF THE TOOL? WHAT DO I GET FROM IT?" FOCUS GROUP PARTICIPANT 8

This feature might be implemented in two forms: a text introduction to the digital guide and a guided tour of its functionalities.
Filters were mentioned again and are, without any doubt, an essential requirement to enable the actionable aspect of the guide.

"HAVE RATINGS/REVIEWS FROM USERS, SO I CAN UNDERSTAND HOW GOOD OR ACCURATE THE RESOURCE IS." FOCUS GROUP PARTICIPANT 9

Reviews can be interesting but can be challenging to implement.
A state-of-the-art view with the latest news suggested by a participant could be helpful but also challenging to maintain and review.

The feedback provided was crucial in shaping use cases and requirements, for the last proposal presented in the next section. Overall, it was determined that the current network map could raise awareness about CD, but it needs a more practical application to projects. Therefore, the use cases "Solve" and "Plan" were developed and will be described in the following section.

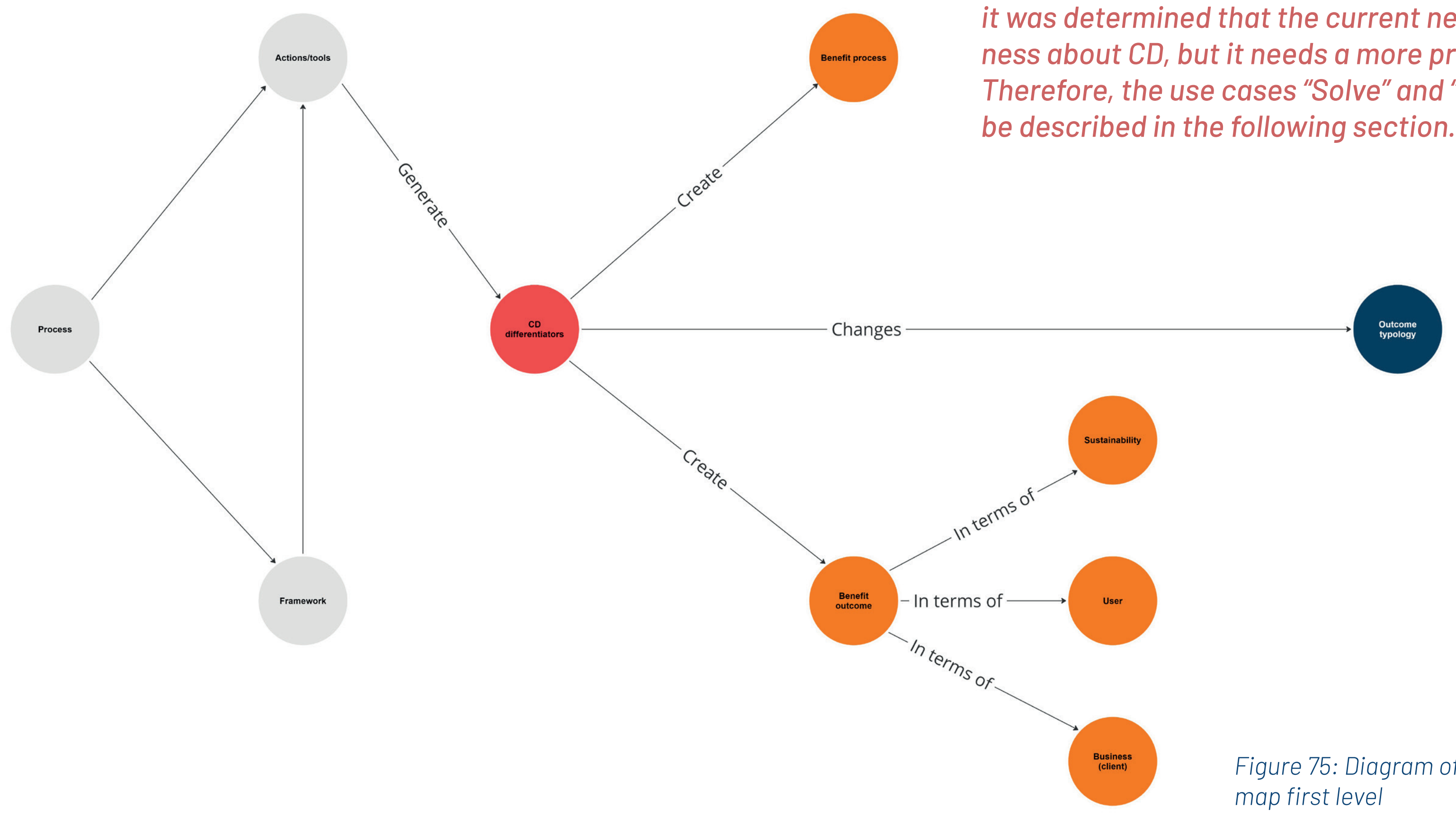


Figure 75: Diagram of the network map first level

5.5 A DIGITAL GUIDE CONCEPT TO EXPLORE CD IN ID

RQ 3.3: WHAT TYPE OF TOOL COULD BE USED IN THE FUTURE TO BETTER UNDERSTAND AND UTILIZE CD IN ID?

In the future, it would be ideal to develop a digital version of this thesis, collecting the theoretical part presented previously and taking advantage of the interactions during the project with professionals to deepen the more practical aspect of Computational Design (CD) in Industrial Design (ID). An ideal scenario would lead to the digitization of the topics covered in the thesis and the creation of a digital guide that can collect this information and be enriched by external users to keep pace with the world of the CD, which is in constant development. In order to give a hint on the potential development of this work, preliminary steps have been developed towards the creation of a digital guide on CD in ID, targeted to professionals in the sector. Considering that the work was carried out in continuous collaboration and within the VanBerlo design agency, the hypothetical user of this guide will be considered an employee of the agency, which in a broader sense, can represent an exponent of the industrial design community.

5.5.1 PERSONA

To more clearly visualize the hypothetical user of this digital guide, a Persona (Figure 76) has been created. This Persona aims to integrate and represent the background, goals, and possible pain points of a hypothetical user who approaches CD discovery in a professional context, in this case, an industrial designer in VanBerlo. The primary source of information used to create this Persona is the research on the CD professional's perspective described in Chapter 4.

Figure 76: Persona representing an hypothetical user for the digital guide on CD (Image created with Midjourney)

Name: Ava

Age: 32

Occupation: Product Designer at VanBerlo

Background: Ava is a product designer with years of **experience** in designing physical products. She has worked with various clients in the consumer goods industry and has won several design awards for her work. Ava is **passionate** about **sustainability** and believes that designers have a crucial role to play in creating products that have a **positive impact** on the environment and society. Ava is always **eager to learn** and stay up-to-date with the latest trends and advancements in the design world.

Goals: Ava is **interested** in exploring **new technologies** that can be incorporated into the design process to **create** sustainable products, **optimize** the process and **unveil** new design opportunities. She wants to learn about new tools and design strategies that can positevely change the impact of the products her agency designs and improve their quality. However, as a **busy professional**, Ava has **limited time** to invest in learning new topics.

Pain points: Ava is often **overwhelmed** by the amount of information available online and **struggles to find reliable sources of information**. She finds it challenging to keep up with the latest developments in design and new technologies due to her demanding job and other personal commitments. At the same time she feels that the **learning curve** of new tools could be too steep and the value not clear enough to justify the time investment. Ava also wants to ensure that any new tools or technologies she adopts align with her **values.**

Personality: Ava is a passionate individual who takes her work seriously. She is an open, curious and busy person. She is detail-oriented, meticulous in her work, and values collaboration and communication with her team and clients. Ava is committed to creating products that are sustainable and have a positive impact on society, while possibly having fun with her greatest passion: design.

Figure 77: Product journey for the digital guide on CD prototype

5.5.2 PRODUCT JOURNEY

The second artifact that aims to outline the possible use of a digital guide on the CD is a product journey (Figure 77). This product journey was created to identify the possible touchpoints between the user and the digital guide and visualize how these interactions can influence the final experience. At the same time, the journey identifies the guide's goals in the different phases of use and the necessary design actions to reach them.
It may be particularly relevant to take a look at how the goals of the guide change during different stages of use.
The first opening phase of the guide is essential. In this phase, the user will decide if the guide is worth the time investment. Therefore, the tool must inspire trust and encourage users to continue browsing. Then the user will start searching for a specific piece of information or simply explore the guide. In this phase, the tool should reduce the time for getting to a particular solution while promoting CD exploration. Once the user has landed on a specific page, the page must communicate its content clearly and accurately, being both functional and inspiring. At some point, the guide could refer to external sources. It is essential that the user, after consulting the guide and any external sources, feels like having a starting point to apply the knowledge in an actual project and is interested in reconsulting the guide to learn more. For the knowledge to be applicable during projects, the information in the guide must be easy to retrieve. In an ideal scenario, the users should be able to save the pages that interest them most, thus creating an accessible personal archive to visit multiple times.
Furthermore, the information must be easy to share with colleagues and customers. If the usage phase has been successful, the guide should create a sense of achievement and growth and the user should be encouraged to share his experience with other colleagues so that they start using the guide, which ideally should enable more possible people to have a positive impact through the CD. The KPIs and the relative points of view of the user relating to the goals described above can be explored in the product journey in Figure 77.

5.5.3 REQUIREMENTS

A set of requirements and potential tests have been defined for the hypothetical development of the digital guide in the future.

Accuracy
Does the design cover the most critical implication of CD in the industrial design practice?
Test: Ask experts for feedback.
Reliability:
The information in the design should always cite sources or be verifiable. Where this is impossible, the lack of references should be made clear and explicit and explain the process behind eventual assumptions.
Discoverability
Can information be accessed easily? Can the users find the solution to their problem with the minimum time investment?
The tagging system should be strictly linked to the user's problem, interests, professional traits, and all the elements that can make the computational design solutions discoverable without knowledge prerequisites about computational design.
Test: Ask the users to search for a solution for a design problem they could have. Did they find the solution? How long did it take? Is a reasonable amount of time within a project? (Ask project managers)
Understandability
Does the design help the users familiarize themselves with the topic?
No jargon, straight-to-the-point information, it should be accessible, and the users should not spend time searching words meaning outside the design.
Actionability
Is the information applicable to a design project?
Test: ask seniors. Find similar case studies. Do they feel ready to apply CD strategies in their work?
Engagement
Is the guide engaging? Does it spark interest in the topic?
Test: Are users willing to invest time in exploring the design? Would users recommend the design to colleagues?
Does the design increase awareness about CD and its potential?
Test: Ask users their opinion about how CD could influence their work.

5.5.4 THE DIGITAL GUIDE PROTOTYPE

Creating a toolkit or guide on CD was one of the project's initial goals. In any case, a precondition for creating it was to thoroughly investigate the world of CD and the industrial design professional perspective toward it. In the project exploration and research were prioritized over design, and most of the time was invested there. At the end of the project, the amount of content resulting from the research is undoubtedly the heart of the project.

However, an attempt has been made to draft a preliminary guide that applies the research findings to the day-to-day activities of an Industrial Design (ID) professional. While this draft does not represent a comprehensive design, it is envisioned as a starting point for crafting a potential guide on CD. The most helpful components are likely to be the categorization of the topics, the navigation flows developed based on the use cases, and the entire navigation structure. This proposal would like to be a starting point to stimulate CD use in ID.
The draft was created within a relatively short time frame in comparison to the overall research duration and is intended not as a culmination of the research but rather as a proposal for future development.

The development of this digital guide concept took place after the focus group described in Chapter 4.2.2. It became clear during this session that professionals at VanBerlo desired something more tangible and concrete than the network map presented in section 5.4. While the network map fulfilled the need to depict and explain the complexity of CD, it lacked a robust connection with everyday practice within the studio.

Thus, use cases were developed, representing the needs identified during interactions with professionals. The content of the research, particularly the categorization derived from the network map, was transformed into a navigation structure, as illustrated in Figure 78. This navigation structure depicts the branching of the topics in the sequence a user could encounter while consulting the guide.

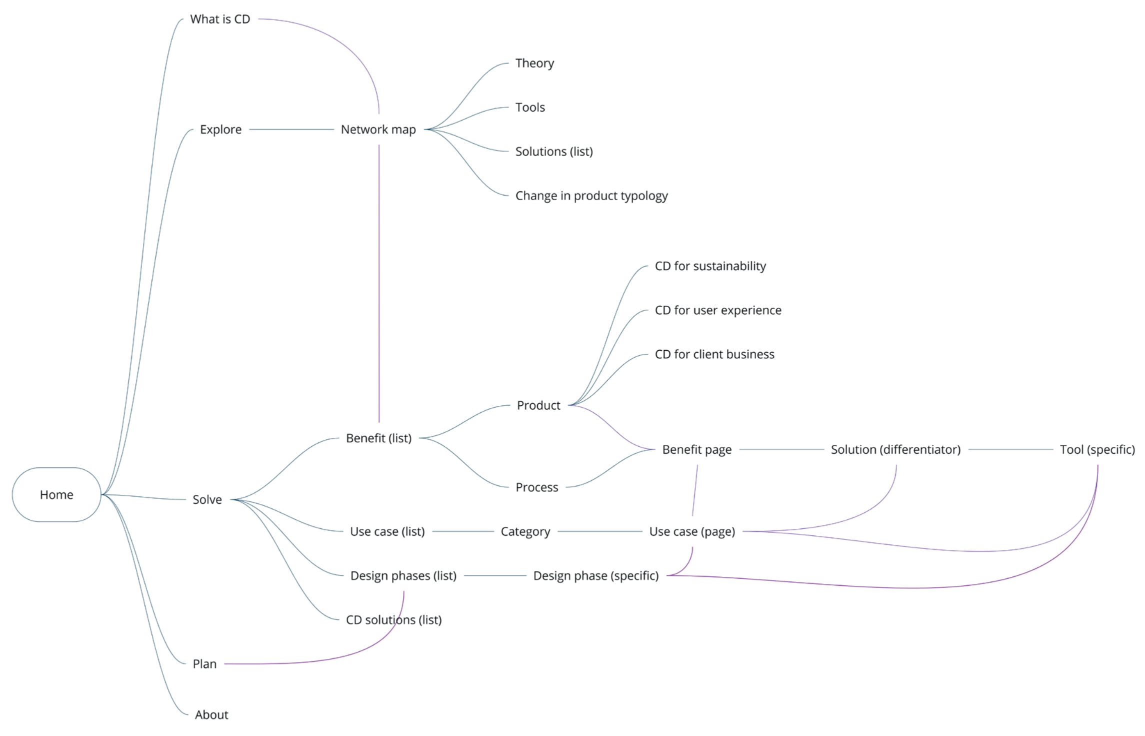
The design is developed to meet the users' needs on three use cases defined during the user research: Explore CD, Solve a design problem, or Plan for a design activity/project using CD strategies.

The interaction design of the digital guide has two main elements:
• A user interface prototype in Figma aimed at organizing the content and assisting the users in achieving their goals.
• A navigation structure that offers an overview of the information flows within the website.

Given the timeline and resources of the project, it was only feasible to explore and prototype one flow of the digital guide (Solve). The prototype remains a proposal for future development and does not intend to portray the complete design of a website, an objective beyond the project's scope. Nevertheless, the prototype on Figma aims to convey the design's intent and inner logic.

The prototype serves to represent the user flows defined through the use cases. The level of detail aims to give an idea of how the visual elements of the design help to communicate the information contained in the information architecture. The design should allow someone with limited knowledge about this research to continue building the website without thinking about the design from scratch because the interface design and the content's building blocks are already drafted.

Figure 78: Digital Guide's Navigation Structure



THE DIGITAL GUIDE'S BUILDING BLOCKS

The landing page

The landing page (Figure 79) shows a brief sentence describing the goal of the digital guide. Clicking the text on the top right corner allows access to the three main navigation flows: Explore, solve and plan.

The landing page has three functions:

1. Intrigue the user and spark interest in the content.
2. Give an immediate feeling of the guide content and communicate its intent.
3. Direct to the most important pages in the website, anticipating users' needs.

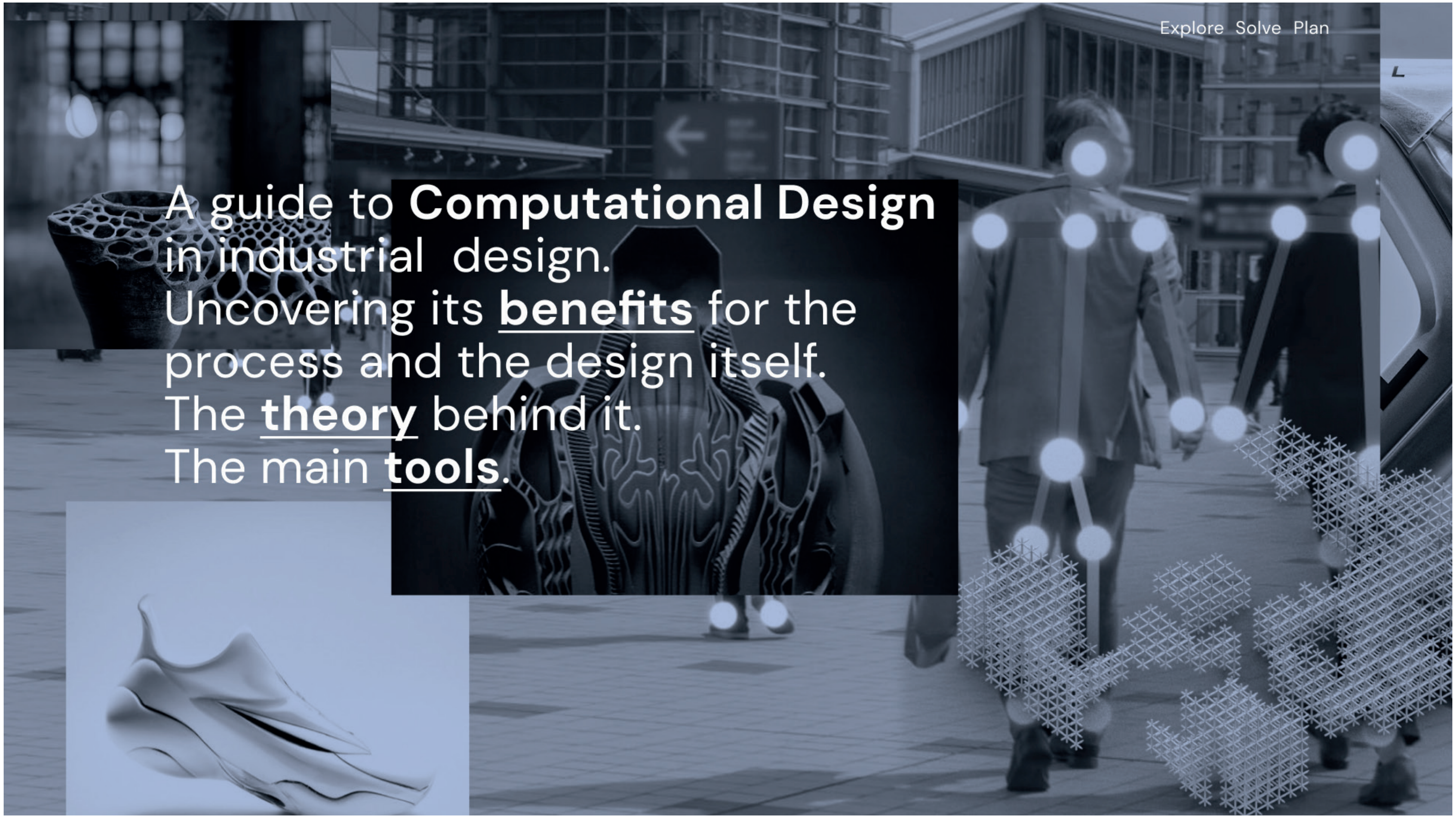


Figure 79: Landing page: collage of images from Tedeschi (shoe) Hyperganic (Central image), and images created with midjourney

The guide is composed of two main types of pages:

1 - **List page** (Figure80): This type of page presents the user with an array of possibilities. Its primary purpose is to assist users in finding what they seek - typically a solution to a problem - by offering an overview of CD elements associated with information helping the user relate their problem to CD strategies. (e.g.Sought benefit, case study, product domain or design phase)

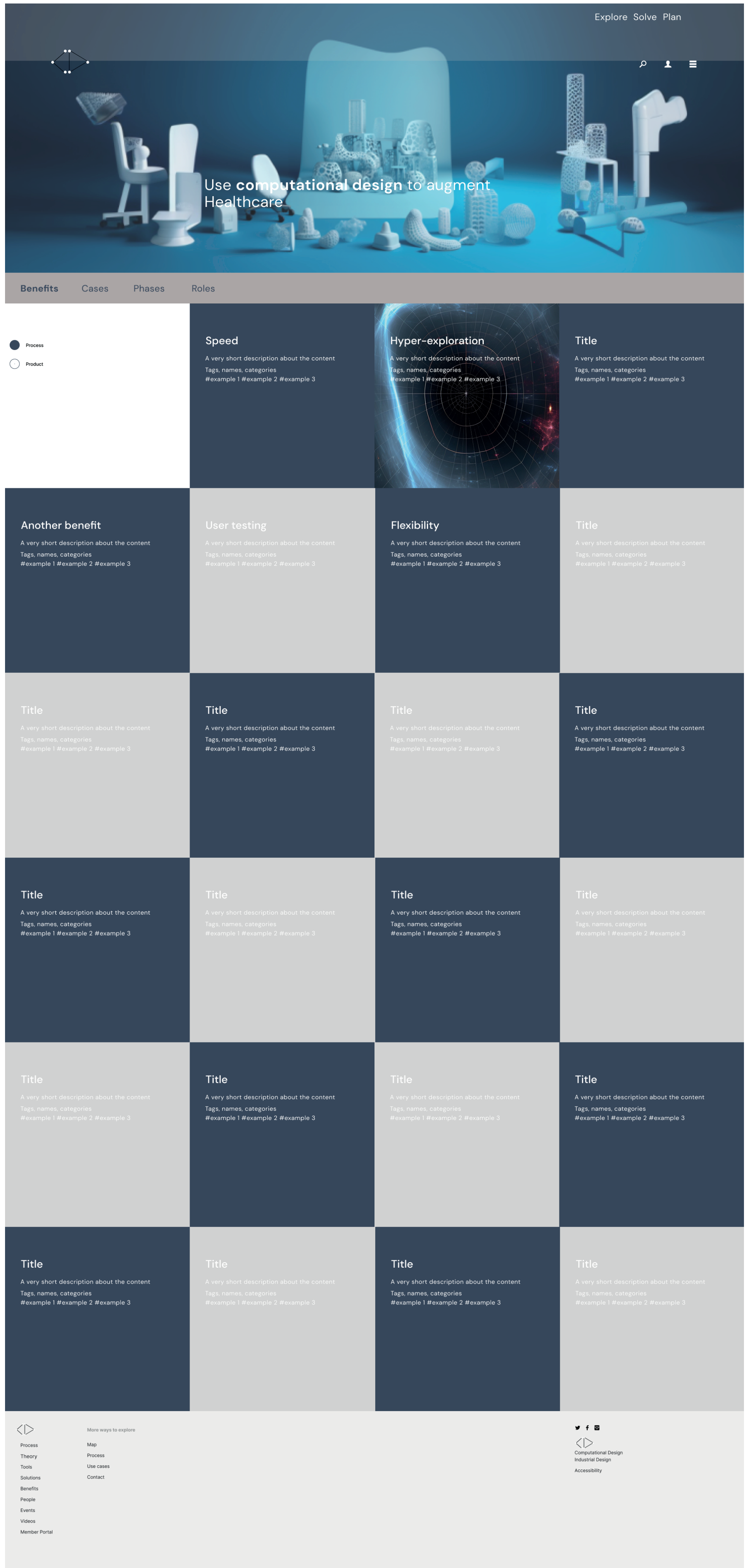


Figure 80: List page: CD strategies

2 - **Content page** (Figure 81): in this typology, the user will find specific information regarding a specific topic. Every topic might be introduced through a short description, and depending on the subject, the page may contain descriptive and informative text in the case of theoretical content and actionable content (e.g. link to tutorials) in the case of content directly applicable to a project.

Figure 81: Content page, images created with Midjourney

Left rail
The left rail (Figure 82) on content pages is designed to assist users with navigating the page efficiently. It includes options to navigate to the previous page at the top, the main topics of the page in the center, and a list of related pages at the bottom. For example, on the benefit page, the related pages may include CD strategies and related tools on the CD strategy page.

Search bar
Allowing users to search for specific information is crucial so they are not restricted to following the guide's structure when browsing.
In addition to this the search bar is often seen by users as an escape hatch when they are stuck in navigation, for this reason the search bar should be available on every page of the website (Nielsen Norman Group, 2001.). Ideally the pages within the site should be tagged with elements relatable to the user. Some examples could be:

- Design goals, e.g. sustainability or mechanical performance
- Product domain e.g. healthcare, consumer electronics
- Design phase

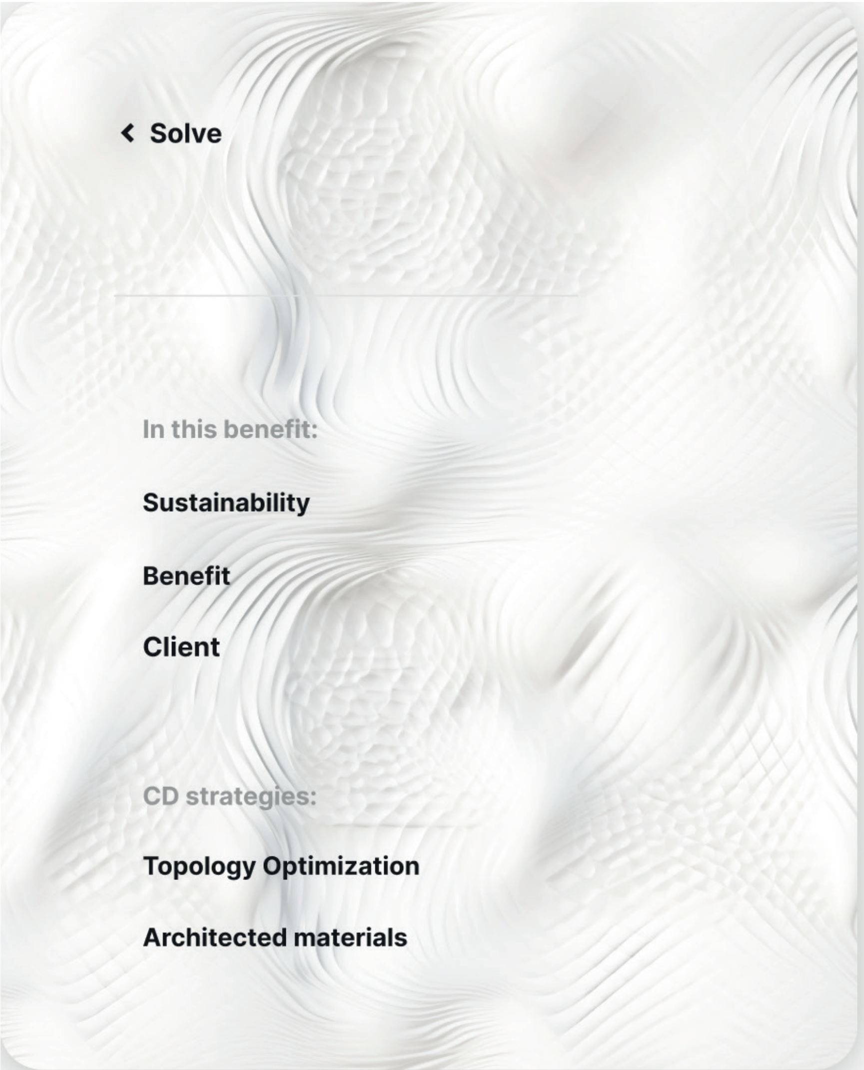


Figure 82: Left rai on content pages

NAVIGATION FLOWS

This is a brief overview of the information flows proposed based on the use cases previously defined thanks to the product journey. Each flow can be accessed from the top right corner of the landing page in Figure 79 and will lead the user to the guide's pages.

Solve
The user, upon selecting the "Solve" path from the landing page, will be directed to a "list page". This page serves as a crossroads that presents to the users elements that might aid them in finding solutions to their problems. The key categories defining the lists on this page should resonate with the users, aiding them in the discovery process, and should not necessitate any prior knowledge in CD. For this reason, the lists available on this page are: Benefits, case studies, and design phases.

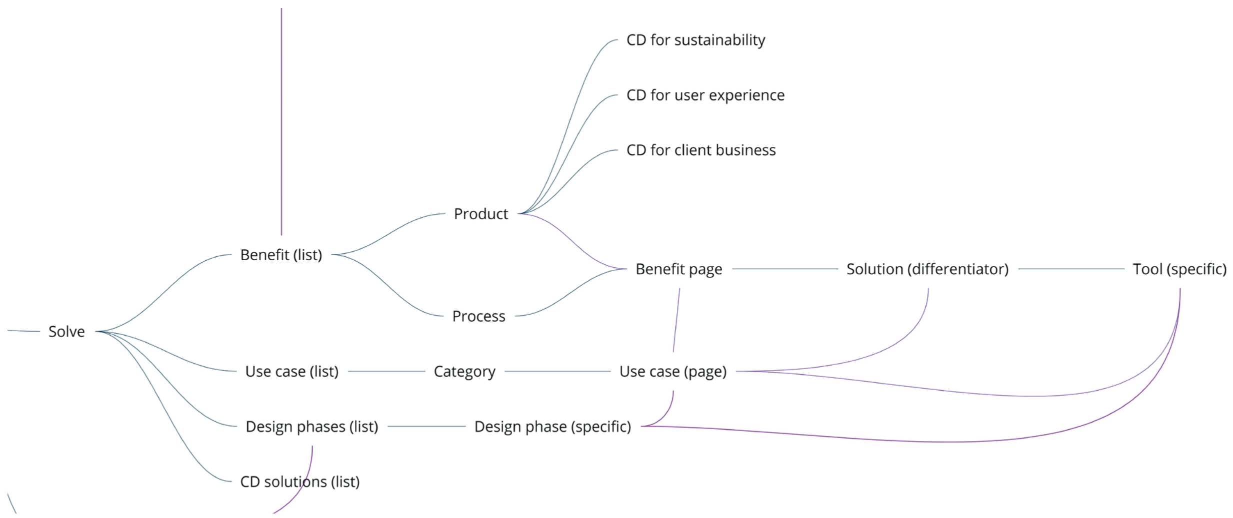


Figure 83: Solve navigation flow

Benefits List page
The solve flow begins from the benefits list page (Figure 84). This page consists of a list of CD benefits contained in a square grid. Each module of the grid includes an evocative image of the benefit, a one-sentence description, key advantages in terms of sustainability, usability, and client business, and several tags to help users determine if the benefit might be suitable for their problem.

The second key element of the benefits page is a radio button enabling the user to switch between the two main categories of benefits:

1. Benefit for the process: this type of benefit contributes to streamlining the design process, helping designers to achieve an improved quality of the final design, explore a wider solution space or achieve greater efficiency while working. For instance, hyperproduction of images.

2. Benefit for the product: This type of benefit has a direct effect on the product itself, enabling specific characteristics that increase the value of the product itself. This added value should always be confronted and contextualized with respect to sustainability, usability and business for the client. For instance, body fitment or lightweighting.

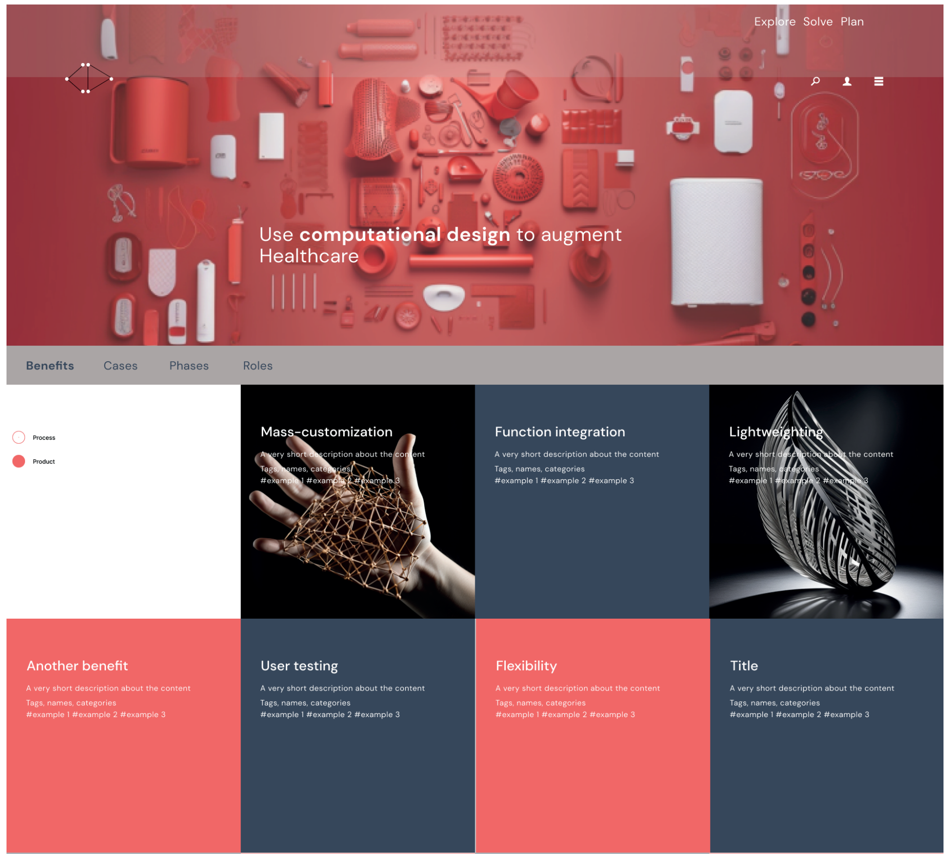


Figure 84: List page: CD benefits, images created with Midjourney

Benefit content page
After clicking on an element on the benefits list page, the user will land on a specific benefit page (Figure 85), which can be of two types:

Product: This benefit page will provide a description of the benefit and its implications in terms of sustainability, usability and client business; the final part of the page will direct to CD design strategies. Through the left rail menu, it is possible to jump through the page's key elements.

Process: This page contains a description of the benefit, its contribution to the design process, possible implications for the final product, and links to CD strategies to achieve it.

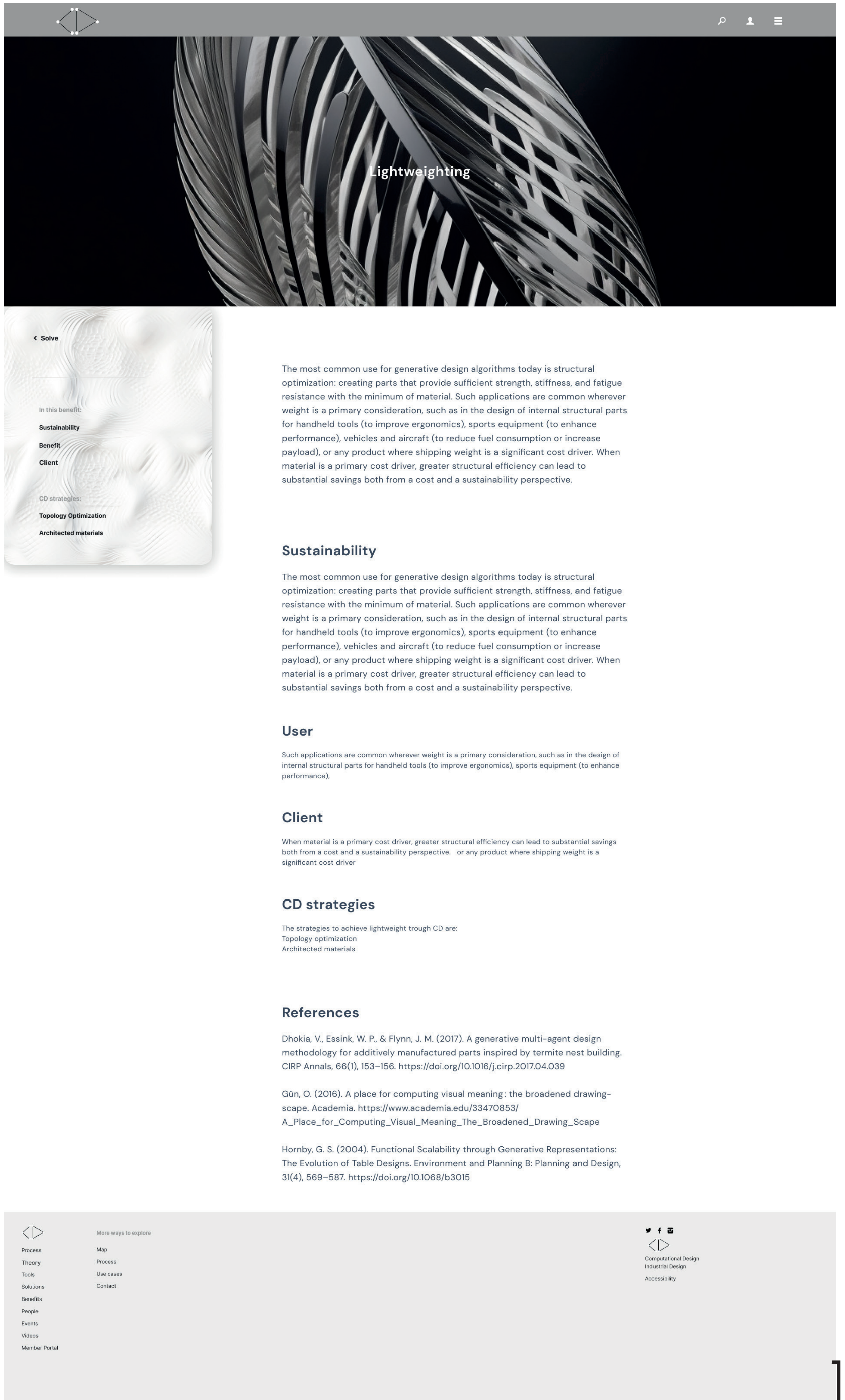
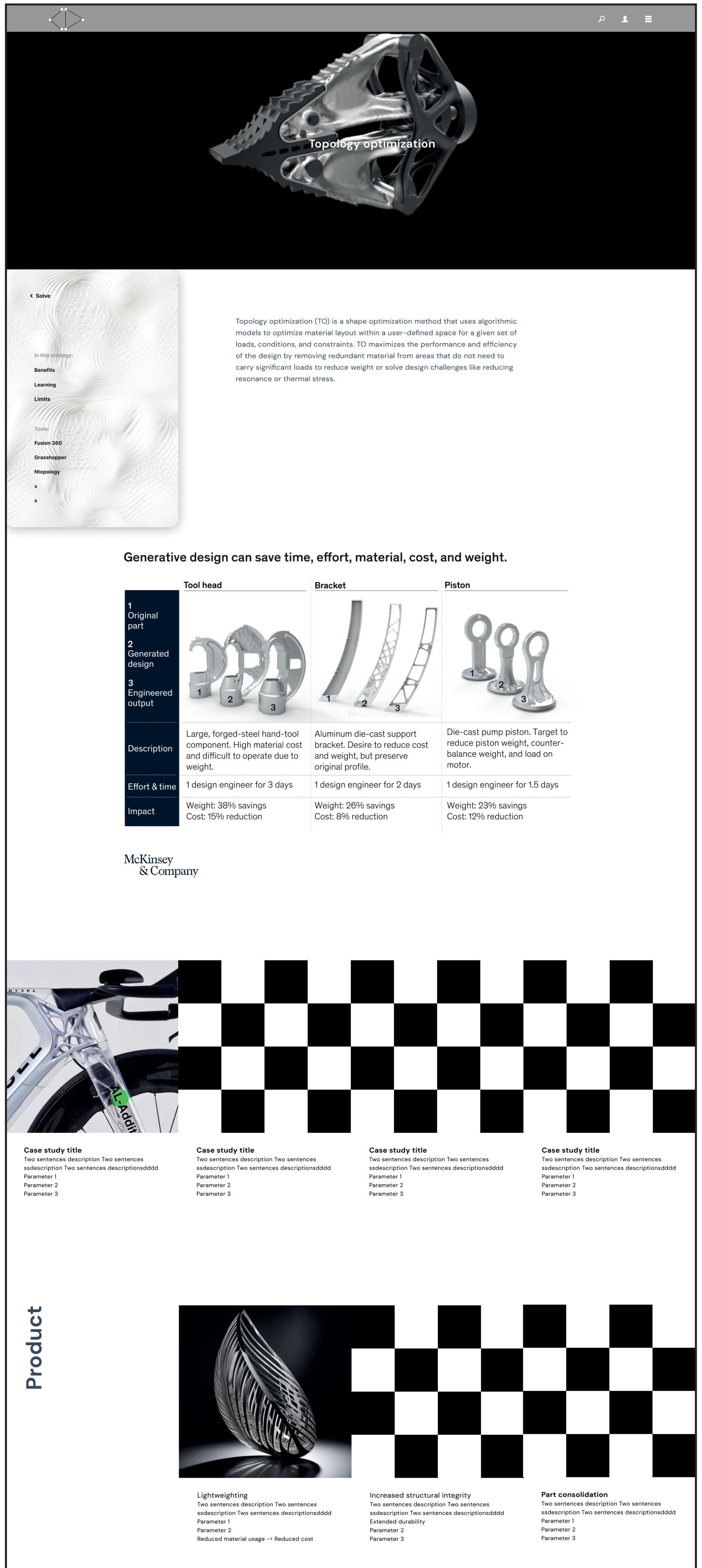


Figure 85: Benefit content page, images created with Midjourney

CD strategy page
This category of page (Figure 86) contains a description of a CD strategy. A collection of case studies, its contribution in terms of process and product, the benefits in this page will be represented by the same blocks used in the benefit list page and clicking on them will direct the user to the benefits page related to the strategy in question. For instance, if the CD strategy page is about topology optimization, accessing the benefit page about lightweighting will be possible.

A learning section (Figure 86) follows the benefits section. In this part of the page, the user will find a series of learning resources organized into four macro categories: " getting started", "intermediate", " advanced", and " learning path". Each learning resource will specify the type of software, the format (article, video), and, when available, the expected completion time.



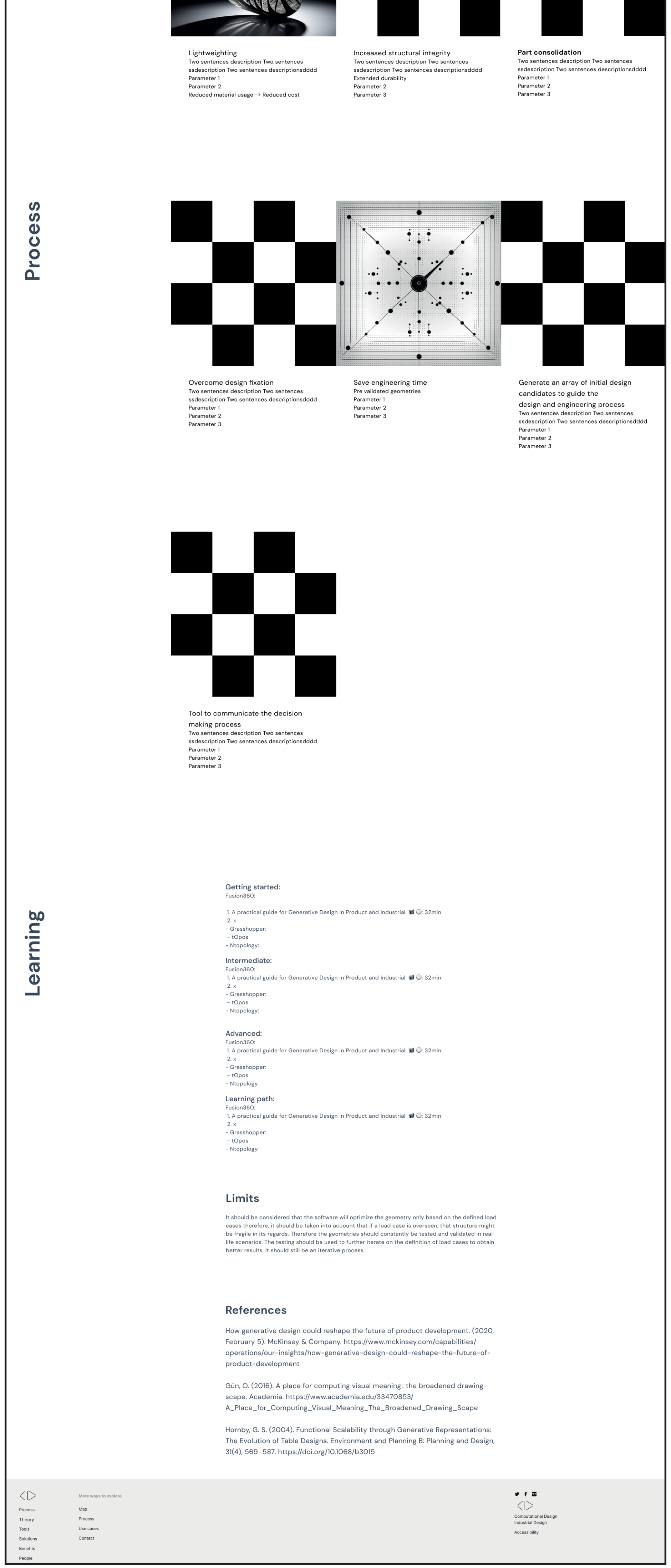


Figure 86: CD full-length strategy page images created with Midjourney

Plan
When the “Plan” option is selected from the landing page, the user is guided to the Plan page. This page is designed to assist the user in planning a design project using CD strategies. It starts with a brief description of the planning process and its steps. The user is then presented with several design phases, such as ideation, development, and testing, each associated with a set of suitable CD strategies.

Explore
The user will be directed to the Explore page by clicking on “ Explore” from the landing page. Here the user will go through a short guided introduction to the CD network map defined in section 5.4.

The main goal of this page is showcasing CD as a whole and give an overview of the topic, showing the main concepts and their interrelationship. This representation aims to create a simple and easy-to-remember visual map, following the model described in section 5.4.
After the introduction (Figure 85), the user will be able to click on one of the main concepts or start an explorative experience. The zoom-in will unlock a more detailed landscape containing sub-categories of concepts (Figure 90).

This landscape might become quite intricate, which might be good to show the topic’s complexity but a problem for the information’s readability. To solve this problem, these interaction strategies come into play:
• When hoovering on a topic, the relationships with other nodes will be highlighted, and a page preview will appear.

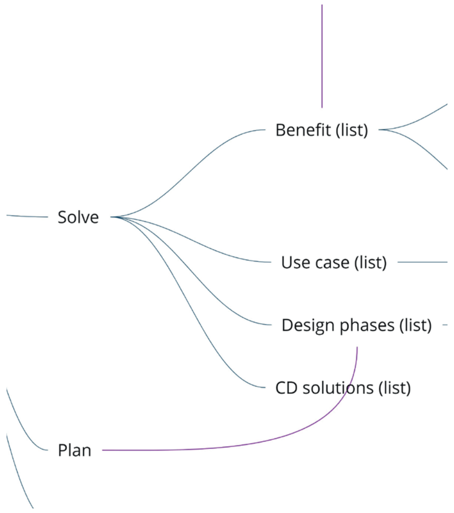
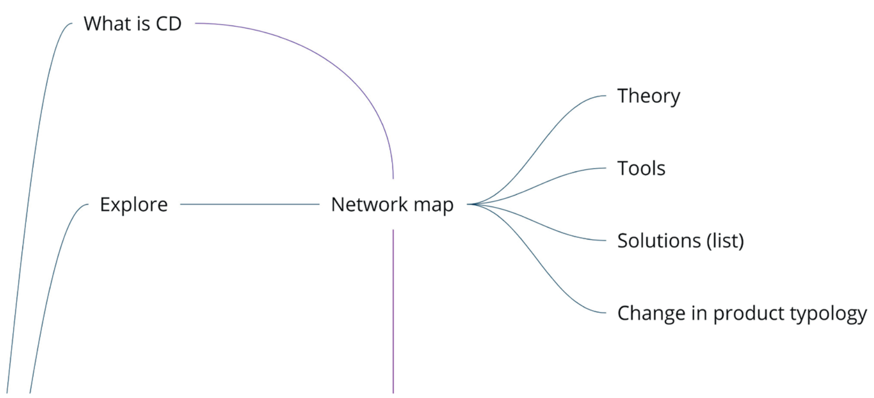


Figure 87: Plan flow

Figure 88: Explore flow



• An isolate function to better analyze the topic’s relationship.
• A research function to quickly filter topics.

Hopefully the user exploring this visualization will have a grasp on CD and its strategies. This exploration process might inspire the user to explore existing and think about new ones. CD in ID has potential that still needs to be fully explored, and this can be helped through exploration and cross-pollination, hence the network map visualization.

As previously mentioned, this digital guide concept is only a proposal, which has not been tested, representing the author’s personal perspective on what a digital guide on CD might look like in light of the research.

In conclusion, the digital guide is an initial attempt to bridge the gap between the theoretical and practical worlds of Computational Design in Industrial Design. It is a tool that could enhance the adoption and implementation of CD within the industry. The next step would be to further refine and expand this initial prototype based on feedback from its intended users and CD experts and continually update it to reflect the rapidly evolving world of Computational Design.

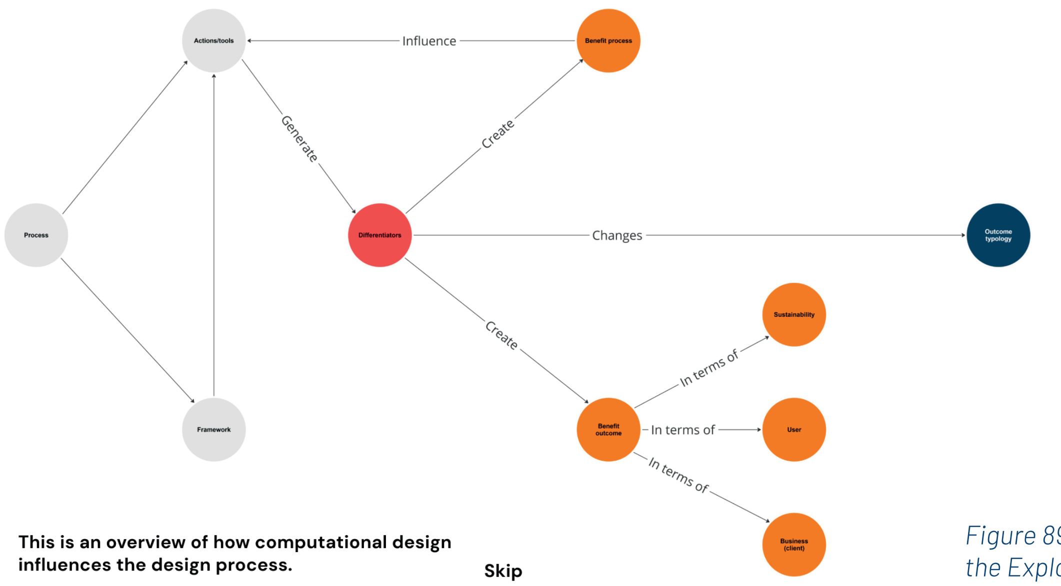


Figure 89: Clickable introduction to the Explore flow

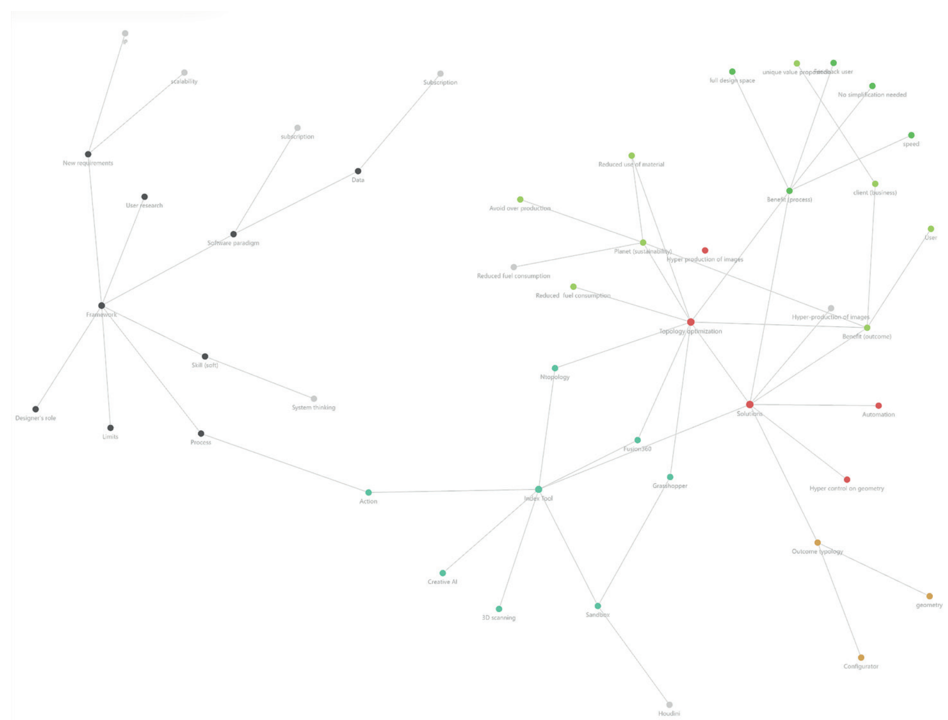


Figure 90: CD map in the explore page

6
CONCLUSIONS AND REFLECTION

6.1 THESIS CONCLUSIONS

The thesis presents an extensive exploration of the applicability and potential of Computational Design (CD) within the field of industrial design.

The first part of the thesis dives deep into the concept of Computational Design. The research starts at a high, abstract level. The chapter outlines the **definitions**, related **theoretical concepts**, and **methodologies** of Computational Design. The exploration concludes by highlighting a multitude of **opportunities** that Computational Design presents for industrial design. Based on an extensive literature review, CD exerts interviews and small experiments; it can be concluded that Computational design can be conceptualized as an approach in which the designer defines a series of instructions, rules, and interrelationships that precisely delineate the necessary steps for realizing a proposed design and its corresponding data or geometry using computers and computation. Essentially, this methodology enables design activities to be either assisted or entirely executed by computers.

Engaging with this approach demands a fluency in computational thinking, which encompasses the mental skills and strategies necessary for designing computations that enable computers to work for us and elucidate the world as an intricate informational process. Within a design context, this culminates in a **paradigm shift** from representing the geometry of a specific product to establishing the computational logic that can generate and represent it. An additional significant shift involves the necessity to design the computational **system** that can create a product and its variations rather than just the individual artifact. In this perspective, it is vital to identify the **interconnections and interdependencies** that characterize a design problem and, subsequently, convert these into **parameters** or **generative logic**. Within the realm of industrial design, these interconnections and interdependencies can correlate with design requirements, the broader context of use, or environmental factors. The definition of these parameters gives life to a multidimensional problem, whose solution space can be explored by leveraging the computational power of machines. In essence, CD offers a methodology that empowers designers to work with enhanced efficiency and explore a spectrum of solutions augmenting human creativity, thereby reshaping the traditional design process.

This approach induces various implications for both the design process and the designer's role. The design process becomes more constraint-driven, necessitating the definition of the parameters mentioned earlier, and the process phases become less defined and more blended, infusing conceptual phases with technical requirements that can be tested early in the design process through simulation and inform generative systems.
Another critical point is that the design process relies less on historical precedents or typologies, and more on the generative capabilities of the algorithm, the constraints defined by the designer, and their intuition. **The designer's role** evolves into being the "**conductor"** of the generative design process, where the final design is a product of the designer's imagination intertwined with the generative abilities of computer tools. The design process gravitates more towards a software paradigm, approaching the design of physical objects using methods akin to software development. This could result in adopting a more agile process that, coupled with the efficiency enabled by CD methods and additive manufacturing, could help faster iterations and a more flexible approach. The ultimate result of the design process may be, in addition to the conventional 3D geometry, a software engine capable of generating product variations. The main benefits of CD for the industrial product design process can be defined in three dimensions:

1. **Efficiency** enhancement: CD enhances the speed and efficiency of the design process due to the computational power of machines, allowing for quick changes, automation of design procedures, efficient management of information, and reduced number of iterations.

2. Fostering **Exploration**: CD contributes to exploring novel solutions beyond human imagination, boosting creativity rather than replacing it. It allows designers to investigate new dimensions and possibilities, fostering a deeper exploration of the design space.

3. **Quality** amplification: CD provides a systematic approach to the design process, culminating in enhanced performance and superior end product quality. It enables optimization and simulation to satisfy specific design criteria, advanced modeling for refined design outcomes, and faster learning and improvement through faster iterative processes.

Among the most promising generative strategies are **Genetic Algorithms (GAs)** and growth strategies inspired by nature. These methods facilitate an exploration of the design landscape while assuring quality by searching the fitness functions.
Architected materials and lattice structures enable remarkable control over geometry, facilitating the engineering of diverse mechanical properties, usually achieved with different materials within a single material. This approach could potentially reduce the variety of materials used in a product, thereby enhancing recyclability prospects.

Often, additive manufacturing is necessary for manufacturing the complex geometries generated by these generative methods. However, other manufacturing processes can also be taken into account while developing a computational design system.
Concerning generative AI, its potential is immense**.**
Generative AI algorithms empower designers to **explore a more expansive solution space** by generating images from natural language prompts at enormous speed, thus stimulating dialogue and innovation. They expedite the visualization of **future scenarios** and concepts, enabling **faster design process iterations** and improved communication with stakeholders. Generative AI is still limited in creating industrial design engineering-worth 3D content.

Chapter 3 concludes with a series of potential opportunities that could positively influence the future of industrial design via the integration of CD.
Among these potentials, **design automation** can notably enhance efficiency during the design process. **Mass customization** presents the possibility of providing customized products to individual user preferences. Configurators can be utilized for mass customization and during the design process for exploring product variations and allowing non-designers to express their views on designs.
CD's **hyper-control over geometry** can enable the creation of architected materials and open up novel possibilities in product aesthetics by creating complex geometries that would be challenging to achieve using traditional methods.
The opportunities of CD extend to the realm of design for **sustainability**. An in-depth analysis of **multi-objective optimization** based on circular economy parameters was conducted. A case study from existing literature was used to develop a diagram demonstrating a multi-objective optimization process approach applied to circular economy design.
During the graduation project, several small-scale experiments were conducted, all revolving around a trigger bottle. These included a configurator for user research, an optimization of the bottle based on a subjective parameter, and an experiment with an interactive genetic algorithm plug-in for Grasshopper: Biomorpher. A final experiment aimed to use chatGPT to create 3D geometry from text prompts.

Chapter 4 presented research on the industrial design professionals' perspective on CD and its adoption. This research was critical to identify **opportunities and challenges in adopting CD** in industrial design. The research methods applied were interviews and a focus group.
Participants expressed substantial interest in the subject, and several opportunities were recognized in applying CD in industrial design. These include t**rend investigation, extraction of archetypes, idea generation, design validation, geometry optimization, and sustainability**.
Among the prominent barriers to adopting a CD approach in industrial design is the **time investment**, which must be justified by clearly defining the **value** CD methodologies can bring to a project.
Another challenge lies in navigating the multitude of tools available in the CD landscape.

The report's concluding section (Chapter 5) outlines a series of recommendations for prospective developments aimed at better navigating the landscape of Computational Design. The objective is to elucidate its significance and the potential value it can add to the process of industrial design. The artifacts displayed in this chapter are intended to present strategies for rapidly conveying and s**parking interest in the potential of CD** within the field of industrial design. Ultimately, these might serve as a catalyst for **inspiring** a more profound investigation and experimentation with this transformative topic.

The first work in this section is a diagram represented in Figure 72, which aims to provide an overview of the key elements characterizing the computational design field, plotted against the Double Diamond Model (Design Council, 2023),
The primary aim of this depiction is to serve as a tool for quickly identifying a generative method and discerning the potential contribution it can offer at a given phase of the design process. Despite potential ambiguities, this diagram can serve as a foundation for further exploration into a more nuanced, quality-driven computational design process.
The second work is a prototype of an Interactive List of Case studies of industrial products designed by tough computational methodologies. The case studies can be filtered by generative method, benefit, and phase of the design process. The tool could help designers to identify product categories in which computational design can be used and spot the relevant computational strategies.
The third prototype is an interactive network map of CD developed in Obsidian. The map aims to create a taxonomy of CD to provide an overview of the topic's concepts and their relationships, referencing the links between theory, methods, tools, and the benefits they bring to the design process.
The fourth exploration is an initial-stage prototype for a digital guide to explore CD possibilities within the realm of industrial design.
While this draft does not represent a comprehensive design, it is envisioned as a starting point for the future development of a digital guide on CD. The prototype comprises a user interface designed in Figma, and a navigation structure that provides an overview of information flows within the website. This initial proposal is aimed at stimulating the utilization of CD in industrial design.
The aforementioned works were developed within a relatively short timeframe in relation to the project's overall duration, and research on CD was prioritized, being the precondition for the hypothetical development of a guide on CD in industrial design. They should not be viewed as the culmination of the research but rather as proposals for potential future development. The categorization of CD topics, the navigation flows developed based on the use cases, and the entire navigation structure discussed in chapter 5 can indicate

where to start in developing a digital guide to stimulate CD use in ID.

The findings of this research must be understood in the context of the project's limitations. The study predominantly emphasized the subject's theoretical aspects, which are still in development and not fully defined. The highlighted opportunities have been gleaned from literature reviews and expert interviews.
However, practical experiments have been scarce and limited by the time frame of the project and the focus on more abstract aspects of CD. Going forward, the opportunities should undergo further testing and validation in a real-world environment for more conclusive results. These tests could help understand which paths are worth following in integrating CD in industrial design.

Concerning a future integration of CD within an industrial design agency, it should be fostered through ongoing interaction with experts in computational design. Additionally, a significant investment of time and resources should be dedicated to formulating a strategy for exploring and researching the opportunities that emerged from this research and potentially unearthing new ones.

In conclusion, CD offers efficiency enhancement, fosters exploration, and amplifies design quality. It empowers designers to leverage computational tools, driving a paradigm shift in the design process. While challenges exist, the research presents promising opportunities for CD adoption in industrial design. However, the thesis only scratches the surface of CD potential in industrial design. Additional research and CD adoption in professional contexts are crucial to fully exploring CD's possibilities. It should be emphasized that human intuition and creativity, along with traditional methodologies such as sketching, continue to play a crucial role in the design process and are complementary to CD.

6.2 REFLECTION

I would like to start this reflection by emphasizing that I am happy and grateful for this project. I realize how the project stretched my mind in many ways. Thanks to this thesis, the support from my supervisory team at the TUDelft, and the collaboration with VanBerlo, I had the opportunity to explore in depth a realm I've yearned to explore since my bachelor studies.

My first challenge was understanding Computational Design (CD), an area that's still growing and changing. During the research, I investigated the multifaceted nature of CD, the theoretical concepts related to it, some opportunities in the field of industrial design, and methods and tools to materialize these opportunities. Interviewing experts in CD during the project has been a fantastic enriching experience. Talking to individuals who are contributing to shape, a field I'm deeply passionate about, was an invaluable experience. Each conversation answered questions, filled gaps that my literature review couldn't cover, and made me reflect on the meaning and potential of CD in industrial design.
Developing the project at VanBerlo was great. It is an agency and a group of people to whom I am particularly attached, considering I had already interned in the studio before the graduation project. Daily chats with industry professionals, exchanging opinions, and a mentor who consistently guided me toward growth and reflection enriched my graduation journey. In addition, developing the graduation project at VanBerlo allowed me to have continuous feedback organizing interviews and focus groups to discuss the future of CD in the context of industrial design. It has been great to see the interest and development within the studio in recent months towards CD and generative AI, and I am honored to have taken part in the related discussions.
Research into the perspective of industrial design professionals at VanBerlo has revealed enthusiasm for CD. The opportunities identified during discussions at the studio overcome barriers and challenges. I am confident that CD will be increasingly integrated into the industrial design industry.
One goal that still remains in my desire is to create a guide to foster the exploration of CD in industrial design. However, I am confident that the research in this report might help in the hypothetical future development of such a tool. The attempt to communicate and categorize knowledge on CD led me to explore unexpected fields, introducing me to new areas and concepts such as ontologies, taxonomies, knowledge graphs, and knowledge management. This knowledge has not been implemented in the research, if not partially, in the network map on CD. However, these incredibly fascinating concepts will undoubtedly benefit my future professional and personal growth.
Looking back, I could've done a better job in some areas, especially in project planning. I hit a few stumbling rocks along the way and underestimated the time required to write the report and analyze interviews. My initial intention to expand the research with a digital guide and a case study showcasing the application of CD throughout all stages of the design process was undeniably too ambitious and unrealistic. Despite this, I'm pleased with my exploration into the world of UX/UI and the subsequent creation of recommendations for future developments in computational design exploration and communication. The experience also included creating examples of the identified opportunities using Grasshopper and some plugins, although it was a minor parenthesis. Although I would have enjoyed spending more time on physical prototyping, a process I truly enjoy, I am confident that the uncovered CD opportunities and the CD tools I intend to master will keep me busy exploring and prototyping in the foreseeable future.
Before starting the project, in the "personal ambitions" section of the project brief, I wrote:
"Through this project, I want to create the knowledge foundations to understand computational design related to the field of industrial design, to lay the foundations that will allow me to thoughtfully bring this approach to my future practice."
Making the analogy of CD as a design project that extends beyond the boundaries of this graduation project, I am only at the beginning of the "explore" phase.
I can't wait to take action by applying the knowledge acquired during the project to design products using CD. I would like to elaborate on the implications of applying multi-objective optimization to sustainable design and, maybe in the future, experiment with living materials and explore the interaction between Computational Design and Biodesign.
This project made me deeply understand the value of combining apparently distant disciplines and fields. In the future, I would like to continue investigating how design combined with other disciplines can positively impact our planet and society, continuing to experiment and have fun while doing it.

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