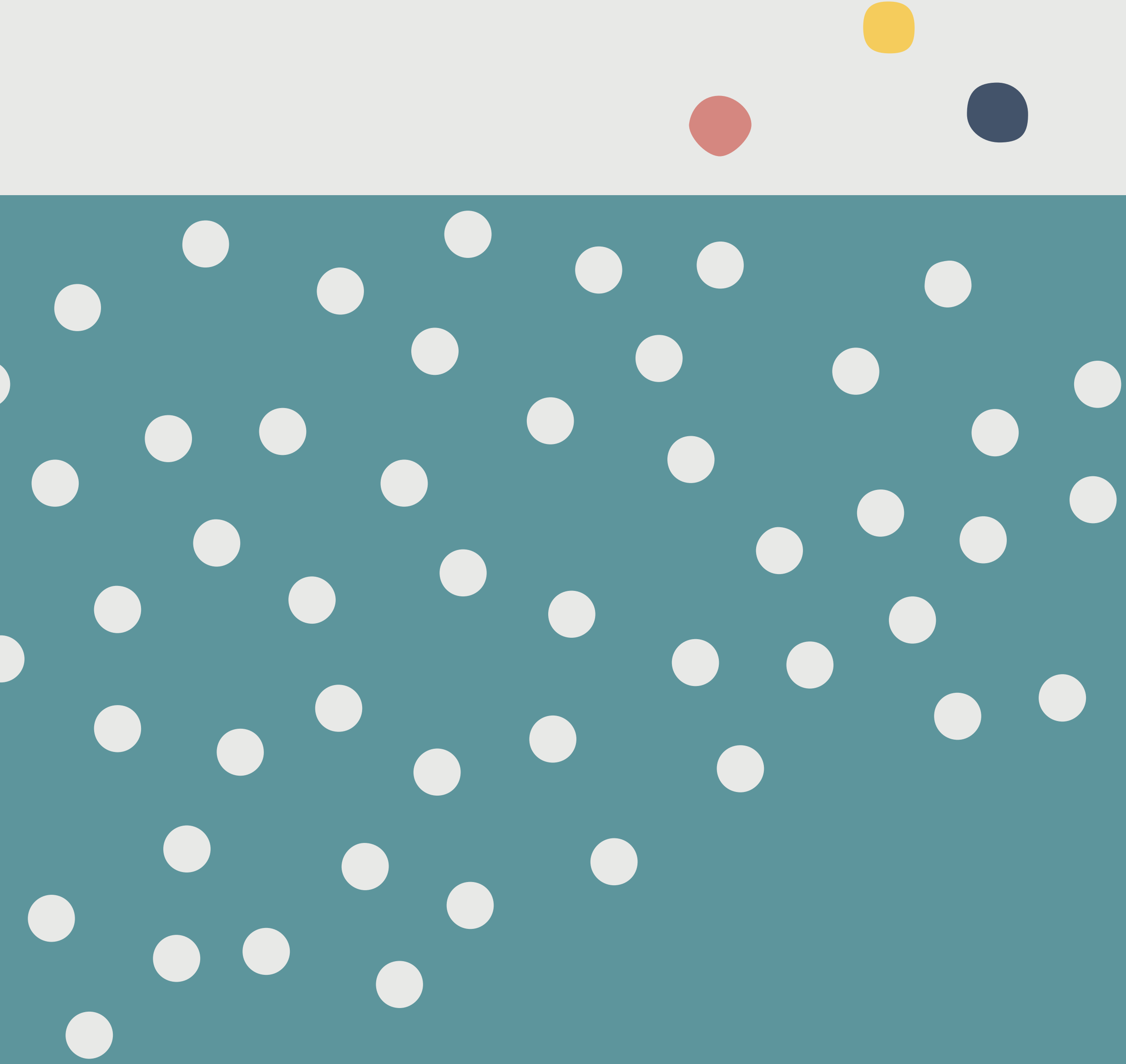
Design for Mass Personalization
in Digital Manufacturing Context



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DESIGN FOR MASS PERSONALIZATION IN DIGITAL MANUFACTURING CONTEXT

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PREFACE

As a consumer myself, I often urge to modify the products I own or even create others from scratch since existing ones are barely a perfect match. Not to mention that I have never been fond of being one of the crowd. In that sense, personalization, or in a broader sense considering the diverse needs of individuals, is a topic that I value greatly and feel fortunate to work on. It has been a long and sometimes exhausting journey until reaching this point of putting down the last words, though I am pretty content with the experience and the outcome. Before starting, I would have never imagined carrying out this research in various locations and interacting with so many people. I am very glad that it turned out this way and genuinely grateful to everyone who believed in my ideas and somehow contributed to this work.

Firstly, I want to express my gratitude to my supervisors for their guidance, support, and patience throughout this process. Besides this research, I have learned a lot from them. I am incredibly grateful to Gaetano Cascini for giving me the chance to carry out this research in the first place and for the freedom to work on the subjects that I enjoy. I am deeply indebted to Jouke Verlinden for his mentorship and always being encouraging and inspirational. Although joining halfway, he has had a significant impact on this work.

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I have been fortunate to know amazing people and work in creative and inspiring places throughout this research. I had the great pleasure of working with all my colleagues in Mechanical Engineering at Politecnico di Milano, Polifactory, and Product Development at the University of Antwerp.

Unquestionably the part of this research I enjoyed the most was the personalization of saxophone mouthpieces since I could relate to it as an amateur saxophonist. It is always fun to do something related to music. I am very grateful to Montserrat Pàmies-Vilà and Vasileios Chatziioannou for a great deal of support they provided. Their expertise in music acoustics was invaluable to this study. I would also like to thank Hans de Jong and the saxophone students of The Royal Conservatoire Antwerp for their valuable feedback on this study and their participation in the user study,

I would like to thank Atom Lab for supporting the case study of personalized footwear, and specifically Sergio Dulio for his valuable insights and feedback. I must also thank all the experts interviewed for their valuable feedback and suggestions.

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SUMMARY

Industrial production has been through a number of paradigm shifts driven by market conditions or customer desires. Today, increasingly diverse customer needs and fierce mass-market competition drive the industry to seek new solutions to attract customers. The advancements in digital manufacturing lead the shift toward smart, data-driven, and flexible production systems that allow providing on-demand and one-off products efficiently. This shift in industrial production enables *Mass Personalization* (MP) to answer individual customer needs affordably, which is gaining increasing attention of businesses as a means to take the competitive edge. MP envisages profound product variability through manufacturing process flexibility, along with active customer participation in design to answer specific needs effectively. However, a challenge exists with the scarcity of design methods and tools dedicated to *Design for Mass Personalization* (DfMP). In addition, conventional design methodologies fall short to address the product variability and customer involvement that can answer the specific needs of individual customers. Addressing these challenges, this thesis aims to develop a prescriptive design methodology for MP, focusing on the utilization of manufacturing flexibility in the process of designing a personalizable product; and an effective customer co-creation process that answers to specific needs. The main objectives are:

- To determine the necessary product architecture that allows exploiting digital manufacturing capabilities in creating variety.
- To determine the ways of customer-design interaction to address specific needs and fulfill these with the personalized product.
- To develop prescriptive guidance and tools to be used in the DfMP process.

To reach the objectives above, the research process includes four main cycles. The first cycle includes a literature review to understand the necessary design considerations for MP, followed by an analysis of the state of the art in the design literature of relevant domains. Based on the findings, the second cycle introduces a design methodology for MP with both adapted elements from the literature and novel elements proposed where needed. The last two cycles are case studies to verify the proposed design methodology. The two case studies focused on the personalization of knitted footwear and 3D-printed saxophone mouthpieces respectively. At the end of the process, a final example of an industrial application is also demonstrated.

From a design perspective, the literature on MP highlights user experience, co-creation, and product change as key characteristics to reach the aim of fulfilling specific customer needs. To provide sufficient variability, the level of product differentiation should be at the basic design level, through changes enabled by manufacturing process flexibility. In this regard, considerations of digital manufacturing processes, such as *Additive Manufacturing* (AM), in the design process appear to be prominent. The literature also emphasizes the need to actively involve the customers in the design to answer their needs effectively, and the importance of this co-creation activity as a part of the user experience and value creation. Looking at the design methods related to product change and variability, product family and platform design appear as the most established with modular configurations, followed by parametric approaches for personalization. A related domain is *Design for Additive Manufacturing* (DfAM), which demonstrates the possibilities of varying multiple functions and parameters in a consolidated design. The existing design methods are insufficient to define variability at such a level. A similar challenge also exists in the design process for creating variety. Therefore, the first two research questions address the necessary variability definition and design process for MP. The most common form of customer involvement in this context is the product configurations that allow users to configure a product in a predefined product portfolio. The configuration structures are based on modularity and independence of the functions of the modules. Hence, these are insufficient to structure the product differentiation where the variability level is beyond modularity. The third research question raises this point to investigate an alternative way to facilitate customer co-creation. The literature on DfMP is mostly descriptive frameworks, and largely from a production perspective. Hence, there is a gap in prescriptive guidance for designers in DfMP, which is addressed by the fourth research question.

This thesis work presents a dedicated design methodology for MP, focusing on effectively creating variability in the design and eliciting specific customer needs through co-creation. The proposed methodology guides the designer through the development process of a user-modifiable design and demonstrates how to facilitate the user involvement in reaching a personalized design. It proposes a flexible and adaptable seed design architecture, and an interactive customer co-creation process. The overall design process is structured with a DfMP framework that outlines a design process where the designer facilitates customer co-creation over a modifiable seed design. To effectively create design variability based on the capabilities of flexible manufacturing processes, a novel seed design architecture is proposed. This architecture defines the variety and commonality through design features and by combining the common and varying design features with the information on limitations and dependencies of variability, the seed design allows keeping control over complexity while offering an almost continuous variety. The seed design development process is guided in two phases to form a variable seed design and manage its variability for customer co-creation. The first phase guides the designer in the process starting from addressed categories of needs to the identification of varying design parameters. Through filtering with a set of constraints, the variability of the parameters is expressed as a solution space, and these are translated into a design space where the user can operate. The second phase starts with investigating the dependencies between design parameters and personal requirements, which are then used to devise a design solution algorithm. As a means to facilitate the interaction between the user and the design, the proposed methodology uses an algorithm that modifies the design parameters based on the user input, considering the dependencies and constraints. Hence, the algorithm enables the interaction of the user with the design in real-time, while ensuring a reliable final design. Generic principles of the algorithm that can be adapted to each design case conclude the seed design development. The output of the proposed design process is a seed design with certain variability and the means to co-create a personalized design with the user. The overall design process is then completed by each individual user reaching a personalized design.

The first case study includes the functional, ergonomic, and esthetical personalization of a shoe that is manufactured by 3D printing and digital knitting. Footwear is one of the first products coming to mind in terms of personalization, as it is related to both comfort and self-expression. Therefore, it is a very suitable case to demonstrate the use of the proposed design methodology. This case study applies the methodology to a personalized footwear design case with a knitted upper and a 3D-printed sole. Besides the fit and the appearance, the variability of certain functionality of the knitted upper is investigated through the variation of yarns and knit patterns. The study follows the prescribed design process by identifying the design parameters for personalized fit, appearance, and comfort, and by forming solution and design spaces. Finally, the design solution algorithm for this case and an example co-creation process on a user interface are illustrated. The study is supported by interviews with experts to evaluate the design process and content of the study. The potential of the proposed design methodology is largely confirmed by the experts.

The second case study demonstrates the functional personalization of a saxophone mouthpiece to tailor the performance for musicians. The mouthpiece is where the sound is produced in the saxophone and its design is highly influential on the performance. Therefore, the choice of a mouthpiece is a very personal decision and there is an existing demand of saxophonists seeking the one that provides the sound they wish or fits their playing habits. Besides, the simple construct and high value of mouthpieces make it a very suitable case for MP and on-demand production with AM. Towards building a seed design, a literature study and survey of existing products reveal potential design parameters, and mouthpiece features to personalize. A challenge encountered in this is yet the lack of quantitative knowledge on mouthpiece design. Therefore, an acoustical analysis is carried out to obtain quantitative relations between mouthpiece design and performance. To that aim, twenty-seven 3D-printed mouthpieces with nine varying design parameters are tested using an artificial blowing machine, to determine their effects on four selected mouthpiece features. The experiment analysis reveals that seven of the tested design parameters affect the mouthpiece performance in varying amounts. The influence of the design parameters on the mouthpiece features, based on statistical analysis, is implemented in a seed design, where a largely coupled design case emerges. Following that, a user study with five saxophonists is devised to verify the outcomes. The proposed co-creation scenario is successfully tested with saxophonists personalizing their mouthpieces through a graphical user interface, and then testing the 3D-printed personalized mouthpieces. The participants confirm the performance variance in seven out of ten cases, and they prefer the personalized mouthpieces in four out of five cases. The user study shows the ability of the design methodology to cater to specific needs. Overall, this case study verifies the applicability of the proposed methodology, and its ability to address coupled design cases.

Finally, an industrial application case on FARO dental lights is exampled to illustrate the use in a practical setting of a commercial product. This case also demonstrates the potential of the design methodology for the hybrid cases where there are both personalized and modular components. Overall, the case studies show the potential of the methodology to deal with coupled mass personalization cases and provide for the specific needs of customers. The three main objectives of this thesis on creating variety, customer involvement, and prescriptive design guidance and tools for MP are achieved by devising a design methodology for MP and testing it through case studies. The outcome of this research contributes to the design thinking in MP to exploit the flexibility that emerging digital manufacturing technologies provide, to enable meeting diverse customer needs efficiently and effectively. A systematic approach to DfMP will allow expanding MP to more products and act as a foundation for the customer co-creation-oriented design in the context of this emerging paradigm.

SAMENVATTING

De industriële productie heeft een aantal paradigmaverschuivingen ondergaan die werden aangedreven door de marktomstandigheden of de wensen van de klant. De steeds diversere behoeften van de klant en de felle concurrentie op de massamarkt dwingen de industrie op zoek te gaan naar nieuwe oplossingen om klanten aan te trekken. De vooruitgang in digitale productie leidt tot een verschuiving naar slimme, datagestuurde en flexibele productiesystemen die het mogelijk maken om op efficiënte wijze producten op aanvraag en eenmalige producten te leveren. Deze verschuiving in de industriële productie maakt *Mass Personalization* (MP) mogelijk om betaalbaar in te spelen op individuele klantbehoeften, wat steeds meer aandacht krijgt van bedrijven als middel om een voorsprong te nemen op de concurrentie. MP voorziet een grote productvariabiliteit door flexibiliteit van het fabricageproces, samen met een actieve deelname van de klant aan het ontwerp om doeltreffend op specifieke behoeften in te spelen. Er is echter een probleem met de schaarste aan ontwerpmethodes en -tools voor massapersonalisatie (*Design for Mass Personalization*, DfMP). Bovendien schieten conventionele ontwerpmethodologieën tekort om de productvariabiliteit en klantbetrokkenheid aan te pakken die de specifieke behoeften van individuele klanten kunnen beantwoorden. Om deze uitdagingen het hoofd te bieden, wil deze dissertatie een prescriptieve ontwerpmethodologie voor MP ontwikkelen, met de nadruk op het gebruik van productieflexibiliteit in het ontwerpproces van een personaliseerbaar product; en een effectief co-creatieproces met de klant dat beantwoordt aan specifieke behoeften. De belangrijkste doelstellingen zijn:

- De noodzakelijke productarchitectuur bepalen die het mogelijk maakt de digitale fabricagemogelijkheden te benutten bij het creëren van variëteit.
- Het bepalen van de manieren van interactie tussen klant en ontwerp om specifieke behoeften aan te pakken en deze te vervullen met het gepersonaliseerde product.
- Ontwikkeling van prescriptieve richtsnoeren en instrumenten voor gebruik in het DfMP-proces.

Om de bovenstaande doelstellingen te bereiken, omvat het onderzoeksproces vier hoofdcycli. De eerste cyclus omvat een literatuurstudie om inzicht te krijgen in de noodzakelijke ontwerpoverwegingen voor MP, gevolgd door een analyse van de stand van zaken in de ontwerpliteratuur van relevante domeinen. Op basis van de bevindingen wordt in de tweede cyclus een ontwerpmethodologie voor MP geïntroduceerd met zowel aangepaste elementen uit de literatuur als nieuwe elementen die waar nodig worden voorgesteld. De laatste twee cycli zijn case studies om de voorgestelde ontwerpmethodologie te verifiëren. De twee case studies focusten respectievelijk op de personalisatie van gebreid schoeisel en 3D-geprinte saxofoonmondstukken. Aan het

eind van het proces wordt ook een laatste voorbeeld van een industriële toepassing gedemonstreerd.

Vanuit ontwerpperspectief worden in de literatuur over MP gebruikerservaring, cocreatie en productverandering aangemerkt als de belangrijkste kenmerken om te voldoen aan specifieke behoeften van de klant. Om voldoende variabiliteit te bieden, moet het niveau van productdifferentiatie op het basisontwerpniveau liggen, door middel van veranderingen die mogelijk worden gemaakt door de flexibiliteit van het fabricageproces. In dit verband lijken digitale fabricageprocessen, zoals Additive Manufacturing (AM), een prominente plaats in te nemen in het ontwerpproces. De literatuur benadrukt ook de noodzaak om de klanten actief bij het ontwerp te betrekken om doeltreffend op hun behoeften in te spelen, en het belang van deze co-creatieactiviteit als onderdeel van de gebruikerservaring en waardecreatie. Wanneer wordt gekeken naar de ontwerpmethoden in verband met productverandering en -variabiliteit, blijken productfamilie- en platformontwerp het meest ingeburgerd met modulaire configuraties, gevolgd door parametrische benaderingen voor personalisering. Een verwant domein is *Design for Additive Manufacturing* (DfAM), dat de mogelijkheden demonstreert van het variëren van meerdere functies en parameters in een geconsolideerd ontwerp. De bestaande ontwerpmethoden zijn ontoereikend om variabiliteit op een dergelijk niveau te definiëren. Een soortgelijke uitdaging bestaat ook in het ontwerpproces om variabiliteit te creëren. Daarom hebben de eerste twee onderzoeksvragen betrekking op de noodzakelijke variabiliteitsdefinitie en het ontwerpproces voor MP. De meest voorkomende vorm van klantenbetrokkenheid in deze context zijn de productconfiguraties waarmee gebruikers een product kunnen configureren in een vooraf gedefinieerde productportefeuille. De configuratiestructuren zijn gebaseerd op modulariteit en onafhankelijkheid van de functies van de modules. Zij zijn dus ontoereikend om de productdifferentiatie te structureren wanneer het variabiliteitsniveau boven de modulariteit uitgaat. De derde onderzoeksvraag stelt dit punt aan de orde om een alternatieve manier te onderzoeken om co-creatie met de klant te vergemakkelijken. De literatuur over DfMP bestaat voornamelijk uit beschrijvende kaders, en grotendeels vanuit een productieperspectief. Er is dus een leemte in prescriptieve begeleiding voor ontwerpers in DfMP, die wordt behandeld in de vierde onderzoeksvraag. Dit proefschrift presenteert een specifieke ontwerpmethodologie voor MP, gericht op het effectief creëren van variabiliteit in het ontwerp en het ontlokken van specifieke klantbehoeften door middel van co-creatie. De voorgestelde methodologie leidt de ontwerper door het ontwikkelingsproces van een door de gebruiker aanpasbaar ontwerp en laat zien hoe de betrokkenheid van de gebruiker bij het bereiken van een gepersonaliseerd ontwerp kan worden vereenvoudigd. Het stelt een flexibele en aanpasbare seed design architectuur voor, en een interactief klant co-creatie proces. Het algemene ontwerpproces is gestructureerd met een DfMP raamwerk dat een ontwerpproces schetst waarbij de ontwerper klant co-creatie faciliteert over een aanpasbaar seed design.

Om effectief ontwerpvariabiliteit te creëren op basis van de mogelijkheden van flexibele fabricageprocessen, wordt een nieuwe seed ontwerparchitectuur voorgesteld. Deze architectuur definieert de variëteit en gemeenschappelijkheid door middel van ontwerpkenmerken en door de gemeenschappelijke en variërende ontwerpkenmerken te combineren met de informatie over de beperkingen en afhankelijkheden van de variabiliteit, maakt het seed ontwerp het mogelijk de controle te houden over de complexiteit en tegelijkertijd een bijna continue variëteit aan te bieden. Het ontwikkelingsproces van het seed ontwerp wordt in twee fasen geleid om een variabel seed ontwerp te vormen en de variabiliteit ervan te beheren voor co-creatie met de klant. De eerste fase begeleidt de ontwerper in het proces, beginnend bij de geadresseerde categorieën van behoeften tot de identificatie van variërende ontwerpparameters. Door filtering met een set van beperkingen wordt de variabiliteit van de parameters uitgedrukt als een oplossingsruimte, en deze worden vertaald in een ontwerpruimte waarin de gebruiker kan opereren. De tweede fase begint met het onderzoeken van de afhankelijkheden tussen ontwerpparameters en persoonlijke eisen, die vervolgens worden gebruikt om een ontwerpoplossingsalgoritme te bedenken. Om de interactie tussen de gebruiker en het ontwerp te vergemakkelijken, maakt de voorgestelde methodologie gebruik van een algoritme dat de ontwerpparameters wijzigt op basis van de input van de gebruiker, rekening houdend met de afhankelijkheden en beperkingen. Op die manier maakt het algoritme de interactie van de gebruiker met het ontwerp in real-time mogelijk, terwijl een betrouwbaar eindontwerp wordt gegarandeerd. Generieke principes van het algoritme die aan elk ontwerpgeval kunnen worden aangepast, sluiten de ontwikkeling van het seed design af. De output van het voorgestelde ontwerpproces is een seed design met een zekere variabiliteit en de middelen om samen met de gebruiker een gepersonaliseerd ontwerp te maken. Het totale ontwerpproces wordt dan voltooid door elke individuele gebruiker die tot een gepersonaliseerd ontwerp komt.

De eerste casestudie omvat de functionele, ergonomische en esthetische personalisering van een schoen die is vervaardigd door middel van 3D-printen en digitaal breien. Schoeisel is een van de eerste producten die in gedachten komen als het gaat om personalisatie, omdat het gerelateerd is aan zowel comfort als zelfexpressie. Daarom is het een zeer geschikte case om het gebruik van de voorgestelde ontwerpmethodologie te demonstreren. Deze casestudie past de methodologie toe op een gepersonaliseerd schoeiselontwerp met een gebreide bovenkant en een 3D-geprinte zool. Naast de pasvorm en het uiterlijk, wordt de variabiliteit van bepaalde functionaliteit van het gebreide bovenwerk onderzocht door de variatie van garens en breipatronen. De studie volgt het voorgeschreven ontwerpproces door het identificeren van de ontwerpparameters voor gepersonaliseerde pasvorm, uiterlijk en comfort, en door het vormen van oplossings- en ontwerpruimten. Ten slotte worden het ontwerpoplossingsalgoritme voor deze casus en een voorbeeld van een co-creatieproces voor een gebruikersinterface geïllustreerd. De studie wordt ondersteund door interviews met experts om het ontwerpproces en de inhoud van de studie te evalueren. Het potentieel van de voorgestelde ontwerpmethodologie wordt grotendeels bevestigd door de experts.

De tweede casestudie demonstreert de functionele personalisering van een saxofoonmondstuk om de prestaties van muzikanten op maat te maken. Het mondstuk is de plaats waar het geluid wordt geproduceerd in de saxofoon en het ontwerp ervan heeft een grote invloed op de prestaties. Daarom is de keuze van een mondstuk een zeer persoonlijke beslissing en er is een bestaande vraag van saxofonisten die op zoek zijn naar een mondstuk dat het geluid geeft dat zij wensen of dat past bij hun speelgewoonten. Bovendien maken de eenvoudige constructie en de hoge waarde van mondstukken het een zeer geschikt geval voor MP en on-demand productie met AM.

Een literatuurstudie en een onderzoek van bestaande producten brengen potentiële ontwerpparameters aan het licht, evenals mondstukkenmerken die gepersonaliseerd kunnen worden. Een uitdaging hierbij is echter het gebrek aan kwantitatieve kennis over mondstukontwerp. Daarom wordt een akoestische analyse uitgevoerd om kwantitatieve relaties tussen mondstukontwerp en prestaties te verkrijgen. Daartoe worden zevenentwintig 3D-geprinte mondstukken met negen verschillende ontwerpparameters getest met een kunstmatige blaasmachine, om hun effecten op vier geselecteerde mondstukkenmerken te bepalen. De experimentele analyse toont aan dat zeven van de geteste ontwerpparameters de prestaties van het mondstuk in verschillende mate beïnvloeden. De invloed van de ontwerpparameters op de mondstukkenmerken wordt, op basis van een statistische analyse, geïmplementeerd in een seed design, waarbij een grotendeels gekoppeld ontwerpgeval naar voren komt. Vervolgens wordt een gebruikersonderzoek met vijf saxofonisten opgezet om de uitkomsten te verifiëren. Het voorgestelde co-creatie scenario wordt succesvol getest met saxofonisten die hun mondstukken personaliseren via een grafische gebruikersinterface, en vervolgens de 3D-geprinte gepersonaliseerde mondstukken testen. De deelnemers bevestigen de prestatievariatie in zeven van de tien gevallen, en ze verkiezen de gepersonaliseerde mondstukken in vier van de vijf gevallen. De gebruikersstudie toont het vermogen van de ontwerpmethodologie om in te spelen op specifieke behoeften. In het algemeen verifieert deze casestudie de toepasbaarheid van de voorgestelde methodologie, en haar vermogen om gekoppelde ontwerpgevallen aan te pakken.

Tenslotte wordt een industrieel toepassingsgeval van FARO tandheelkundige lampen getoond om het gebruik in een praktische omgeving van een commercieel product te illustreren. Dit geval demonstreert ook het potentieel van de ontwerpmethodologie voor de hybride gevallen waar er zowel gepersonaliseerde als modulaire componenten zijn.

Over het geheel genomen tonen de casestudies het potentieel van de methodologie aan om te gaan met gekoppelde gevallen van massapersonalisatie en te voorzien in de specifieke behoeften van klanten. De drie hoofddoelstellingen van dit proefschrift over het creëren van variëteit, betrokkenheid van de klant, en prescriptieve ontwerpbegeleiding en tools voor MP worden bereikt door het ontwerpen van een ontwerpmethodologie voor MP en het testen ervan door middel van case studies. Het resultaat van dit onderzoek draagt bij aan het ontwerpdenken in MP om de flexibiliteit te benutten die opkomende digitale fabricagetechnologieën bieden, zodat efficiënt en effectief aan uiteenlopende klantbehoeften kan worden voldaan. Een systematische benadering van DfMP zal het mogelijk maken om MP uit te breiden naar meer producten en zal fungeren als een basis voor het klantco-creatiegericht ontwerpen in de context van dit opkomende paradigma.

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GLOSSARY

Symbols

h_{baffle}	Baffle height
s_{throat}	Throat size
r_{throat}	Throat shape
s_{chamber}	Chamber size
r_{chamber}	Chamber shape
l_{window}	Window length
l_{table}	Table length
l_{lay}	Lay length
h_{tip}	Tip opening

Abbreviations

MP	Mass Personalization
DfMP	Design for Mass Personalization
CP	Craft Production
MC	Mass Customization
DRM	Design Research Methodology
DS	Descriptive Study
PS	Prescriptive Study
RC	Research Cycle
ANOVA	Analysis of Variance
AM	Additive Manufacturing
CN	Customer Need
PFA	Product Family Architecture
DfAM	Design for Additive Manufacturing
OAP	Open Platform Architecture
FR	Functional Requirement
DP	Design Parameter
PV	Process Variable
DSN	Design Structure Network
DSM	Design Structure Matrix
OEM	Original Equipment Manufacturer
C	Constraint
PR	Personal Requirement
npi	Needles per inch
E	English System

Definitions

Mass Efficiency Efficiency of Mass Production in terms of cost and lead time

Mass Personalization Production paradigm, and business trend, of offering bespoke products to the customers with mass efficiency, while actively including them in the design process

Manufacturing Process Flexibility Ability to manufacture different designs or products at the same time without dedicated tooling

Digital Manufacturing An integrated manufacturing approach centered around a computer-based system that is collaborative and responsive to meet changing demands and conditions

Customer Co-Creation Active participation of the end-user in the design personalization process

Specific Customer Needs Diverse needs of individual customers

Seed Design A product design template with variable parameters that can be adapted to specific customer needs

Personal Requirements Technical descriptions of what can be personalized in the design

Design Space The variability of the seed design in the functional domain, a space of possible product functions

Solution Space The variability of the seed design in the physical domain: a space of possible design variations to realize a given function

1

INTRODUCTION

The advancements in digital manufacturing, along with the ongoing paradigm shift in industrial production, are disrupting not only the traditional means of production but also the way to provide for customers. The shift towards smart, data-driven, and flexible production systems enables providing on-demand and one-off products efficiently. In the light of these advancements, *Mass Personalization* (MP) is gaining significant attention to answer diversifying customer needs. The MP paradigm envisages the design and manufacturing of one-off products tailored to the individual needs of customers with mass production efficiency. While MP may cater to customer needs better, it may also provide a competitive edge to companies. To exploit these benefits of MP, the designers' role and approach have to adapt for designing products in the MP context. Besides the manufacturing flexibility, how to design the products to inclusively meet the individual needs while maintaining mass efficiency is of utmost importance to truly exploit MP.

Along with the benefits, MP also brings new design challenges. Products should have the adaptability to specific customer needs, and the design process should involve customers to a higher degree to elicit those needs. The traditional design methodologies treat the product development with a conventional production mindset, which has different considerations and concerns that do not necessarily apply to flexible manufacturing systems. Therefore, the existing design methodologies may lack in designing for the product variability in the MP context, involving customers in the design and providing them sufficient design freedom. Hence, designing for MP requires a different perspective and approach to effectively benefit manufacturing flexibility and to truly answer to personal needs.

This thesis work aims to develop a dedicated design methodology for MP that considers the distinct challenges coming along, leverages the benefits for all stakeholders, and focuses on the use of digital manufacturing. The objective is to provide a new perspective and tools to designers and companies in effectively employing MP and broadening it to a wider range of consumer durables.

This chapter introduces briefly the context of MP, followed by the related design challenges, the research aim and objectives, the research approach, and finally, the outline of the thesis.

1.1. CRAFT PRODUCTION TO MASS PERSONALIZATION

Although getting increasing attention mainly in the past two decades, personalized products have a much longer history. In the artisanal production of the pre-industrial era, made-to-order or bespoke products were a common practice, while not being accessible to the majority [7]. This form of production still exists to this day, while being largely replaced by industrial production. Looking at the history of industrial production (Figure 1.1), there have been a number of paradigm shifts, mainly driven by market conditions or customer needs and desires, and enabled by technological advancements [8]. With the First Industrial Revolution, the production paradigm changed from manual work to machine production, which is referred to as *Craft Production* (CP) [9]. In CP, the products were made-to-order, at a high cost, and with limited availability. Later on, to supply for the increasing demand for products, the introduction of large-scale manufacturing systems with moving assembly lines shifted the paradigm to *Mass Production* [1]. Mass production allowed the supply of large amounts of standardized products at lower costs. While the vast reduction of costs made the products accessible to the majority, the products lost their uniqueness with the *one-size-fits-all* approach.

Mass production sacrificed product variety for cost efficiency and productivity, but later the fierce market competition required new competitive advantages. As a result, the attention shifted from solely supply to markets and customer satisfaction, and the increase in product variety started with *Market Segmentation* [10]. The idea of market segmentation is to divide the market into segments of demand and cater the products according to these segments. As the competition increased, the markets were divided into smaller segments, which expanded product variety further. With the increasing demand for product variety, the attention on the market began to shift towards the customers and their more specific needs [1]. Hence, the paradigm of *Mass Customization* (MC) emerged to answer the diverse customer needs at near mass-production costs. MC aimed to expand product variety by providing modular and configurable products using reconfigurable manufacturing systems and flexibility of production lines and supply chains. The involvement of the customer in the design, or configuration, of the product also began at this point, by changing the customer's role from *choose* to *configure*. Although there are successful applications, MC is still far from the expected impact, with limited adoption by both companies and customers [11]. Two major underlying issues are the cost and complexity born from the modularity and the lack of customer interest in sole configurations [8, 11]. While the initial limits the product variety, the latter is an outcome of the limited quantity and quality of product variants. The limited options that are supplied by the manufacturer constrain the fulfillment of individual needs [8].

Customer needs are increasingly diversifying to this day, and still, largely mass-produced products fall short to answer these individual needs [12]. Besides the diverse customer needs, increasing global competitiveness, and dynamic market trends steer companies into the quest of serving individual customers at near mass-production costs [13]. Today, another industrial transformation is in progress that may allow the products to be both accessible and personal. The market desire for personalized products acts as a driving force in the paradigm shift towards smart manufacturing as envisioned in

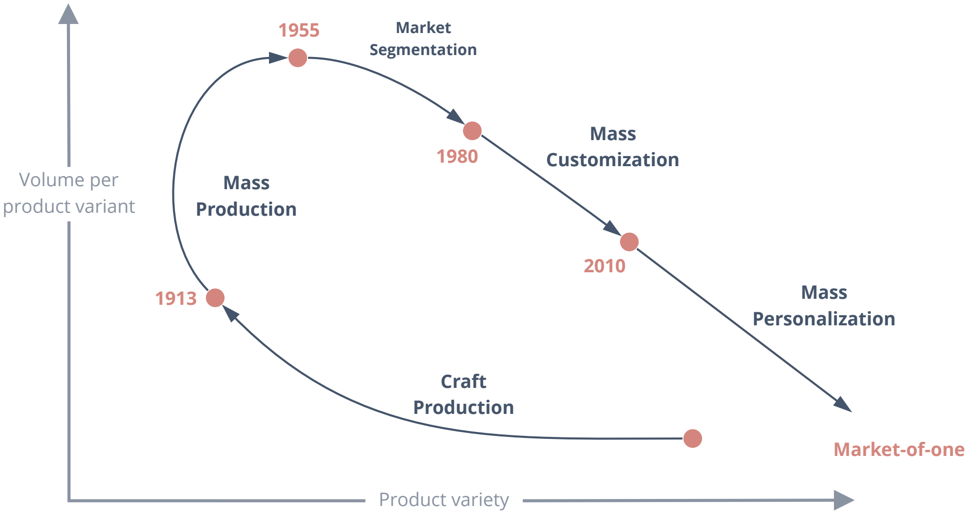

Figure 1.1: Volume-Variety relationship comparison of production paradigms [1, 2].

Industry 4.0, where manufacturing is on-demand, responsive and autonomous, using cyber-physical systems with advanced intelligence and flexibility [14]. The advancements in digital manufacturing technologies enabled the paradigm of MP, which aims to provide unique products to fulfill the needs of individual customers [15]. Digital manufacturing, particularly when considered in smart factory settings, addresses the cost and complexity arising from the stocks and management of modularity in MC, by integrating flexible manufacturing processes with information systems. This paves the way for providing tailored products to customers on-demand, with near-mass-production efficiency. Hence, MP differentiates from CP and artisanal practices that also provide made-to-order or personalized products, but with a high price tag due to the craftsmanship and additional labor. Whereas, MP is about affordable personalization, which makes it an interesting and viable strategy for businesses [16, 17]. The product differentiation that started with market segmentation, followed by MC serving the *market-of-few*, reaches the extreme case with MP aiming for the *market-of-one* by fulfilling needs at the personal level [5]. Fulfilling personal needs requires understanding the individual customers; which in this case transforms the involvement of the customer in the design process from *configure* to *co-create*. [18].

Along with the paradigm shifts in manufacturing, product design has also changed significantly over time [8]. According to Koren et al. [19], there are three main actions in all manufacturing paradigms: *make*, *design* and *sell*. What differentiates between the paradigms is the order and the participants of these actions. CP follows the sell-design-make order, where the craftsman both designs and manufactures the product. With mass production, product design becomes a separate professional activity, and the process comes to the design-make-sell order with the stocks of standard and professionally designed products. MC and MP require customer input, which brings the process into the order of design-sell-make. In MC, all the module variants are designed by the manufacturer, and the product is made after the customer chooses between the given options. In MP, understanding the individual needs requires an active role of the customer in the design process [8]. Besides, to fulfill these individual needs, the basic design and structure of the product must be changeable and adaptable [17]. As the products adapt more to customers, their involvement in the design process becomes more significant. The individual needs of the customer have to be transmitted to the design effectively. Therefore, the creation of variety through basic design and structure changes, and the effective customer involvement in design should be considered while designing products for MP. Hence, the *Design for Mass Personalization* (DfMP) has several differentiation points from the traditional product development; such as the roles of the designer and the user in the process, and the consequent considerations to realize the design or the product. The traditional development process is a single flow of actions starting from user needs and ending at a final product, executed by the designer. When designing for modularity or product families, the process is similar, with an expansion of options at the component level [20]. Hence, the user chooses between provided options. While designing for MP, the customer is a part of the design process. The product undergoes profound changes in an open process where the design is started by the designer and completed by the user. Therefore, DfMP is not only designing a product but also managing a dynamic process of facilitating users' design contributions. The active involvement of the user in the process, managing this involvement with mass efficiency, and the complexity of tailoring a product requires a dedicated design approach.

The applications of MP are still limited to date; rare applications of consumer durables are present in footwear, jewelry, or figurines [21]. Few successful applications are present in medical products, such as orthodontic aligners[1] (Figure 1.2a) and hearing aids[2] (Figure 1.2b). In the case of the medical examples, the advantage provided to the customer is affordable personalization. There are also examples that uses personalization as the means of value creation, such as personalized nutrition from Care/of[3] (Figure 1.2c) and personalized jewelry from Nervous System[4] (Figure 1.2d).

1.2. RESEARCH PROBLEM

A prerequisite of catering to the individual needs of customers is creating product variety to fulfill those diverse needs. The common way to achieve product variety is creating different product configurations by varying modules or components on a common platform [22]. However, the application of this approach to MP has two major limitations in the extent and definition of variety. The idea of modular configurations bases on the flexibility of supply chains and reconfigurability of assembly lines [23]. Increasing variety in this context often results in higher cost and manufacturing complexity [24]. Therefore, this approach tends to limit the variety and promotes commonality to reduce the complexity. However, such a limitation on variety contradicts the core idea of MP: fulfilling diverse individual needs. Moreover, the variety-induced complexity does not necessarily apply in the digital manufacturing context (discussed further in 2.1.1); as the primary

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[1] Invisalign clear aligners: www.invisalign.com/how-invisalign-works/living-with-invisalign-clear-aligners

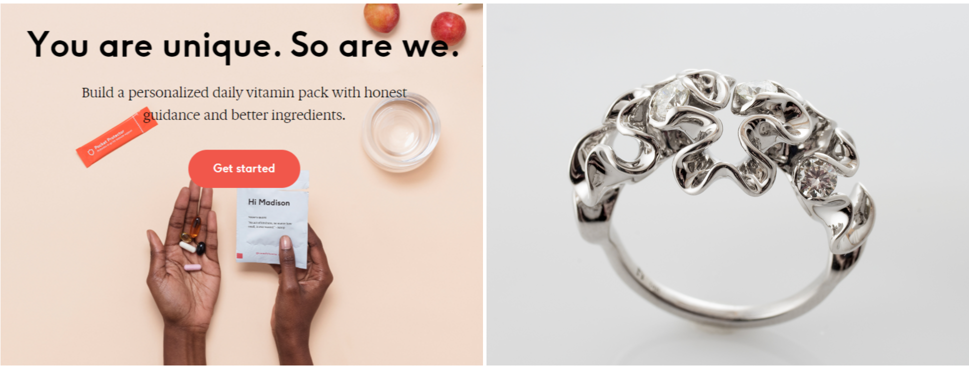
[2] Resound hearing aid: www.resound.com/en/hearing-aids/types/custom

[3] Care/of personalized nutrition: takecareof.com

[4] Nervous System personalized jewelry: n-e-r-v-o-u-s.com/cellCycle/?t=0

(a) Invisalign orthodontic aligner

(b) Resound hearing aid



(c) Care/of nutrition

(d) Nervous System personalized ring

Figure 1.2: Example applications of MP.

enabler of product variety is the manufacturing process flexibility [25]. Modularization defines variety over a set of varying modules, where each varying module fulfills a specific requirement. However, manufacturing process flexibility allows variability of the basic design, which may provide more profound variety. Besides, digital manufacturing may allow the integration of multiple functions and their working principles even in a single component [26]. Therefore, the modularization approach is insufficient to benefit such design variability potential. In conclusion, the existing approach is limited in exploiting digital manufacturing capabilities to create product variety, or variability, for MP.

A similar challenge is also present in adapting products to customers using standard configuration structures. These configuration structures cater for modularization at the assembly level, and they define hierarchical relationships of the optional or common components. The variety definition in MP may go beyond the component level, and also introduce certain design complexity. However, the standard configuration structures are insufficient for managing this. Increasing variety also requires involving the users in the design process more. However, stimulating the users' freedom of expression or understanding their needs or desires is also a challenge in the configuration form.

On top of the two main challenges mentioned, there is a lack of dedicated design methods and tools for guiding the design process for MP. There are adapted solutions in the literature, mainly from product family design and platform-based product development, which are extensively studied for MC [20]. However, as also explained for the first two challenges, these methods and tools originally target the MC paradigm, thus they approach the design process with an assembly and supply chain flexibility perspective. Therefore, they are principally limited in exploiting the full potential of MP. The lack of design methods and tools for MP to benefit digital manufacturing capabilities, and the necessity of a methodology to design personalizable products, are also highlighted by previous research [21, 27].

1.3. RESEARCH FOCUS

Design methodologies explain how to design or how the design should be [28]. Tomiyama et al. [28] categorize design methodologies by positioning in a two-dimensional space of *concrete vs. abstract* and *individual vs. general.* The methodologies falling into *concrete and general* category seek concrete descriptions that may be applied to a wide range of products. Among these, prescriptive methodologies with a systematic approach, such as Pahl and Beitz [29], are well known and widely adopted in the industry [30]. In this respect, to overcome the lack of design guidance and allow the utilization of MP effectively, the intended solution of this thesis is a prescriptive design methodology catered for MP. Addressing the challenges mentioned above, this thesis work focuses on the utilization of manufacturing flexibility in the process of developing a personalizable product; and an effective customer co-creation process that answers to specific needs. The main goals are providing guidance to designers throughout the development process of a user-modifiable design, and facilitating the user design effectively and efficiently.

The main objectives of the research towards a design methodology for MP are:

- O1: To determine the necessary product architecture that allows exploiting digital manufacturing capabilities in creating variety.
- O2: To determine the ways of customer-design interaction to address specific needs and fulfill these with the personalized product.
- O3: To develop prescriptive guidance and tools to be used in the DfMP process.

1.4. RESEARCH APPROACH

In their review, Fu et al. ([31]) categorized the research methodologies used in the derivation of design principles as:

- Methods building on existing principles, and validating or testing the theory.
- Methods making generalizations through analysis of existing designs, derivation from design practice, observation/experience of expert designers.

The major source of input to these methodologies is the existing literature, which is followed by an analysis of consumer products, patents, as well as observing, studying and interviewing designers or engineers. The initial approach first proposes a theory based on previous findings and then demonstrates it on applications, while the latter starts from existing applications or experience, and then reaches a theory through analysis and generalizations. As indicated earlier in this chapter, MP is relatively new for product design and the application cases of MP are rather limited. While design methods and tools specific to MP are also scarce, the literature on design for MC and other possibly relevant design domains is sufficiently mature. Therefore, this research follows the first approach of building on existing literature, with the assumption that, parallel to the historical succession of manufacturing paradigms, the design methods and tools can also build on the successors. Hence, the taken approach is to analyze and possibly adapt, the existing methods, tools, or frameworks for devising a design methodology for MP, and to demonstrate it in application cases. The alternative approach was to make generalizations from existing products or experiences. However, besides the scarcity of MP applications, there is also a lack of variety in these existing applications; the majority are limited to either only personal fit, such as the medical examples, or parametric designs allowing direct manipulation of form or aesthetics. Therefore, the lack of variety in the analyzed data might hinder the potential of the aimed design methodology.

A common research methodology in design science is the *Design Research Methodology* (DRM) of Blessing and Chakrabarti [32]. Their formulation of the DRM process has four main stages:

- Research Clarification (RC): a literature review to formulate research goals.
- Descriptive Study I (DS-I): empirical or review-based study to deepen the understanding.
- Prescriptive Study (PS): synthesis of experience and assumption to improve upon the existing situation.
- Descriptive Study II (DS-II): empirical data analysis to evaluate the effect of the suggested improvement support.

They define three types of studies used in these stages: a *review-based study* that is based only on a literature review, a *comprehensive study* that includes a literature review and a further study such as an empirical study, developing or evaluating support, an *initial study* that closes the project showing the consequences of the results and preparing it for the use of others. Based on the combinations of these three study types, they also propose seven types of design research projects. One of these is the *Development of Support*, which applies for the cases where the literature indicates the need to develop support to improve the existing situation, and existing support is non-existent, or insufficient in the context of new technologies, requirements, or contexts. Hence, this type of design research follows a review-based DS-I, followed by a comprehensive PS to develop support, and an initial DS-II for evaluation. This type of design research project is reasonable in the DfMP context since MP is a relatively new concept for product design, and an initial comprehensive study may not be possible without an existing implementation in the market or literature [33].

This thesis follows a four-stage research process, as shown in Figure 1.3. RC-I starts with a literature review to improve the understanding of the MP paradigm. This thesis

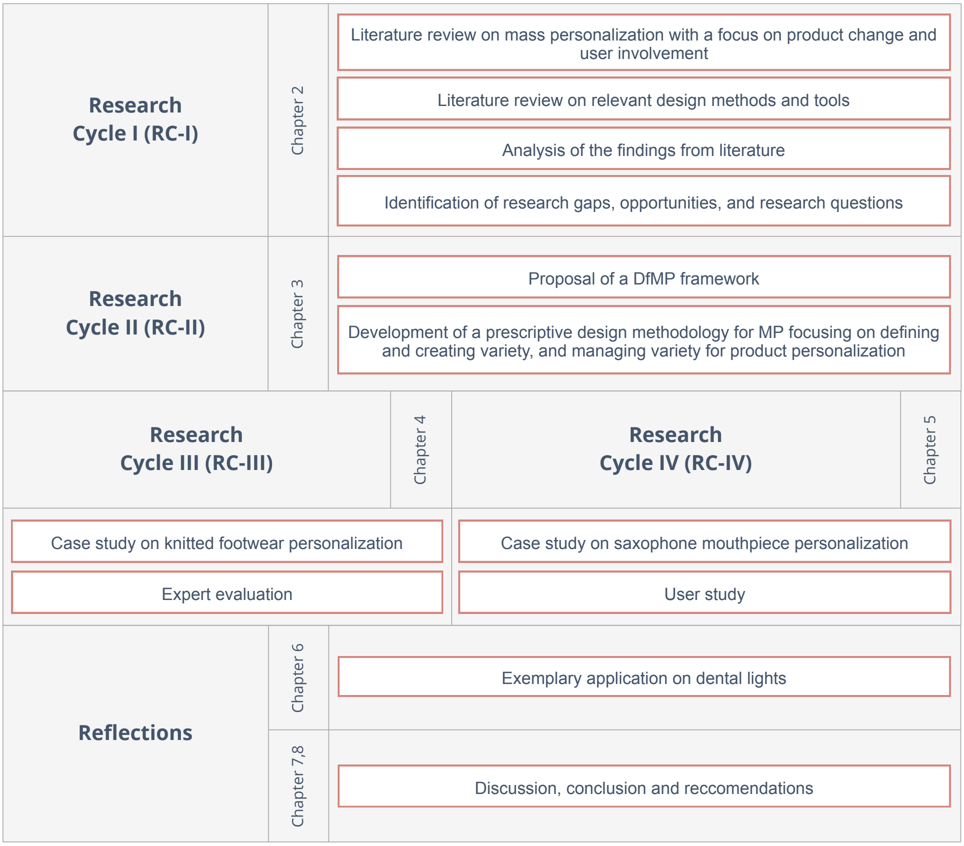


Figure 1.3: Research process.

approaches MP from the product perspective, and considers the topics at the product-manufacturing and product-user intersections, with a focus on product change. Hence, the literature on MP is reviewed from this perspective to mainly understand how it differs and what are the needs in terms of the design process to realize MP. Based on the insights gained in the first part, the second part of RC-I discusses the state of the art in relevant design methods and tools. A critical analysis of the state of the art concludes RC-I with detailed research questions, gaps, and identification of possible design tools and approaches that are adaptable for DfMP.

RC-II aims for the main theoretical contribution of the thesis with the formulation of the aimed design methodology based on the understanding and inputs from RC-I. Hence, the approach is to synthesize the understanding of the needs and peculiarities of MP with the state-of-the-art design literature to build a design methodology catered for MP with adoptions from existing methods and tools, and introduction of new ones where needed. Therefore, the first step is the introduction of a framework to clarify the design activity. This is followed by a definition of variety for MP. Based on this definition, the prescription of a design process that is composed of two main parts addressing the first two research problems follows. The first part explains how to create variety, and the second one illustrates how to manage this variety with customer involvement.

RC-III and RC-IV cover two exemplary applications of the design methodology proposed in RC-II, to demonstrate the practical outcomes, and to make some reflections on the benefits, challenges, and limitations. For this purpose, these research cycles include case studies in two diverse domains to demonstrate the range of applicability in industrial cases. In both cases, there is an existing demand for personalization, and both are based on existing RD topics that led to commercial solutions. The main contribution of these stages is to the practice, while there is also a theoretical contribution in terms of personalization in these domains. The challenge in this research is that there is a significant amount of domain-specific knowledge to be considered. Therefore, both RC-III and RC-IV start with a literature review to improve the understanding of the selected products and the associated customer needs.

RC-III includes a case study on knitted footwear that explores all three aspects of personalization: the fit, appearance, and functionality of the product. Thus, it provides a good overview of applying the complete methodology. In addition to 3D printing, there is also digital knitting in this case to illustrate the usage of another digital manufacturing process. The study uses the literature review as the input of the design process and combines it with the process capabilities to create product variability. To further support the case study, an expert evaluation follows with the interviewing experts from various related domains to evaluate the design process, its implications, and its use in the footwear context.

RC-IV includes a case study on 3D-printed saxophone mouthpieces, which focuses on the functional personalization of the product. This is a very suitable case to demonstrate how multiple functions can be varied in a single part by fine-tuning its design. Hence, the benefit of the methodology becomes more evident, as there is also a coupled design case while tailoring the performance of the mouthpiece. This stage also includes an experimental process to characterize the performance of the mouthpiece with respect to design variations. The experiment design employs the *Taguchi Method* [34], and the measurements are analyzed with the *Analysis of Variance* (ANOVA) [35]. Besides providing input to the case study, the experiment also contributes to the understanding of mouthpiece design. A user study concludes this research cycle to test the outcomes of the case study with end-users and to understand how users perceive and react to the proposed co-creation scenario.

1.5. THESIS OUTLINE

Following this introductory chapter, this thesis includes four chapters disclosing the thesis research, an application example, a discussion, and a final concluding chapter. Chapter 2 begins with a literature review on MP to improve the understanding of the paradigm from a design perspective. Then, the review and discussion of relevant design methods and tools follow. A critical analysis to identify the research gaps and questions concludes the chapter.

Chapter 3 proposes a DfMP methodology. First, a DfMP framework is introduced to demonstrate the considered approach for the development process and user co-creation. Based on a proposed seed design architecture, a two-phase seed design development process is presented to define the variability of seed design and to manage the variability for user co-creation.

Chapter 4 applies the proposed design methodology to the first case study to illustrate its use and benefit. This study examines the seed design development of a shoe consisting of a knitted upper and a 3D-printed sole and explores the digital knitting and additive manufacturing capabilities of MP. The study finalizes by presenting the evaluation of a group of experts on the case study.

Chapter 5 presents the second case study on MP of 3D-printed saxophone mouthpieces. In this case, how to tailor the performance of the mouthpiece for players is studied. For this purpose, an experimental investigation on how design changes affect performance is carried out. A user study concludes the chapter to validate the experiment results, and test the co-creation scenario proposed.

Chapter 6 presents an exemplary application of the methodology in an industrial case. The design methodology is illustrated on a dental lamp personalization case, based on a product from Faro S.p.A., the funder of this research.

Chapter 7 includes a general discussion of the research outcomes in response to the research questions, and identified limitations. The findings of the practical cases in RC-III and RC-IV are reflected in the first two research cycles to position the theoretical contribution with respect to the literature.

Chapter 8 concludes the thesis work by summarizing the findings related to the research questions; implications for the scientific community, designers, and industry; and the possible directions of future work on DfMP are presented.

2

LITERATURE REVIEW

The purpose of this chapter is to improve the understanding of MP and to provide a foundation for the aimed design methodology. In this regard, the first section expands on MP, focusing on its key dimensions from the design perspective, and attempts to clarify what are the objectives, requirements, or enablers of MP. This is in a comparative form showing how MP differs from the previous paradigms to highlight the different needs in terms of the design process. In the light of the findings above, the following three sections review and discuss the state of the art in design methods and tools related to creating product variety, adapting products to customers, and DfMP frameworks. The last section analyzes the findings to position them according to the needs of MP, identifies the gaps, and proposes the research questions. A large part of the content below has been published in *Design Science* [36].

2.1. MASS PERSONALIZATION

MP has various definitions in the literature, commonly referring to the procurement of bespoke products to the customers with *mass efficiency*[1], while actively including them in the design process [5, 37, 38]. There are also different terms referring to the same concept, such as *Ultra Personalization* [39], *Mass Individualization* [8] and *Individualized Customization* [9]. There is also an overlap in the usage of MP and MC terms in the literature. Therefore, it is beneficial to clarify what qualifies as MP in this context. This thesis research follows the definition of Tseng et al. [37]:

> *Personalization goes beyond configuration-to-order product lines and needs to explore market potential by leveraging product functionality with the realization of affective and cognitive needs, hence enabling product differentiation beyond the original set of product offerings. While customization assumes fixed product architectures and pre-defined configuration models, personalization implies possible changes to the basic design and product fea-*

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[1] Near-mass-production cost and lead time.

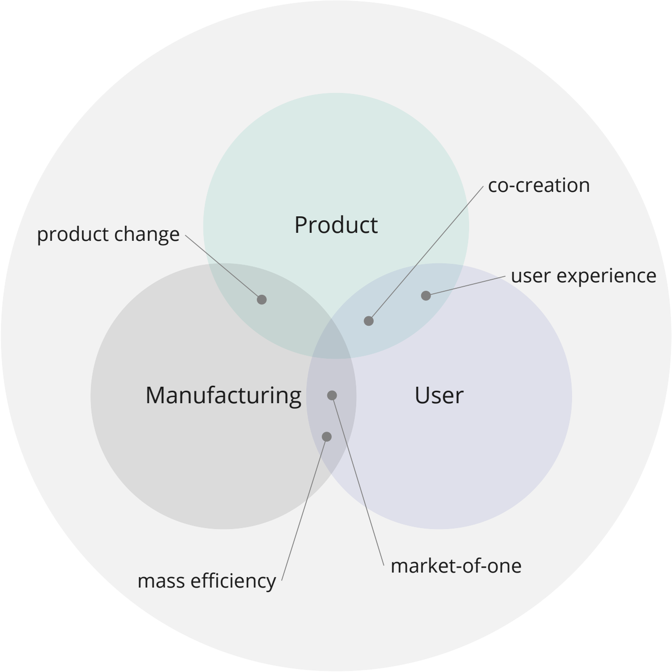

Figure 2.1: Main subjects of MP from design perspective, and the key topics at their interactions.

> *tures. The adaptability and changeability of product designs become essential for personalization.*

Besides the definition of MP, a clarification on the scope of products covered might be necessary. There is also the usage of the MP term in the context of digital products and services[5]. This thesis work addresses the MP of consumer durables.

MP paradigm interacts with various disciplines, and it can be treated from different perspectives at several levels, such as product development, production systems, or business and marketing [5]. From a design perspective, MP has three main interacting subjects: product, user, and manufacturing (Figure 2.1). At the interaction of these, Zheng et. al. [38] identify the three key characteristics of MP as user experience, co-creation, and product change. In addition to these, Zhou et al. [5] include market-of-one and mass efficiency as key dimensions as well. Each of these topics is of key importance to the application of MP. This thesis approaches MP from the product perspective, and considers the topics at the product-manufacturing and product-user intersections, with a focus on product change. The rest of this section expands on MP in this respect.

2.1.1. MANUFACTURING AND PRODUCT DIFFERENTIATION

Product differentiation to gain leverage in the market is not a new approach. The age-old artisanal practice of tailor-made products is an initial example. In mass production, this appears as market segmentation of products, where usually a single product is offered in each market segment. Mass customization classifies customers into different segments and clusters the needs of the customers in the same market segment. Then, according to these clustered needs, customers are offered different product configurations within a predefined product family [40]. In mass personalization, customer needs are fulfilled at the personal level. The basic product design and features may change to provide unique products tailored to each individual [37].

Moving from mass production to mass personalization, each new paradigm takes forward the concept of the previous and requires more responsive manufacturing systems [1]. MC paradigm mainly relies on the traditional mass-production methods, and flexibility in the supply chain and assembly processes allows different product configurations [23]. The product differentiation in MC bases on the modularity and commonality of components to provide variance for customers [41]. In MP, the flexibility needed is at the lowest level of manufacturing. Industry 4.0 introduces information and communication technologies into manufacturing to develop smart factories with intelligent and adaptable processes. The Industry 4.0 roadmap includes the ability to produce affordable and highly personalized products with reasonable lead-time [42]. The envisioned smart manufacturing enables mass personalized production with highly flexible processes [43]. Lu et al. [14] describe smart manufacturing as *"fully-integrated, collaborative and responsive operations that respond in real-time to meet changing demands and conditions in the factory, in the supply network, and in customer needs via data-driven understanding, reasoning, planning, and execution of all aspects of manufacturing processes, facilitated by the pervasive use of advanced sensing, modeling, simulation, and analytics technologies".* Digital manufacturing technologies are key components of the smart manufacturing paradigm for data-driven and flexible production. Digital manufacturing includes both additive and subtractive processes that are controlled with computer-based systems integrating processes such as CAD, simulation, visualization, and analytics [44].

The value of digital manufacturing becomes more evident as the product, and its manufacturing gets more complex [13]. In this context, *Additive Manufacturing* (AM) processes become prominent by virtually providing *"complexity for free"* [45]. The layer-wise material deposition and not requiring dedicated tooling allow AM processes to open up new design opportunities, such as lightweight design optimizations, hierarchical structures or part consolidation [46]. The provided design freedom and flexibility also allow product differentiation by changes at the basic design level, which creates a great potential for MP. Therefore, to enable MP, AM processes are of particular importance among digital manufacturing technologies.

As MP relies on a different manufacturing paradigm than MC, the design considerations should also be accordingly to integrate design and manufacturing seamlessly. From the Industry 4.0 perspective, although smart factories can support personalized products with efficiency, to completely exploit the benefits, products should be designed for smart manufacturing [47].

2.1.2. CUSTOMER INVOLVEMENT

As the level of change in product differs, the *customer needs* (CNs) addressed by different mass-market strategies change as well. The customer needs can be categorized as generic and specific needs. In mass production, generic customer needs of a market segment are identified, and relatively important needs for the majority are implemented into the product [48]. Mass customization groups these generic needs of the same segment, instead of generalizing them, and aims to meet similar needs with similar products in a family [49]. Mass personalization goes further and addresses the specific, mainly affective and cognitive, needs. Besides the informed customer decisions, unexpected needs of individuals are exploited [5].

The needs that MP addresses are not only related to the product, but also to the experience of the personalization process because of active customer participation. In MC, the customer makes passive choices within established offerings. The products and configurations are already available before the customer is involved. While in MP, customers actively take part in the design process, co-creating a personal product [17]. The product is unfinished when the customer involves, and the unknown and changing customer requirements necessitate an agile approach for MP [42]. The real-time interaction of the customer with the design is necessary for the development, and this also contributes to the experience and satisfaction [5, 16]. Aheletoff et al. [42] also pointed out the importance of real-time interaction in terms of informing the customer of any extra cost associated with a product specification. This co-creation activity is also a value creation process, via both utilitarian and hedonic innovation. Besides the augmented usability value of the product, there are also sensorial, emotional, and symbolic values to contribute to the user experience [38]. Zhao et al. [11] also suggest that a co-creation approach may increase perceived usefulness, enjoyment, and satisfaction, compared to product configuration. The advanced customer participation also requires MP to be considered not only from a product development perspective but also to be handled as a service design task [50].

MC targets a market of few, and its leverage is mass efficiency while offering different configurations. MP aims for a market of one, and it relies more on value creation than efficiency. However, there is a limit to the created value outperforming the cost. Previous research confirms that personalization indeed adds value for customers, however their willingness to pay for this added value is up to 30% more compared to mass-produced counterparts [51], [6]. The Deloitte consumer review [52] also reports similarly; about a third of the customers are willing to pay only 10% more for a personalized product, while another third is willing to pay 20 to 40% extra. These findings cover product categories such as clothing, footwear, jewelry, electronic gadgets, and homeware. An exception to these is with medical products, where the added value is more significant, and customers may prefer a personalized product even regardless of its cost since there is a health-related benefit. But, for the rest of the consumer durables, targeting mass efficiency is still crucial to attract customers. The major cost drivers of MP are the design personalization process and manufacturing. The flexibility of digital manufacturing is a prerequisite for MP, while automation of design personalization is a major necessity to achieve mass efficiency.

2.1.3. DIFFERENCES TO MASS CUSTOMIZATION

The major differences between MC and MP are summarized in Table 2.1. MP is an evolution of MC as a result of advancements in manufacturing and increasingly diverse CNs,

Table 2.1: Major differences between mass customization and mass personalization, adapted from [1, 5, 6].

Comparison	**Mass Customization**	**Mass Personalization**
market	market of few	market of one
customer needs	explicit needs of a market segment	individual needs
customer role	choose and buy	design, choose and buy
customer participation	end-user configuration	end-user co-creation
value proposition	product variety	tailored product and hedonic values
product change	variety based on modularity and commonality	changeable and adaptable product/service platform
production system	reconfigurable manufacturing	on-demand manufacturing

and it is seen as the advanced version of MC [5]. However, MP is not applicable to all products and is limited by its "personal" nature. It is useful where there can be value creation via exploiting personal needs and user experience, such as in consumer durables. Besides, mass efficiency is not achievable for all products to align the value creation with customer willingness to pay. MC, on the other hand, is more widely applicable in any context where varying solutions are needed. Therefore, it is not completely appropriate to see MP as a successor to replace MC. Both paradigms may be applied in different contexts for different scenarios, and they can even complement each other in some aspects [5].

2.2. DESIGN FOR PRODUCT VARIETY

The traditional product development process for mass production generalizes the CNs, and the process converges to a single product that fulfills those needs the most effectively [48]. On the contrary, in design for MC or MP, the development process diverges up to a feasible point to create product variety to fulfill a range of different CNs [37, 40]. As a common practice, the variety is created over a design template that can be adapted to the needs of the specific customer to realize a final product. A design template includes certain varying design parameters that form a solution space, where diverse customer requirements can be satisfied [53].

The created product variety, in terms of the level of product change or the extent of variety, depends on the architecture of the design template. The architecture contains the definition of varying parameters and commonality of certain aspects, and in some cases includes also information regarding design guidelines, restrictions, and manufacturing or assembly instructions [53–55]. In terms of the definition of varying parameters, Li et al. [55] classifies the templates as rigid and variable geometry, structure, and functional ones. Rigid geometry templates are common in the MC context, which are formed using *Product Family Architecture* (PFA). In PFA, the product change is at the level of modules or components to develop product variants [53]. The variety created in a PFA by different combinations of modules or components results in a solution space with discrete options. As MP aims to fulfill more specific CNs, it requires more continuity in the solution space. As a result, the limited examples of MP use varying geometry templates that include the dimensional variability of the parts of a product, or of the design elements of a single-part product [54, 56]. While digital manufacturing technologies allow certain dimensional variability in general, AM processes are particularly capable of offering more profound changes in the product. The three-dimensional geometric freedom and varying material distribution enable a wide range of new design opportunities [30]. This includes the ability to create functional variability through design alterations; such as design optimizations through cellular structures or topology optimization [57]. Therefore, the design domain of AM may give insights into defining variability in many other forms than modularity or simple dimensional variety.

As much as the definition of variety through the design template architecture, the process followed to identify the design parameters and how they relate to the requirements is also important for creating product variety. The sections below discuss different forms of design templates and the design processes to create variety.

2.2.1. PRODUCT FAMILY AND PLATFORM DESIGN

The design for MC bases on product family and platform design methods to create product variety. The concepts around product family design, platform-based product development, and PFA have been studied extensively by previous research [20, 22, 58]. In this context, the design template appears in the form of a product platform and a set of modular components in a PFA [58]. A product family is a set of products that share some common components and functions, which is called a product platform. The variety among the product family is provided by the modularity of components interfacing the product platform [20]. While commonality among the product family provides cost savings and standardization, variety allows covering the needs of more customers [41]. The potential cost savings with commonality come with the potential value decrease in the product due to loss of uniqueness. Therefore, there is an effort in product family design is to find an efficient trade-off between these two conflicting terms [24].

There is also an effort to adapt the product family approach for personalization by introducing personalized modules as a third kind, in addition to the product platform and varying modules. The personalized modules are produced customer-specific for each order and combined with the platform and variant modules. They also share a standard interface with the modular architecture, and they are decoupled as far as possible from other components for the ease of configuration process [59]. Another type of module is a scalable one, which is similar to personalized modules, but in a more primitive version. A scalable module provides variety by stretching or shrinking some of its parameters within a continuous range or discretely [22]. Same as personalized modules, scalable modules are also decoupled as far as possible, and remain at the bottom of the configuration hierarchy.

Product family design and platform-based product development methods are well-established and already applied in a wide range of products for MC. This approach bases on reconfigurable manufacturing systems, thus creating variety by modularization or variety-commonality trade-off are valid and beneficial in that context [1]. However, these considerations do not necessarily apply in the digital manufacturing context, where the variety can be provided through flexible and responsive manufacturing processes [25]. Therefore, this is a major limitation in the use of product family and platform design for MP. Introduction of personalized, and scalable modules are attempts to improve the applicability of this approach to MP. Both of these types of modules may provide a certain degree of personalization to the product. However, they are still considered from a modular design perspective, as they still have standard interfaces to the platform, and are functionally and structurally independent of the rest. The design of a scalable module is simpler; it provides limited, but continuous, variety. Hence, it may be sufficient for certain personalization cases. Moreover, personalized modules may help more to adapt the product to the customer. However, how to design a personalized module is not elaborate, and it is foreseen as a dedicated design effort for each customer. Besides, it is also considered a separate development process from the PFA [26]. Consequently, how to develop personalized modules with mass efficiency is still an open question.

2.2.2. DESIGN FOR ADDITIVE MANUFACTURING

Since MP is principally a production paradigm, DfMP should include the considerations of manufacturing technologies and processes that MP relies on. In this regard, Design for Additive Manufacturing (DfAM) is of particular importance, as AM is one of the key enablers of MP. DfAM includes a set of methods and tools to link design and manufacturing processes, considering AM capabilities and limitations [60]. Laverne et al. [30] categorize the DfAM methods according to the way they assist designers as opportunistic DfAM, restrictive DfAM, and dual DfAM. Opportunistic DfAM methods aim to propose new shapes or concepts with a creative approach to explore the geometric or material complexity offered by AM. Restrictive DfAM methods focus on the design assessment, to ensure the compliance of the design with the limitations of AM, such as performance and characteristics of AM machines or usable materials and their properties. Dual DfAM implies the methods combining the previous two approaches. The authors claim the dual DfAM methods as more suitable for designers, stating that *they use the potential of AM in a realistic way* [30].

Rias et al. [61] describe four levels of complexity that AM is capable to introduce in products: shape, material distribution, structure hierarchy, and functionality. Given the flexibility of AM processes, it is also reasonable to consider the opportunity of design variability for MP at these four levels. The subtopics of opportunistic DfAM, such as cellular structures, topology optimization, multi-material printing, or part consolidation, demonstrate how to improve the design of products at different levels [57, 62]. These different approaches employ varying parameters at different scales, from microscale voxel-based material layout or multi-material distribution to larger parts or design features. For instance, topology optimization seeks to optimize the material layout within a solution space by fulfilling given constraints to reach a certain structural design goal [63]. In this case, variety is in the material layout, and the pre-given solution space and constraints resemble the concept of commonality. There are also examples of product personalization with DfAM approaches; Teixeira et al. [64] developed personalized 3D-printed heel inserts for shoes to improve the comfort according to pressure distribution by using a cellular structure with varying mesh density.

To benefit the capabilities of AM, there are methods combining DfAM methods with PFA. Lei et al. [25] proposed an AM process model for PFA that utilizes topology optimization, and subsequent analyses, to design custom components. The aim of the model is to eliminate the constraints arising from commonality-performance compromise in conventional product family design. Another approach of using DfAM for creating product variety is introducing restrictive DfAM into PFA [53, 59, 65, 66]. Spallek et al. [65] categorize the development processes as standard individualization and specific adaptation. Standard individualization divides the product into individualized and non-individual components, similar to PFA with only personalized modules and platforms. While non-individual components are designed for mass production, individualized ones are designed with a DfAM approach. Specific adaptation is a personalization case, first, the product structure is designed with an individualization scope, then the design process repeats for each customer within a fixed solution space, where process-specific DfAM considerations are present. However, this is not in a mass context, since the authors highlight the necessity of customer-specific design efforts. Although the specific adaptation is stated as true product individualization, the authors underline the disadvantages of the difficulty in developing a design template and the lack of corresponding knowledge in the literature.

Designing for AM enables the integration of multiple functions and their working principles in one part. However, this is in contradiction with the design for variety approach in modularization, which structures the variety with a one-to-one mapping between functional requirements and components [26]. Besides, the major consideration of compromising between commonality and variety becomes insignificant with the design freedom AM offers [25]. In the case of AM, using traditional considerations of design for manufacturing and assembly may limit the design opportunities, and result in failure to fully exploit the potential [46]. Consequently, the product family design approach is principally limited in both exploiting the benefits of AM and effective product development for MP.

2.2.3. DESIGN TEMPLATES FOR MASS PERSONALIZATION

As the aim goes towards meeting more specific customer needs, evidently creating variety becomes more essential. Aheleroff et al. [42] claim adapting the design over a design template is the most important and value-added part of MP. Bingham [21] refers to it as *seed object* or*seed design*, and describes it as *the starting point for all subsequent transformations and is specifically created to allow some form of personalization by the intended end-user/customer*. Boisseau et al. [67] propose a similar definition as *meta-design*, where the designer acts as a facilitator by enabling the user modifications within the open design framework [67].

Besides the theoretical explanations, there are a few practical definitions of design templates in the MP context. Lipton et al. [54] proposed a design template for carpentry products to be used by experts, where the proposed method verifies the design and fabricates it by robotic systems. The template allows controlling dimensional parameters, and then the system does a structural analysis of the design. However, it does not allow designing for the desired functionality, as the user sees the functionality after co-creating the product. Shugrina et al. [56] suggested a method to convert any parametric model to a seed design for online product configurators, with which the user interacts in real-time. The user gets a few parameters to modify while having real-time feedback on the validity of the designs and valid parameter bounds. Considering the AM capabilities mentioned in the previous section, these parametric design templates have certain limitations. The user directly modifies the design in such an approach, however, when the design parameters go beyond the dimensional ones, such as material layout, it becomes nearly impossible for the user to control such parameters. Even if it was possible, another challenge is to estimate the behavior or performance of the product in such a case.

There are a number of approaches building on PFA by defining an *Open Architecture Platform* (OAP) [19, 33, 68, 69]. The motivation for considering OAP under this section is that, although this is a specific case of PFA with personalized components, the primary aim is product personalization. The idea behind OAP is to increase product variety by allowing third-party producers to provide personalized modules. In this case, the user first chooses a platform from the main producer, and then the preferred modules from third-party producers. Afterward, the main producer receives the selected modules and finalizes the product. While this approach may provide increased variety in comparison to PFA, truly personalized modules still require a dedicated design effort for each customer.

2.2.4. DESIGN PROCESS FOR CREATING VARIETY

Besides the architecture of a design template, the process of defining its variability is a determining factor for product variety. The majority of the product development methodologies follow a fundamentally similar path from customer to process domains in the design process. The differentiation is in the way to connect and decompose these domains. The common process is, very briefly, identifying customer needs (CN) first, then translating them into functional requirements (FR), identifying the design parameters (DP) that fulfill the FRs, and finally determining process variables (PV) for production. Established product development methodologies demonstrate similar processes [29, 48].

The design for MC adapts this process for product family design, by clustering the DPs serving the same set of FRs, to provide variability in design [40]. This involves limiting the spread of FRs, in other words, limiting the variance as a trade-off to reduce the related costs. Gauss et al. [22] highlight the lack of interaction between functional and physical domains in the majority of product family design methods, as the FRs and DPs are not decomposed concurrently. Similarly, Pirmoradi et al. [20] state the necessity of considering interdependencies among different design elements as a challenge of product family design. There is also a disconnection between the customer and functional domains, since the majority of the methods derive FRs from existing solutions, but not from CNs [22]. Jiao et al. [58] also points to a lack of customer modeling and integration in product family design. While the lack of interaction between the customer and functional domains may prevent addressing the needs effectively, the lack of interaction between functional and physical domains may result in a suboptimal solution space.

A prominent method to improve the link between adjacent domains is *Axiomatic*

Design (AD), which supports the transformation process from customer domain to functional and physical domains. Axiomatic design theory brings a systematic method to the design specification process [70]. With a top-down approach, the variables of customer, functional, physical, and process domains are decomposed to clarify the design task (Figure 2.2). AD maps the domains to each other, with the reasoning of *what to achieve* and *how to achieve it*, and decomposes them by zigzagging between domains (Figure 2.3). According to AD, the independence, and information axioms must be followed to achieve the best design solution. The independence axiom suggests maintaining the independence of FRs by appropriate selection of DPs. Only uncoupled or decoupled design cases satisfy the independence axiom. The aim is to reduce the complexity and thus avoid unintended consequences in the design solutions. Suh [70] defines the complexity here as *a measure of uncertainty in achieving the specified FRs.* If multiple designs fulfill the independence axiom, then the best design with the minimum information content is chosen according to the information axiom [3]. These axioms are utilized at each step of the decomposition.

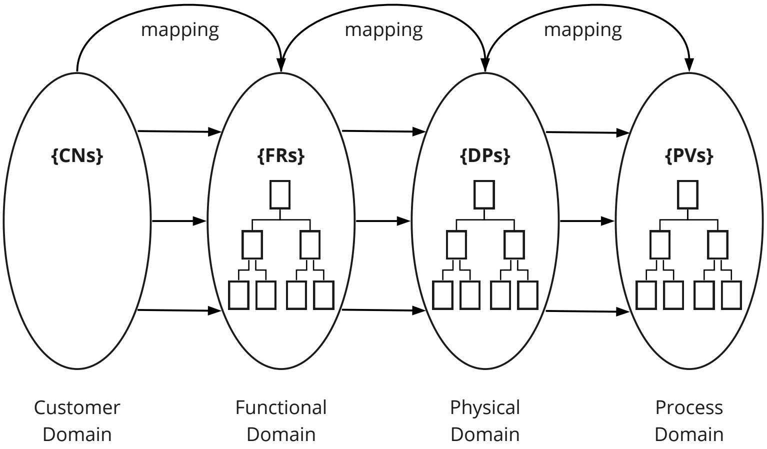

Figure 2.2: The axiomatic design domains.

Although largely used in traditional product development, there are also efforts to apply AD principles to design for MC. Jiang et al. [71] explored the use of AD in the functional and physical decomposition of the PFA. Tseng et al. [40] adopted axiomatic design principles for product family design, by introducing a PFA that defines building blocks to be configured to individual products. Marchesi and Matt [72] exampled the use of AD in design for MC, with a study on the conceptual design of prefabricated housing.

Another approach to AD is from a DfAM perspective; Salonitis [73] pointed out the lack of manufacturing considerations in the functional and physical domains of AD, and proposed a modified method focused on DfAM. The proposed method includes also the process domain in the zigzag decomposition of FRs and DPs to consider manufacturing guidelines in the early design phase. Although this method does not intend to create variety, it sets a valuable example of considering manufacturing capabilities or limitations at early stages. This is especially significant to set the boundaries of design variability

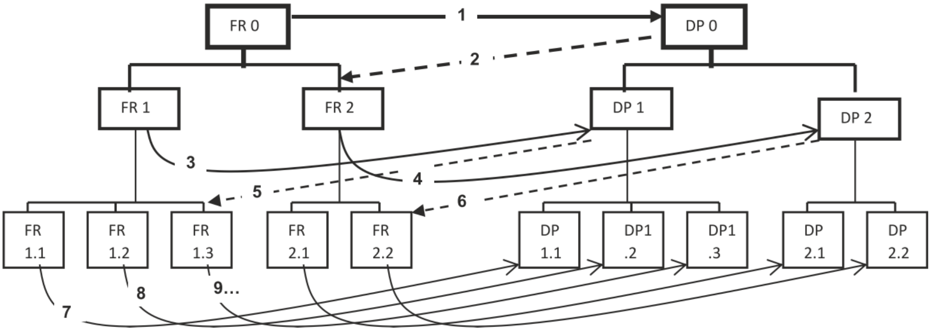

Figure 2.3: Zigzag decomposition example between functional and physical domains [3]. The arrows with numbers indicate the direction and order of the flow.

that process flexibility enables.

The variance of design possibilities in MP is much greater, which results in higher complexity in design specification and solution steps [74]. The complexity arises from the variables in the customer, functional and physical domains, and the interdependence of these variables. Hence, it becomes more critical to define these variables and understand how they affect each other to create effective product variability that meets the customer needs. In this sense, the disconnection between domains in the design processes for PFA is a limitation for MP. Although AD improves this condition, it is also based on functional independence, and thus avoids design coupling. As also Section 2.2.2 discusses, this may not be always ideal or possible when a single component contains multiple functions, or when the DPs are at such basic structure or material level that their effects are inseparable. In such cases, aiming for an uncoupled design may reduce the variability significantly. Therefore, DfMP should consider accepting a certain degree of design complexity. A major gap in DfMP literature arises at this point on how to structure different domains concurrently and manage their interactions under large and coupled variability. One of the few attempts on this topic is by Ko et al. [66]; they proposed a computational approach to include restrictive DfAM in the development of personalized products. The proposed method identifies the interrelations between AM considerations, customer needs, and product features using finite state automata and affordance. However, this method does not cover how to define the variables in different domains. A method that does define the variables is the *Design Structure Network* (DSN) of Loureiro et al. [74]. DSN aims to help the design specification step for MP. The method demonstrates the interdependencies of FRs and DPs visually on a network, decomposes them, and suggests principles to manage the network complexity. Among the reviewed literature, DSN is the only method that primarily focuses on MP, and presents a prescriptive solution. It does provide an alternative to the what-how mapping of AD, however, it only focuses on the concurrent decomposition of the functional and physical domains. For instance, the variability range of the identified FRs and DPs is still an open question.

2.3. PRODUCT CONFIGURATION

Designing a product template is a diverging process to create variety, and the following step is converging to a specific design solution for each customer, to finalize the overall design process. The variability of the design template creates a design solution space that includes all theoretically possible design solutions [55]. The design solution step translates the requirements of a specific user into DPs, and looks for a design solution in a given solution space. In the case of MC, increasing variants in a product family create higher cost and manufacturing complexity [59]. Hence, this brings up the necessity of solution space management to sustain mass efficiency. Gembarski and Lachmayer [75] proposed an approach for complexity management of solution space in MC, regarding two dimensions of variety and uncertainty. This approach bases on finding a balance between CNs and portfolio capabilities by increasing or reducing the complexity. The authors also proposed a solution space development tool for geometry-based design tasks [76]. The tool aims to lay out the dependencies between requirements, parameters, and restrictions on a matrix to support design solution decisions. Skjelstad et al. [77] introduced manufacturing considerations in solution space management for MC, to balance the customer and manufacturing perspectives. They also identified solution space archetypes with varying importance of product form, fit, and function. The efforts on solution space management in a way confirm the lack of interaction between domains in the development process, as discussed in the previous section. They help to improve the connections between domains by adjusting a rather pre-formed solution space to requirements. A significance of these efforts is showing different approaches to set the boundaries of design freedom. The main criteria for setting the boundaries appear as interconnections between domains, cost, and manufacturing. Since MP relies on process flexibility, manufacturing considerations become more significant to understand the limits of variability. In a way, the methods introducing restrictive DfAM into design processes partially address this issue as well [26, 65, 73]. The main motivation for limiting the solution space in MC is to reduce the cost and manufacturing complexity. This is not necessarily the case for MP, since the variability at the process level has much less significance on cost. However, variety may increase the design complexity in this case, due to the coupling of the design [74]. Therefore, while forming a solution space in DfMP, the potential coupling between the variables of functional and physical domains should be considered as well. This is not a criterion in the approaches for MC, since in PFA the dependence between FRs and DPs can only be uncoupled or decoupled [22]. As a result, the applicability of existing methods and tools for forming or managing solution space are limited in the context of DfMP.

The end product configuration in product family design requires a configuration structure. The generic bill-of-material is a common method to structure the hierarchical relationships of the components [22]. It places the components on a tree structure with common and optional nodes to obtain different configurations.Careful consideration of dependencies and correlations among the elements affecting design is important to avoid suboptimal design solutions [20]. In this respect, *Design Structure Matrix* (DSM) is an established tool to visualize and structure interdependencies between different domains [78]. Instead of the top-down approach with zigzag decomposition in axiomatic design, DSM takes a bottom-up approach by clustering or reordering elements in the matrix to simplify the design task. Some product family design methods use DSM to decouple the design or to identify different modules by clustering the components [79–81]. Yu and Cai [82] employed DSM to show the hierarchical dependencies among structures and design processes in PFA, which helps the configuration process to create product variants rapidly. The DSN of Loureiro et al. [74] is also a method that builds on DSM. However, in this case, the focus is on the decomposition of functional and physical domains in DfMP, and the authors do not elaborate on how to reach a personalized design solution. The standard configuration structures base on the solution space concept with discrete options. However, the design freedom and process flexibility of AM enable customer-specific designs within a continuous solution space. [59]. Expressing a continuous solution space in a standard configuration structure is a challenge since it is a solution for modular reconfiguration of products at assembly. Another limitation of the standard configuration structures is the accumulation of the challenge of dealing with a coupled design. The generic bill-of-material method can not address this due to its nature of decomposing the design into independent elements. DSM-based methods can decouple the design to a certain degree. However, if the design still remains coupled eventually, there is no solution to configure the product, other than modifying the design or sacrificing a part of the solution space.

Product family design predefines the product portfolio based on customer requirement patterns and not by considering individual customers, which creates the risk of suboptimal fulfillment of personal needs. Due to the need of limiting variety for lower complexity, an average solution aim at a group with similar customer needs. The large and continuous variety that MP promises allows reflecting the personal needs in the final design solution. Translating the personal needs into a personalized design necessitates more customer involvement in the process. Therefore, the traditional product configuration is limited by its nature to address this necessity, and an alternative way that can facilitate the customer co-creation for MP is essential. Li et al. [55] pointed out the gap in the literature on this topic and proposed a template-based design approach for design co-creation. This approach divides the product into several design elements linked to a skeleton structure, and modifies these at multiple parameter levels, considering design guidelines and manufacturing considerations. It allows the user to define the skeleton and design elements on a CAD system and helps the user explore the solution space with finite element analysis and parameter-based optimization. This approach demonstrates a noteworthy interactive user co-creation example, while this approach is limited to structural elements, and requires expert users. Addressing novice users, Shugrina et al. [56] proposed a co-creation method that allows users to interactively modify the geometry of a given template. This method uses geometry caching to store a pre-sampled solution space and uses this while co-creating a design with the user to keep the design in the valid region of the solution space. This method only considers the geometrical modifications due to its approach of geometry caching to check solution space validity, and it has a limitation on the number of DPs. However, it is a valuable example in terms of real-time interaction with the user and generating manufacturable designs. Kumar [16] suggests that real-time customer interaction with the design space would allow a more reliable measurement of customer satisfaction. Zhou et al. [5] highlighted the importance of obtaining the latent needs and processing them in real-time in design and solution spaces. Besides the real-time interaction, generating manufacturable designs is especially important to carry out the customer co-creation with mass efficiency, since there is a need for an alternative to customer-specific design labor. The traditional product configuration does not have this issue, due to using a predefined product portfolio. But in the case of MP, there is an uncertainty of customer needs and resultant designs. Hence, there is a need for a tool to interact with the customer, and generate a reliable design solution. The development of algorithms and approaches for this purpose may enhance the customer co-creation process. There are also similar approaches in product configuration; multidisciplinary design optimization is one of these for reconfiguration of the product family to obtain the desired performance and optimal configuration [20]. Berry et al. [69] proposed a systematic product architecting algorithm for personalization, though this is focused on identifying the level of personalization and corresponding DPs. The works of Li et al. [55] and Shugrina et al. [56] demonstrate the most suitable examples to help customer co-creation using algorithms, however, both works focus on a very specific aspect of product change. Therefore, there is a need for a more generic solution to streamline the co-creation process.

2.4. DESIGN FOR MASS PERSONALIZATION

MP is often considered in the same context as MC for design approaches. However, as outlined previously, there are specific challenges and points of attention that emerge with the MP paradigm. It is crucial for DfMP to understand these challenges, and cater to the product development accordingly. DfMP should consider all key dimensions of MP in connection during the product development process. The previous sections discussed the state-of-the-art design methods, tools, and approaches for MC and MP. Each of these addresses a specific part of the design process. The literature on design for MC is well-developed, with product family and platform design methodologies. However, as discussed, the approaches and tools in these have limited use for MP. A gap in the literature is an overarching design methodology to guide designers in the product development process for MP. Kaneko et al. [27] also drew attention to the necessity of a methodology to design products for MP, for realizing personalization at full potential.

Most of the DfMP literature is rather descriptive frameworks. As one of the earliest works on DfMP, Tseng et al. [37] proposed a technical framework composed of customer, functional, physical, process, and logistics domains. They suggest connecting these domains by utilizing a what-how mapping. The customer domain contains known and latent needs, which are translated into functional requirements in the functional domain via customer co-creation. The framework defines a product ecosystem within the functional domain, which acts as a design space for the customer. However, this work divides the product into *hard* and *soft* components, which stand for the physical product and user experience respectively. The framework uses PFA for the physical product and adds a personalized user experience and service layer to that. With a similar perspective, Zhou et al. [5] proposed a framework that demonstrates a personalization scenario that describes the product in three layers a core unchangeable part, configurable hard components, and adaptable soft characteristics. This framework also considers personalization as an experience and service. There are also other perspectives on Design for MP frameworks. Hsiao et al. [50] proposed a service design approach, proposing a model between customer, service platform, and service provider. Largely focusing on the customer journey, they also include a customer satisfaction evaluation as a final phase. Zheng et al. [38] suggested a user experience-based MP development, based on value creation via use generation and meaning delivery. They proposed a circular framework between UX, cyber and physical models. Focusing on the physical products in another work, Zheng et al. [68] proposed a design process that demonstrates the decomposition of functional and physical domains based on AD, to develop common, optional, and personalized modules in an adaptable open architecture product platform. In their framework of a personalized product configuration system, customers, original equipment manufacturers (OEM), and companies are three stakeholders in the process, in which OEMs and the open architecture product platform are at the center. This framework demonstrates the open architecture concept at the system level. A work that treats the open architecture concept more at the design level is by Berry et al. [69]. They proposed a method for personalized product architecting, considering functional utility and manufacturing cost. In general, the frameworks discussed are illustrating a personalization scenario. While some of them explicitly focus on experience and service aspects, the ones on open architecture have a production perspective and describe a modified product family scenario. Therefore, there is no framework to structure the design activity for MP. Bingham [21] also pointed out this lack of method and conceptual framework to generate personalized designs and effective interaction with digital manufacturing.

2.5. CRITICAL ANALYSIS AND RESEARCH QUESTIONS

2.5.1. CREATING PRODUCT VARIETY

The common way of creating product variety for customers is through a product template. The architecture, or the variability definition, of the design template, is a determining factor for the context of the variety. The most common form of a design template is the PFA. The methods and approaches around PFA are effective in the traditional manufacturing technology context, and they propose solutions or optimize processes accordingly [25]. Hence, their considerations or challenges are not necessarily valid for the digital manufacturing context. For instance, the restrictions due to variety-commonality trade-offs do not apply in AM context. Similarly, there is a one-to-one mapping between functions and modules in PFA, hence it does not allow coupled design cases. However, AM allows multiple functions in a consolidated part. Besides, in a consolidated structure, decoupling the design might not be as simple or restrict the variety significantly. Therefore, the platform and modular architecture is insufficient to create variety for MP. Although personalized modules may offer a solution to meet individual needs, they are still within a modular architecture, and their design requires customer-specific labor. There are only a few examples of design templates for MP, and these are limited to geometrical variability. Opportunistic DfAM methods demonstrate possibilities of defining variability at many levels, thanks to the flexibility and material variety of AM processes. There is a lack of a design template architecture that can exploit the advantages and potential of AM, and possibly other digital manufacturing processes, to create variety for MP effectively. Hence, this brings up the first research question:

> *RQ1: How to define a seed design*[2] *architecture that can contain consolidated parameters or functions, and provide design variety through manufacturing process flexibility?*

Another important factor for designing for variety is the design process that defines the variables of different domains contributing to the design process. Different domains subjected to the DfMP process are similar to the traditional product methodologies, and sufficiently well identified. However, constructing these domains and managing their interactions to obtain personalized designs are still present challenges. Previous literature points out the lack of knowledge in connecting these domains and structuring a seed design [21, 65]. Although several methods for MC exist on this topic, some authors highlight the lack of connection between domains and customer integration in these methods [20, 22, 58]. These challenges may accumulate while applying the methods to MP since it aims for a larger variety and increased customer involvement. AD appears as a prominent method to improve the connection between functional and physical domains. However, according to AD, the best design is the one with the least complexity, thus it does not consider coupled design cases. While there is valid reasoning behind this, in the case of MP, a certain degree of complexity may be acceptable in favor of variety. Besides, a coupled design case may be more likely in cases such as consolidated structures with AM processes. A design process taking these considerations into account is necessary for MP, and therefore, the second research question is:

> *RQ2: How to structure different domains and their interactions in the process to define the variability of a seed design?*

2.5.2. DESIGN PERSONALIZATION AND USER INVOLVEMENT

The majority of the methods to obtain a customer-specific design are for product configuration within PFA. Therefore, the challenges in the definition of variety accumulate in this latter phase. This first appears while forming or managing the solution space. The existing approach bases on the assumption that increasing variety would cause higher manufacturing and managerial complexity [59]. As a result, the effort is to find a feasible variety trade-off to limit the solution space. This is surely a valid assumption when considering increased variants of a component in modular architecture. However, this is much less significant when the variety is at the process level; the variety does not affect stocks or the supply chain, and flexible processes like AM do not require dedicated tooling. However, as also discussed above, more profound variability of the design in MP may result in design complexity instead. Therefore, there are fundamental differences in what to consider while forming a solution space. The manufacturing considerations are also applicable in the case of MP, however, not necessarily in terms of cost or manufacturing complexity. Process capabilities, and related design guidelines or design complexity considerations may help to form a feasible solution space.

Another challenge of existing methods is the continuity of the solution space, and the conventional configuration structures. Existing methods define the solution space

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[2] Among various terms identified in the literature, this thesis uses the *Seed Design* term to refer design templates for MP.

and the configuration structure based on the selection of discrete options. While some methods introduce personalized components, these are independent nodes in the hierarchical structure, and their variety is not a part of the configuration [22]. Nonetheless, as opportunistic DfAM methods demonstrate, a continuous variety is possible with parameters at different levels. Besides, the configuration structures lay out only the hierarchical relationships of components, but not their interdependencies, since this is not the case in PFA. A prominent tool that helps to clarify the interdependencies is DSM. However, addressing a continuous solution space or a tangled relationship between different variables with conventional product configuration is a remaining challenge.

As the level of variety or the complexity of the design increases, the design solution becomes more unpredictable, hence the involvement of the customer in the process becomes more important to provide products that meet personal needs. Several authors highlight the importance of real-time customer interaction in the design co-creation process [5, 16, 42]. This especially becomes evident in coupled design cases, where an iterative solution is necessary. Standard configuration structures do not cover this case, but multi-objective optimization is one solution to find the optimal configuration for the user. However, this results in an uninformed design trade-off for the user and is more applicable for less consumer-oriented products with clear design goals, such as structural parts. In the MP context, Shugrina et al. [56] proposed a method that gives real-time feedback to the user modifications on a product configurator interface and keeps the design in the valid range of the solution space at any instant. This is a very representative application of the real-time interaction that other authors highlight, however, the method is limited to a number of dimensional parameters. In conclusion, the configuration approach is limited, and in some cases not applicable, for MP. There is a need for a different approach that can facilitate customer involvement effectively, and address the personal needs precisely.

In standard product configuration, the product portfolio is predefined and users reach a known solution through the configuration structure. Larger and continuous variety in MP, along with the possibility of a coupled design and increased customer involvement, create the challenge of managing the process of design personalization efficiently. Since achieving mass efficiency is an essential aspect of MP, there is a need for an alternative to the configuration structure, to interact with the customer and finalize the design. In this respect, the validity of the final design, in terms of design guidelines or manufacturing restrictions, also appears as a crucial factor Similar applications in the literature demonstrate the use of different algorithms and optimization methods, which may provide a direction on this topic.

In conclusion, conventional configuration structures are insufficient to address the more intricate solution space and customer involvement in MP, and a similarly efficient alternative is needed to realize the potential of MP. Therefore, the following research question arises:

> *RQ3: What is the alternative to standard configuration structures that can facilitate customer co-creation over a seed design that potentially has continuous and coupled variability?*

2.5.3. DFMP FRAMEWORKS

The majority of the literature on MP are descriptive frameworks to explain the MP process on the system level, and they mostly approach from a production perspective, or personalization of experience and services. In terms of guiding the DfMP process, to the authors' knowledge, there is only one prescriptive contribution [74], which focuses on only design specification. Therefore, an overarching gap exists in guiding designers in the design process of products for MP. Therefore, the last research question is:

> *RQ4: What guiding principles and tools can designers use when designing for MP to create and manage sufficient variety, and to address individual needs?*

There are more challenges and open questions in DfMP, which are not covered in this work. MP relies on value creation by not only the product but also the personalization process. Therefore, the design of the co-creation process focusing on enhancing the user experience is necessary. The level of personalization or the co-creation methods should be compatible with the product and customer profile. The work on these topics is very limited and, hence, the challenge in customer satisfaction with MP is still present.

2.5.4. RESEARCH PLAN

The research approach and the research process of this thesis were described in Section 1.4. To address the research questions above, there are three main research cycles that follow this literature analysis. Firstly, based on the literature analysis and findings, the following chapter introduces a design methodology for MP that proposes theoretical arguments to answer the research questions. The last two research cycles (Chapter 4 and 5) aim to support these arguments towards answering the research questions, by testing them on two different product categories. Chapter 4 includes an expert evaluation that focuses more on the design process and guidance to address RQ2 and RQ4. Chapter 5 contributes more towards answering RQ1 with a highly coupled design case, and with a user study, addresses the RQ3.

3

DESIGN METHODOLOGY FOR MASS PERSONALIZATION

3.1. INTRODUCTION

Based on the findings of the literature review discussed in the previous chapter, this chapter presents a design methodology to address the identified gaps. The approach towards the design methodology is making a synthesis of the adoptions from existing methods and tools, and introducing new ones where necessary based on the identified needs of MP, opportunities, and possible directions. As commonly followed, the design process has roughly two stages: designing a product with variety and adapting this to the specific customer. While designing for product variety, the first point of attention is the definition of variability, and the most common definition is the PFA. To make a similar definition of a seed design architecture that is suitable for MP in the digital manufacturing context, the DfAM domain provides the necessary input. The way that opportunistic DfAM methods benefit process capabilities to optimize designs at different levels, and how they define design spaces, parameters, and constraints are the inspiration of the proposed seed design architecture that defines variability and commonality through design features.

The second important point for the development of a seed design is the process to identify the variables of different domains contributing to the design process. These domains are well-identified in literature [37, 68, 70, 73]. In addition to these domains, a co-creation domain is introduced, which is an extension of the customer domain. The motivation behind this is to clarify the customer input to each of the two design stages, since the input to the first stage is more generic, while to the second stage is the specific needs of each individual customer. A second motivation is establishing a formal link between the initial design stage and co-creation activity to have a more customer-centric design process. For the decomposition of domains, AD appears to offer the most established solution. Hence, the proposed methodology adapts the concurrent decomposition between domains with what-how mapping. However, it is important to mention that this is without using the two axioms of AD. This is due to the presumption that defining intricate variability in a consolidated form makes a coupled design more likely, and the effort to avoid this case may affect variability adversely. Another introduction to the process is the consideration of process capabilities and restrictions, similar to that of the restrictive DfAM approach. These process considerations appear in the process domain and constraints. The use of the process domain here is to understand how to define a design parameter within process capabilities to fulfill a certain requirement. Process limits and restrictions appear as a part of the constraints to form a solution space, which has similar applications in the literature. Additional constraints introduced are dependencies between design elements and personalization scope. The motivation of the initial is to take the consequences of coupled design cases on solution space into account, while the latter is to align the co-creation considerations with solution space.

For the second design stage, where the design finalizes according to customer preferences, there are two main starting arguments: a coupled design requires an iterative solution [3], and similar applications use some form of design optimizations and other algorithms [55, 56]. Besides that, several authors highlight the importance of real-time interaction with the customer for informed design decisions in the co-creation phase to reach a satisfactory design [5, 16, 42]. Based on these, the proposed methodology devises an algorithm that establishes the communication between the user and the design, while iteratively searching for a solution to user requests with the objective of enabling the largest design freedom possible at each step. Another contributor to this stage is DSM, which is an established tool to investigate the interdependencies of a system and is also employed by some conventional product configuration approaches. Within this methodology, it serves the purpose of organizing the dependencies that the algorithm should consider. A presumption on the customer co-creation is that with such intricate variability, the user can not directly control design parameters, or estimate the resulting behavior of the product. Therefore, the preference is that the user input is what the product should perform, unless there is an explicit case for direct control over parameters, such as certain dimensions. Also for this purpose, the proposed methodology defines design and solution spaces, which are often used interchangeably in the literature. In the present definition, design space is for the user and includes what the product may perform, while solution space includes the design parameter ranges that answer how to perform a given function.

The proposed methodology explains the development process from pre-identified customer needs; which are, more specifically, broad categories of possible specific personal needs. The development process starts with expressing these in more technical requirements. The specific needs of the user are elicited through the co-creation process. The methodology does not cover the complete product development process, but it only covers how to develop a product for mass personalization. Hence, the starting point is an existing product or a concept design. From that point, the methodology defines and structures the variability of the seed design. For this process, a new seed design definition is introduced, and the structure and decomposition of its domains are adapted accordingly. The development process has two main phases; the first phase is in a sense designing an unfinished product, and the second phase is devising how a user will complete the design.

To facilitate the user to finalize the design into a personalized product, the methodology proposes an interactive co-creation process, where the communication between the user's design decisions and the changes in the design are managed by a design solution algorithm. There are two main, and critical, considerations in the proposed co-creation process. Firstly, the changes in the design are requirement-driven, meaning that the user does not directly modify the design parameters. Secondly, besides giving more design freedom, the user is also put in a more decision-making role. The relative importance of different needs, hence of different product features, is largely a personal choice as well. In the proposed methodology, as opposed to the traditional approach, the hierarchy or the relative importance of the needs, thus the priority of corresponding product features, is left to the user. Therefore, the user can reach trade-offs between features, knowing that there is more design freedom in the primary decisions. This is enabled by the real-time interaction of the user with the design between the co-creation tool and the solution algorithm. However, the user does not have direct control over the design parameters but does have control over the requirements of the product. Hence, the design is driven by the requirements derived from personal needs, and these requirements are realized by the design parameters.

In the following section, a DfMP framework is introduced to structure the design process, clarifying the roles of the designer and the user. Following that, the designer is guided through the seed design development with a two-phase process. The initial phase is structuring a seed design and its variability, and the second phase is managing this variability to set the stage for the user and to facilitate the user co-creation in a mass manner.

3.2. DESIGN FOR MASS PERSONALIZATION FRAMEWORK

The proposed DfMP framework aims to structure the design activity and serve as a foundation for the proposed methodology. The framework (Figure 3.1) is composed of a two-phase seed design development and a co-creation phase. The initial phase is where the designer develops a user-modifiable seed design, and the latter phase is facilitating the user design by structuring and managing the variability of the seed design. The co-creation phase lays out how to facilitate the user interaction with the seed design to reach a personalized design solution.

The first phase of seed design development forms the design and solution spaces. The seed design can fulfill varying personal requirements within a defined design space. These requirements are realized by varying design parameters in the seed design structure. The predefined and assured ranges of design parameters form the solution space. Hence, the design space defines the variability of the seed design in the functional domain, while the solution space defines the variability in the physical domain. The second phase examines the interaction of the design and solution spaces and organizes these on a dependency matrix. Following that, a design solution algorithm is devised to manage this interaction. Finally, the output of this phase is a seed design with defined variability in functional and physical domains, and the means of interaction between these domains.

In the co-creation phase, the design process is completed by the user, where the product is personalized within the design space, which is mapped to the solution space.

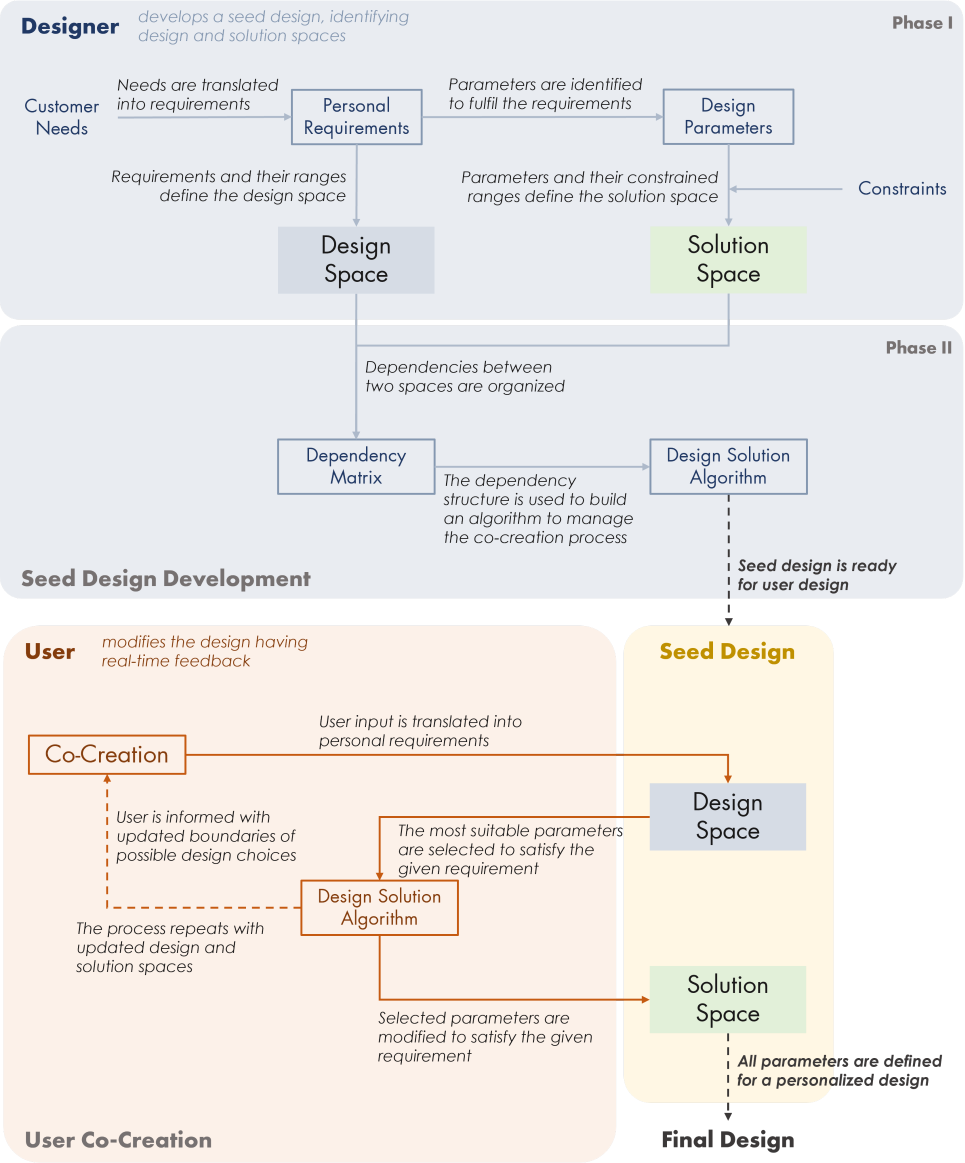


Figure 3.1: Design for Mass Personalization Framework.

Hence, the design changes are dictated by the requirements and realized by the design parameters. The interaction between design and solution spaces, with real-time feedback to the co-creation interface, is managed by the design solution algorithm. A final design is generated when all the parameters in the solution space are set. The aim is to automate the process of generating personalized products, defining the seed design once, and then enabling each customer to complete the design.

3.3. SEED DESIGN DEVELOPMENT

3.3.1. SEED DESIGN ARCHITECTURE

The seed design definition in this context focuses on digital manufacturing process capabilities that enable the integration of multiple functions and their working principles, and the definition of variability at various levels. Hence, the seed design here does not consist of platforms or modular components, but it is more of an integral and flexible architecture that contains common and varying design aspects, and the information on how its design could be modified. Consequently, solution space is also not in the form of a product portfolio, but it includes the variability of a seed design. This definition divides the seed design structure into two main parts (Figure 3.2): a base architecture, and varying design features on it.

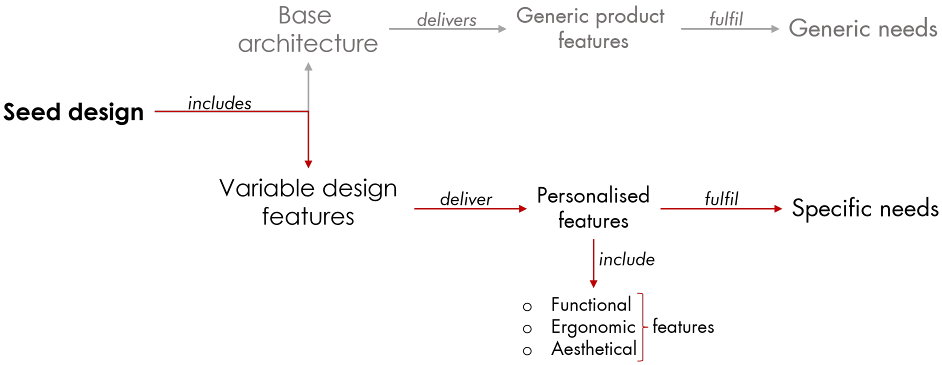


Figure 3.2: Seed design decomposition into base architecture and variable design features, corresponding product features and customer needs. The greyed out branch is out of the scope of the proposed methodology.

The base architecture is the core part of the seed design, which is stable, and consolidated for a given product. It includes a set of common design characteristics that acts as a core design that the variability of seed design builds upon. In this sense, it is analogous to a platform in PFA but serves a different purpose. In this context, commonality has no explicit benefit in terms of cost or manufacturing. Base architecture provides a structure to the seed design and ensures the basic performance that serves generic needs. Besides that, it may provide for any design characteristic desired to be common for any particular purpose, such as preserving brand identity. So, the base architecture can take its source from an existing product, or a new concept designed for this purpose.

The variable design features provide the personalization of the seed design. Definition of these variable features depends on the process capabilities, as well as the personalization requirements. In terms of process capabilities, the reference point is AM, since having the most process flexibility. Recalling the categorization of Rias et al. [61], four levels of complexity that AM allows introducing in products were shape, material distribution, structure hierarchy, and functionality. The opportunistic DfAM methods example various forms of variability at these levels [30, 57, 62]. Based on this, it is possible to define the variability of the seed design from microscale voxel-based material layout or multi-material distribution to macro-scale design features. Such a broad description of variability is to allow the utilization of different definitions that may serve various personalization opportunities.

Combining the common and varying design features with the information on limitations and dependencies of variability, the seed design allows keeping control over complexity, while still having an almost continuous variety or flexibility of product offering. It allows offering an almost continuous variety of alternatives which help to give the customer the most suitable product according to their needs. The aim is to ensure the user a virtually infinite set of options to maximize the fulfillment of their needs, without bringing back the complexity that derives from the management of configurations. The following sections expand on the development of the variable design features of the seed design and the idea behind it.

3.3.2. DEVELOPMENT PIPELINE

MP development pipeline is shown in Figure 3.3. The first phase of the development is to define the variable features of the seed design and the extent of their variation. Hence, in this phase, what a user may request from the product and how its design varies are defined. A seed design is developed as a starting point for customer involvement in the second phase. The process of the first phase starts with identifying categories of differentiating CNs, or in other terms, top-level CNs. These specific CN categories are then expressed as personal requirements (PR). Afterward, the DPs to satisfy the PRs are identified. Following these, the dependencies and constraints (C) on DPs are identified to find the ranges of DPs, and these form the solution space. The dependencies between the requirements and parameters are demonstrated on a matrix. The solution space is mapped onto the design space, forming the ranges of PRs.

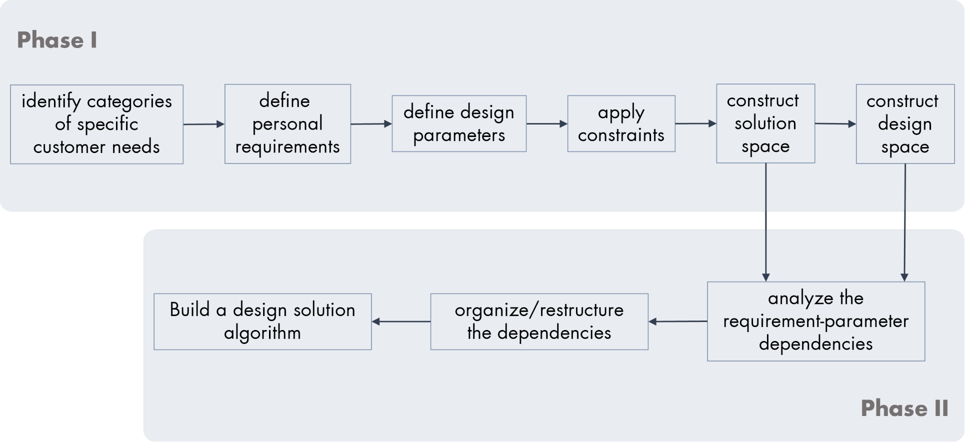


Figure 3.3: Development pipeline for seed design and final personalized design.

The second phase is the development of managing the variability of the seed design to facilitate user co-creation. Hence, this phase defines how the user requests are realized in the design. The process starts by analyzing the dependencies between PRs and DPs. Then these dependencies are organized and restructured where applicable. Following that, a design solution algorithm is devised with certain operating principles to iterate DPs to fulfill PRs. At the end of the development process, a user-modifiable seed design with a system to facilitate user co-creation on it is obtained.

3.3.3. STRUCTURE AND DECOMPOSITION OF DOMAINS

In order to structure the development of seed design, the interaction of different domains contributing to the design process, their interactions, and variables are inspected. Same as in the traditional product development, customer, functional, physical, and process domains are used, and additionally a co-creation domain is introduced (Figure 3.4). The definition and decomposition of the domains are adapted from AD [70] and used in a form that serves in defining the variability of seed design. Hence, the structure and decomposition explained in this section are for the variable part of the seed design, and not for the base architecture.

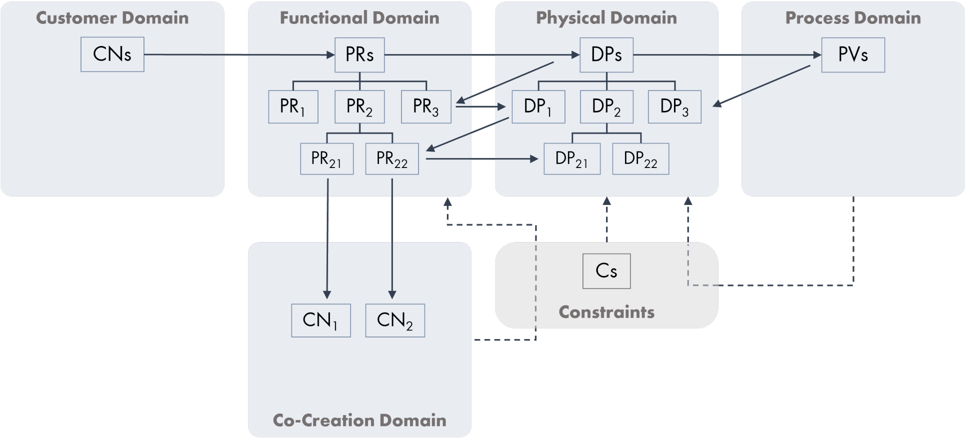


Figure 3.4: The domains considered in the design process, constraints, and their components.

The structure connects the adjacent domains and decomposes their elements when necessary. The aim is to first identify the elements of these domains and then form the design and solution spaces. The customer domain includes only top-level CNs, which are broad categories of possible specific needs. The functional domain includes PRs instead of FRs. Top-level PRs are formulated to satisfy the top-level CNs, and they define what features of the product can be personalized. The physical domain includes varying DPs to fulfill PRs. The process domain includes PVs, which are interpreted differently in this context. Since this process starts from a defined base architecture, the digital manufacturing processes to be used are pre-defined as well. Hence, the process domain does not include the selection of a process, but it includes the capabilities of the pre-selected processes, which help to define DP and to constrain their ranges of variation. The process domain and its connection to the physical domain are not further elaborated on in this work.

The decomposition process takes place in the functional and physical domains. The PRs and DPs are decomposed to lower levels concurrently, while considering process capabilities, until how to achieve the variability is sufficiently defined. Since the aim is to allow more design freedom on PRs at the expense of complexity, the axioms of AD are not necessarily employed here. Therefore, there is no explicit effort to reach a one-to-one mapping of PRs and DPs. To fulfill a PR, all the possible DPs are defined, as long as they provide sufficiently more design freedom. While still acknowledging the benefit of uncoupling the design case, the priority is given to expanding design freedom. The selected levels of PRs are also mapped to the co-creation domain to define what users may control over the design. This is the main motivation for introducing the co-creation domain. Hence, the selected PRs are translated into specific CNs to be elicited through co-creation.

The constraints in this context are used to define the variability. While the constraints are mainly applied to DPs, the co-creation domain constrains the ranges of PRs in terms of the scope of the personalization scenario, which again indirectly limits the ranges of DPs. The process domain constrains the ranges of DPs in terms of process capabilities. These and further constraints are elaborated further in the corresponding section. By applying the constraints, the ranges of DPs are defined, which forms the solution space; and the ranges of PRs are defined, which forms the design space.

3.3.4. PHASE I: DEFINING A SEED DESIGN

CUSTOMER NEEDS

Identifying CNs is an essential step in all product development processes. In the traditional means, certain generalizations on the user data are made for each market segment. These generalized needs are then organized into a hierarchy and their relative importance is established [48]. It is necessary to highlight that "needs" in this context refer to any customer need or desire for the product [83]. While designing for MP, it is important to understand the differentiating customer needs, in other terms, the specific needs. In this case, product-specific clusters of specific needs should be identified, which later define the extent of the personalization offered. The offerings of MP should be unique and personal, hence while setting the personalized features of the product, the considerations should be inclusive of those needs. Two main pillars of MP are higher customer involvement in the design, and the manufacturing flexibility allowing this; the extent of personalization offering is strictly related to these. The value presented by MP is not only about the personalized product, but also the sensorial, emotional, and symbolic values created in the co-creation process [38]. For a better user experience, providing the appropriate level of personalization is important [84]. The level or extent of the personalization scenario is also related to the cost and manufacturing feasibility. Hence, the level of personalization affects both customers and providers, and reaching a trade-off with affordability is necessary for both parties [42].

In this context, the CNs are categorized as generic and specific needs. Generic needs are basic expectations of performance in a product. The generic product features answering to these needs are contained in the base architecture of the seed design (Figure 3.2). Specific needs refer to affective, cognitive, or user-experience-related needs, which are the subjects of MP [5]. The specific needs are fulfilled by the personalizable product features, which may be functional, ergonomic, or esthetical ones. The variable elements of the seed design define these features according to specific needs. The focus of this methodology is on personalizable features, which cater to individual needs and desires. Therefore, CNs in the following sections refer to personal, specific, needs.

The first step of the process is to identify the top-level CNs. These correspond to very broad categories, or descriptions, of possible specific personal needs. For instance, considering a case of eyewear frames, a comfortable fit may be a top-level CN. Here, a comfortable fit does not say what will change in the product. It is translated to personal requirements, and then these are decomposed into more specific requirements. Then these requirements determine what personalization options will be offered to the user. How to identify these top-level CNs is not in the scope of this work.

PERSONAL REQUIREMENTS

The CNs are in the customer language, and these needed to be expressed in technical descriptions to achieve quantitative relations in the design space. In the transition from customer domain to functional domain, the top-level CNs are mapped onto *Personal Requirements* (PR). Cognitive task analysis, quality function deployment, and association mapping present solutions to transfer CNs to PRs in the MP context [5].

A difference of PR definition in this context, in comparison to functional requirement (FR) definitions, is that they do not describe what “has to be done”, but rather what “can be done”. The point of interest is exclusively specific needs, and PRs express a range of possible requirements. Since the personalized features of the product are defined after the general features, the product has already a base architecture. Therefore, the top-level PRs do not state the design objective of the whole product, and instead, they state the personalization objectives.

The product features corresponding to specific CNs may be categorized as ergonomic, functional, and esthetical (Figure 3.2). Since these features are defined through the PRs, the same categorization may also be done for top-level PRs. An ergonomic requirement corresponds to a personal fitting need in this context. Moreover, while functional ones are related to product performance, esthetical requirements are to define the physical appearance of the product. While PRs in one of these categories are sufficient for a personalization case, PRs in all three might be present as well, such as in the footwear case study elaborated on later in the next chapter. Whereas, in the saxophone mouthpiece case given later, there are only functional PRs. The reason for such categorization is to cater to these requirements accordingly, and to structure better the design solution process, as illustrated later in the Design Solution section. For instance, when present in a given MP scenario, the prior needs to meet are the ergonomic ones. Besides, the parameters corresponding to ergonomic requirements are likely to constrain the rest, as they define the size or shape of the product. Such as, in a footwear personalization case, if a personal fit option is provided, it is inherently the primary requirement to be fulfilled. Therefore, the fit requirements should be at the top of the PR hierarchy.

Top-level PRs state design personalization context derived from CNs. These PRs are decomposed to lower levels, based on the DPs, to define more specific design objectives to personalize the design. The customer input to the design in the co-creation process is done on the lower-level PRs. Therefore, the PRs should be decomposed, at least, until the level is appropriate for customer input. These PRs getting the customer input define the design space, where each PR is a dimension with a range. The customer input is taken within these ranges, which define the extent of the personalization offering. Since the customer input cannot be in the language of PRs, the selected levels of PRs are mapped to the co-creation domain to be expressed in the customer language again. This last process of defining how user input is taken is a part of the design of the co-creation activity, which is not covered in this work.

To illustrate the decomposition process, a hypothetical eyeglass frame is taken. Some very broad CNs can be a comfortable fit of the frame and adapt to face shape or skin tone. The comfortable fit need can be translated to a top-level PR as fitting to facial measures. Then the corresponding top-level DP would be the dimensions of the frame. This top-level PR can be further decomposed to lower levels to requirements of specific facial measures. These are then matched with relevant dimensional DPs of the frame. Here, the user input can be transmitted to the design through either the higher or lower level of PRs, depending on the co-creation scenario. For instance, in case there is a process of face scanning, then the user input is taken at the level of fitting to facial measures. Another case might be the user self-measuring or using the dimensions of a previous frame, and in this case, the user input would go through the lower level PRs of specific facial measures.

DESIGN PARAMETERS

The user input through PRs is realized by DPs in the physical domain. DPs define the variable design features of the seed design, and they are selected to fulfill the corresponding PRs. In the context of digital manufacturing, these DPs may provide variability through changing certain dimensions of the product, or through varying topologies, structures, material composition, and so on. Hence, the process capabilities should be considered while defining DPs. DPs should be decomposed to lower levels until PRs can be implemented into the design. A DP can have a range of quantities or a set of options. In the first option, the values the parameter can take would be a continuous range; while in the latter case, it would be discrete values in the set.

The mapping between PRs and DPs can be expressed as a design equation, where r denotes for the in-between dependency:

$$\{PR\} = [r]\{DP\} \tag{3.1}$$

When identifying the DPs, the ideal scenario is that each PR is satisfied by one DP, which corresponds to an uncoupled design in AD. In this case, there is a one-to-one mapping, and each PR is fulfilled by the corresponding DP. Another manageable form is a decoupled design, where the dependency matrix has a lower triangle form [70]. In this case, PRs are satisfied in a hierarchy of least dependent to most dependent. A similar solution is also provided in DSM to provide an order for the definition variable values, by sequencing the rows and columns of the matrix to form an upper triangle [78]. In the case of MP, the proposed method bases on the principles of having sufficient design space for self-expression and implementing personal priorities in the design. Achieving an uncoupled design may require architectural changes in the product. Besides, a PR dependency hierarchy for the design solution in a decoupled design naturally narrows down the range of subsequent PRs. However, customers may have different priorities for the given PRs, and these priorities should set the solution hierarchy while achieving a personalized design. Therefore, a user-centric design solution algorithm is proposed in Phase II, along with a dependency matrix to visualize, organize and simplify the design cases.

While setting DPs, it is still important to aim for less-coupled design to lower the complexity of the dependency matrix. The complexity in this context refers to the number of PR-DP dependencies in the matrix. A trade-off between complexity and the range of PRs satisfied is necessary to provide an adequate personalization experience. Another downside of high complexity in PR-DP dependencies is the possibility of radical changes in the dynamic design space provided to the user during the co-creation process. This may lead to a negative user experience, as the initial state of the design space creates expectations, and the valid state may lead to disappointment.

CONSTRAINTS AND SOLUTION SPACE

The Cs in this context are the limits or restrictions on the ranges of DPs (solution space) primarily, but consequentially restricting the ranges of PRs (design space) as well. The Cs may initially be divided into two groups based on the phases they are applied. The first group is used to set the boundaries of the initial design space. There are four categories of constraints to consider and examine (Figure 3.5), which are explained below. The second is the PR-DP dependency constraints during the co-creation and design solution phase. The dependencies between PRs and DPs result in a temporarily valid design space in the co-creation process. These Cs are handled in the design solution algorithm introduced in Phase II.

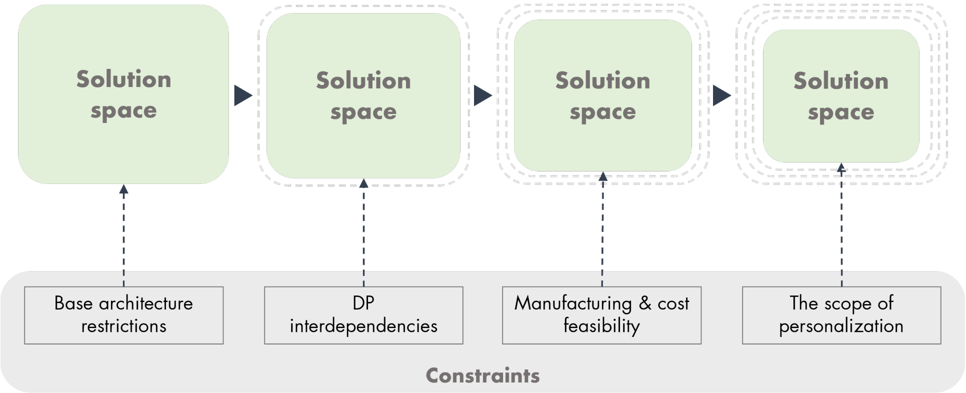


Figure 3.5: Four levels of constraints applied to the ranges of DPs in the solution space.

The aim of constraining the design space is to ensure that the final design is reliable and manufacturable. This is a crucial prerequisite for automating personalized design generation. The initial and broadest ranges of DPs are set according to the base architecture. This implies the natural boundaries of the design variability, that exceeding these would be unnecessary or impractical. For instance, a DP can not change in a way to interfere with the base architecture. Another example could be on the DPs for the ergonomic fit of a product, which would be characteristically limited by anthropometries. The second step of Cs is the interdependencies of DPs. This step is to eliminate possibly counterproductive or unfeasible DP combinations. Hence, certain parts of the DP range may be restricted or allowed conditionally according to dependencies. The latter case would be evaluated while structuring the dependencies for the design solution algorithm.

In traditional product development, manufacturing considerations are in the process domain, after the design is defined [48]. Whereas, in design for manufacturing, these considerations are present since the early design phases [73]. Manufacturing flexibility is a main pillar of MP, and thus designing for MP largely relies on manufacturing and related variables. Therefore, a design for manufacturing approach is more suitable as manufacturing processes or materials are early-phase design decisions, since they are related to the personalization offering. Consequently, the proposed approach considers manufacturing-related variables while defining the solution space. Hence, the third step of Cs is related to the manufacturing and cost feasibility. At this step, restrictions regarding manufacturing methods, processes, and materials are applied to DPs, both to ensure manufacturability and to eliminate unpractical results. Furthermore, depending on the cost target, design solutions potentially resulting in extreme cost variation may be eliminated.

The final step of constraints is regarding the scope of personalization offering. In this case, the constraints are applied to the ranges of PRs first and then reflected onto DPs. Depending on the CNs and co-creation scenario, the range of DPs may be restricted again, if at this step the DP in the solution space exceeds the personalization target. An example of this step would be restricting any DP that goes beyond the intended level of personalization or creating a very large design space, which may get confusing for the user and lead to a poor experience.

Solution space defines the variable portion of the seed design in the physical domain. Hence, it is a space for possible design solutions. The constrained ranges of DPs form the solution space where a personalized final design is achieved on the seed design. Therefore, DPs set the dimensions of the solution space, while Cs define its size. After all, Cs are applied, the final ranges of DPs are mapped back onto PRs to define their ranges, which form the initial design space.

DESIGN SPACE

Design space defines the variable portion of the seed design in the functional domain. Hence, it is a space of possible performances to obtain from the seed design. After the Cs are applied to the solution space, the consequent ranges of DPs define the possible ranges of PRs, which form the design space for the user. The dependencies between PRs and DPs are shown in Figure 3.6. In the dependency matrix, r_{mn} denotes for how DP_n fulfills the PR_m. Therefore, PR is a function of DPs:

$$PR = f(DP) \tag{3.2}$$

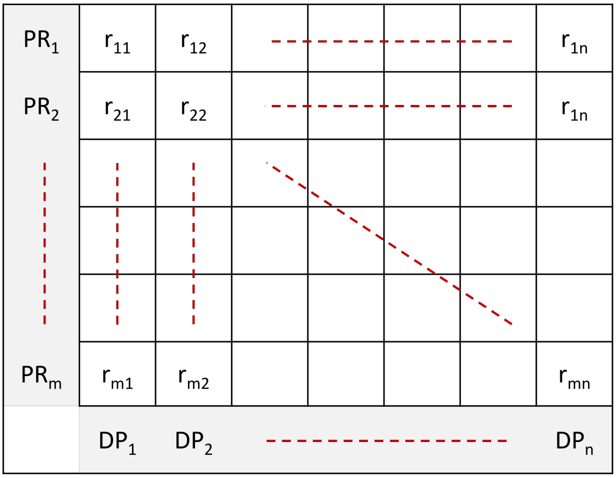


Figure 3.6: Dependency matrix of PRs and DPs.r denotes for dependency.

In case it is possible, at least in a certain range, to linearize the relationship between PRs and DPs, PR_m can be expressed as:

$$PR_m = \sum_{i=1}^{n} (r_{mi} * DP_i) \tag{3.3}$$

The extrema of the equation give the maximum range of PR_m. The maximum range of a PR is established when all dependent DPs fulfill the PR. In the case where a DP affects multiple PRs, this creates a dependency between PRs. These dependencies would restrict the ranges of PRs. While defining the design space at any instance, these dependencies are ignored to provide the most design freedom to the user at the beginning. Since the range of each PR is set independently, they can not have the largest ranges simultaneously, as some DPs are affecting multiple PRs. Following each user input during co-creation, the solution algorithm considers the dependencies and recalculates these ranges, and then returns to the user interface. Hence, the algorithm shows the largest range to the user at any instance, according to the DP values at that instance, but this is only valid for the following choice of the user. Hence, the PR to be fulfilled first would still have its largest range. Therefore, the user has to decide on personal priorities and reach the desired trade-off. The benefit here is that the user has the most freedom at any instance of decision and can get the most out of the desired performance aspect. How this process works is explained in the next section.

Consequently, the initial design space for user co-creation is set by defining the maximum ranges of PRs regardless of the dependencies. With the formulation of a design space, the first design phase is completed. At this point, the variability of the seed design in functional and physical domains is defined. In the next phase, how to structure and manage this variability for user co-creation is elaborated.

3.3.5. PHASE II: FACILITATING USER DESIGN

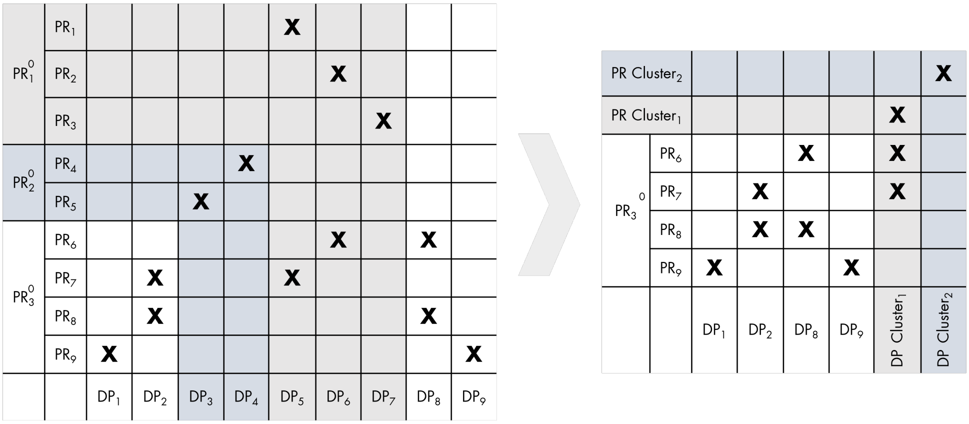
The first phase of the seed design development constructs and defines the variability of the seed design, both in the functional and physical domains. The connection between these two domains is also identified in the first phase with the PR-DP dependencies. Once developing a seed design in the first phase, it is necessary to understand how the user interacts with the seed design through a co-creation interface and finalizes it into a personalized design. The second phase organizes the interaction between functional and physical domains and manages the variability for finalizing the design with each user.

This phase can be seen as an alternative to the traditional configuration structures, which are intended for managing component variety and insufficient for the variability of the seed design in this context. This insufficiency is due to two main reasons: the near-continuous variety of DPs and the high probability of reaching a coupled design case with the variability of basic design features. For the initial, adapting a configuration structure may be possible to a certain degree; while for the latter, it does not present any solution as it principally bases on one-to-one mapping of requirements with components, or modules. Conventionally, coupled design cases are avoided as much as possible, as they require iteration, and may not yield an acceptable design solution [3]. At this point, the participation of the user in the design-decision-making process plays a crucial role in the proposed methodology. The design solution process is an interactive collaboration between the user and the introduced algorithm; while the user decides step-by-step which PR is to be fulfilled and how it is fulfilled, the algorithm iterates corresponding DPs to fulfill the PR in question. Hence, the user decides the order of PRs to be fulfilled, which eases the iteration process significantly. Each user input for a PR may change the valid ranges of other PRs, in case they are coupled, and this results in a dynamic design space. The algorithm updates the design space after fulfilling each PR and gives feedback to the user. Therefore, the user makes conscious decisions at each step knowing the boundaries of the PR in question, and the consequences of previous decisions. Hence, this process ensures reaching an acceptable design solution. Besides easing the iteration of the design solution, there is also the benefit of actively involving the user in the design process. The user may make conscious trade-offs between PRs and reach the most suitable design solution.

In the following sections, the first part is to organize, and simplify if possible, the dependency matrix to ease the coupling and reduce the complexity. Hence, this is a preparation of the PR-DP dependency structure to set an iterative solution. Following that, the second part introduces an iteration algorithm with certain principles to ensure a design solution that is most suitable for the user.

SIMPLIFICATION OF THE DEPENDENCY MATRIX

To visualize the PR-DP dependencies, a matrix is used in Figure 3.6. Here, the dependency matrix is organized and simplified to set the scene for devising an algorithm for the design solution. DSM is a common tool to model, visualize and analyze the dependencies between the elements of complex systems [78]. It also offers suggestions to simplify design cases by sequencing the rows and columns to reach a systematic order for assigning a value to each variable. Reordering the rows and columns or clustering certain



		DP_1	DP_2	DP_3	DP_4	DP_5	DP_6	DP_7	DP_8	DP_9
PR_1^0	PR_1					X				
	PR_2						X			
	PR_3							X		
PR_2^0	PR_4				X					
	PR_5			X						
PR_3^0	PR_6						X		X	
	PR_7		X			X				
	PR_8		X						X	
	PR_9	X								X

		DP_1	DP_2	DP_8	DP_9	DP $Cluster_1$	DP $Cluster_2$
PR $Cluster_2$							X
PR $Cluster_1$						X	
PR_3^0	PR_6			X		X	
	PR_7		X			X	
	PR_8		X	X			
	PR_9	X			X		

Figure 3.7: Example simplification case on a PR-DP dependency matrix. The matrix on the left side is the initial state, and the matrix on the right is the simplified one after clustering and reordering. Top-level PRs are marked with a superscript. X denotes dependency.

elements are two of these suggestions for simplification. In clustering, matrix elements are clustered to identify minimally interacting subsets, hence eliminating or minimizing the interdependencies. These simplification suggestions can be used to simplify and organize the dependency matrix beforehand, to guide the design solution process. To reduce the complexity of the dependency matrix, certain PRs and DPs may be clustered and considered as a cluster in the iteration for the design solution. The clustering is useful in the following cases:

- DPs of an independent PR
- In case the dependency is on a higher level of PR, clustering the lower-level PRs
- DPs for the ergonomic fit

When a PR is independent, this implies that the corresponding DPs do not affect any other PR. Therefore, these DPs can be clustered and considered as a single element to fulfill the PR. If there is a dependency on a higher level of PR, the lower-level PRs in its subset can be clustered and iterated as a cluster. The clustering can be only up to the level where there is user input.

The last case is when the product is made-to-measure. DPs corresponding to requirements of fit would be geometric dimensions. Since the requirements would be dimensions as well in this case, these PRs and DPs would have one-on-one mapping. Therefore, ergonomic PRs, and corresponding fitting DPs, can be considered as a subsystem and clustered to simplify the case. Since these DPs change the size or shape of the product, they may still affect the valid range of other PRs. In such a case, for the sake of simplicity, this dependency should be considered between the fit cluster and the relevant PRs.

To illustrate the organization and simplification of dependencies, a dependency matrix of an arbitrary design case is shown in Figure 3.7. In the example, there are three top-level PRs and in the lower level, there are nine PRs. PR_1, PR_2 and PR_3 are ergonomic fit requirements, and each of them are dependent on one DP. Therefore, these can be clustered to simplify the matrix. PR_4-DP_4 and PR_5-DP_3 have one-on-one mapping and are independent of the rest. Therefore, these can be clustered as well. The third case of higher-level dependency is not present in this example. For instance, if DP_3 and DP_4 were both dependent on one PR, this would imply a higher level of dependency. In the simplified matrix (Figure 3.7), cluster two can be handled independently for the design solution. Cluster one is still dependent on PR_6-PR_7, but since it is an ergonomic fit cluster, it is fulfilled first as explained further in the following section. As a result, only the remaining four PRs and four DPs require an iterative solution.

DESIGN SOLUTION ALGORITHM

To manage the PR-DP dependencies, and hence the interaction between design and solution spaces, a solution algorithm for design personalization is introduced in this section. The solution algorithm manages the dependencies between PRs and DPs, keeping control over the complexity, while still providing an almost continuous variety. In the front end, it allows the real-time interaction of the user with the design. The algorithm dynamically controls the boundaries of these spaces and assigns values to DPs to fulfill PRs with an iterative approach. The objective is to offer the largest design space at each decision step and provide the most design freedom to the user on the preferred design aspects. The algorithm (Figure 3.8) works by iterating the DPs to fulfill the PR at each step. The fundamental principles of the algorithm are:

- If present, fulfilling first the PRs of ergonomic fit
- considering solely esthetical PRs last
- Except for the cases above, setting the hierarchy of the PRs according to the user preference
- Using the least possible number of DPs to fulfill a given PR
- If present, changing independent DPs first to fulfill a given PR
- Iterating from the most effective to the least effective DP for a given PR

When each DP affects only one PR, the complexity of the dependence matrix becomes the lowest, thus no iterations are needed, and each PR can be satisfied with the corresponding DP. For the rest of the cases, where dependencies increase the complexity, the solution algorithm is applied. In the case where the ergonomic fit is a PR, it is fulfilled first. This is because of the assumption that the primary expectation from a made-to-measure product is a personal fit. Besides, it would have a fixed input for each user, hence it is not a CN that the user could actively state a preference. Therefore, PR related to the fit is fulfilled first and in case of dependence, design space is updated before further decisions in the co-creation process. Following this, functional PRs are fulfilled where the design case is more likely to be coupled. Lastly, the esthetical PRs are fulfilled, after providing the right fit and suitable set of functions. The algorithm follows the steps (marked in Figure 3.8) below to reach a personalized design solution:

1. Start the process with the user input and assign a value to the corresponding PR.

2. Then, check if the value is in the valid range. If not, reset the solution space.
3. In the following step, identify the most effective DP for the given PR (within the available DPs at that instant).
4. Incrementally increase or decrease (depending on the PR value) the chosen DP until either reaching the boundary value or fulfilling the PR.
5. After this iteration, update the solution space (and the design space) and check if the PR is fulfilled.
    (a) If no, go back to the DP selection process and continue with the next DP.
    (b) If yes, move to the next step.
6. Check if all the PRs are fulfilled.
    (a) If no, continue the process with the next user input.
    (b) If yes, generate the final design.

All DPs initially start at a median value. According to the input PR value, they are iterated towards either the upper or the lower boundaries of their ranges. Since the design space is in a feedback loop, the input to the PR would be in the valid range, and the iteration of DPs will surely satisfy the PR. In case of input outside the valid range, the solution space goes back to the initial state, and again the fulfillment of the PR is ensured. The operation of dynamically controlling the dependencies and valid ranges also guarantees the reliability of the output final design. Hence, this process automates acquiring customer needs and reflecting them in the design; and it may also provide personalized designs that are ready for manufacturing.

3.4. DESIGN PERSONALIZATION WITH USER CO-CREATION

The seed design development process defines what varies in the product and how, and sets the boundaries of possible requirements from the product and possible changes in the design. Along with these, devising a design solution algorithm to transfer PRs into the design features facilitates user participation in design. While the seed design development starts from categories of possible specific CNs, or top-level CNs, the specific needs of the individual user are elicited in the co-creation process, where the user finalizes the design initiated by the designer. The proposed process allows the user to indirectly change the design by imposing requirements. Hence, the user design is based on needs and driven by requirements. While this allows answering the specific needs, it also saves the user from the confusion of making design decisions that have complex consequences. In the co-creation process, the user interacts with the algorithm behind that adapts the DPs of the seed design to user requests, and continuously updates the design space.

The proposed algorithm manages the backend of the user co-creation. Frontend matters as such how to acquire the specific CNs, or what sort of interaction or experience to provide the users are not covered in this work. In the co-creation phase, the user

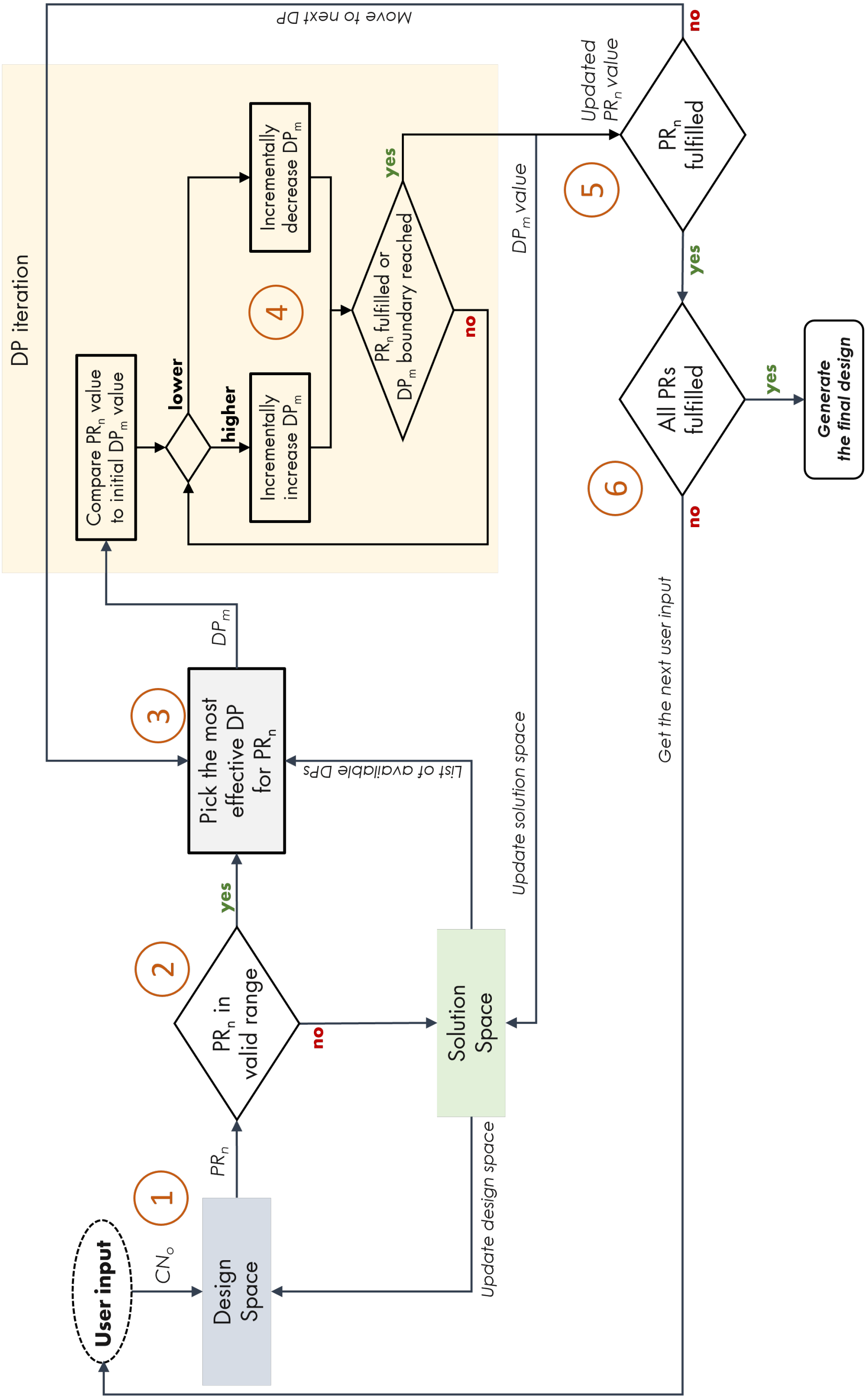


Figure 3.8: Flowchart of design solution algorithm. Circled numbers mark the steps explained.

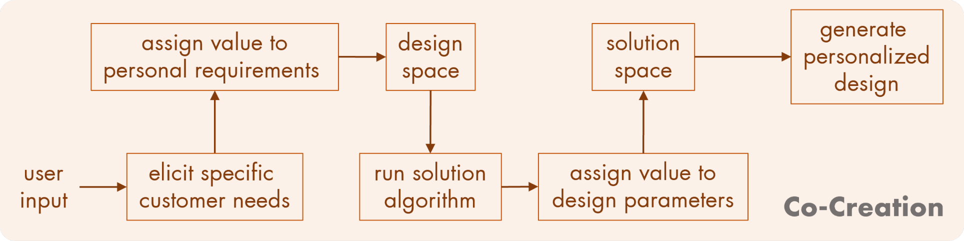


Figure 3.9: Steps of converting user input into a personalized design in the co-creation process.

interacts with the design via a co-creation interface. The process from user input to generating a personalized design is shown in Figure 3.9. The user input in co-creation is transmitted via PRs to the design space. When a decision is made on a PR in the design space, the algorithm iterates the corresponding DPs in the solution space to fulfill the PR. Afterward, according to the new state of the solution space, the design space is updated with the valid ranges of PRs at that instance. The user is then informed of the further design possibilities and then makes an input for the next PR preferred. The process continues until all PRs are decided, and all DPs are set. In the case where the user prefers to exceed the valid ranges of any PR, still within the initial design space, the solution space is reset, and the design space is updated to the new state. This way, the user may get certain trade-offs between design decisions. Once the co-creation process is complete, all the DPs in the seed design are set, and a final personalized design is generated.

3.5. CONCLUDING REMARKS

This chapter set out to develop a design methodology for Mass Personalization. The objective of the chapter was to disclose a set of tools and directions to support DfMP, focusing on consumer durables that are realizable by digital manufacturing. Considering the key offerings of the MP paradigm and based on the analysis of relevant design domains, the developed methodology in this chapter aimed to provide potential answers to the research questions addressed in Section 2.5.

Within the efforts of developing a design methodology, this chapter presented initially a DfMP framework that lays out the overall development scheme, identifies the main constituents of the design process, and clarifies the roles of the designer and the user in this process. The proposed seed design development provided guidance on how to carry out the specific tasks in the framework. The core concept is the defined seed design architecture, which aimed to provide product differentiation through design feature variability. The development process and the co-creation scenario centered around this seed design architecture. The first phase of the development process illustrated how to define and connect customer, functional, physical, process, and co-creation domains, and how to form design and solution spaces considering the complexity of such design variability. While the variability of the seed design allows answering to the specific needs of the users, it also gives users more responsibility and control over the design. The second phase addressed how to organize and manage the design variability, and the possible complexity arising from variability. The PR-DP dependencies are organized with methods adapted from DSM, and with a number of proposed principles. The proposed design solution algorithm addressed the possible design complexity in translating PRs into DPs to personalize the design. It aimed at providing an improved solution, in comparison to standard configuration structures, to solve coupled design cases. The algorithm iterates DPs to fulfill PRs with suggested principles to provide the most design freedom to the user and enables the user to make trade-offs in the coupled cases. The output of the seed design development is an open, or unfinished, product that can fulfill a defined range of varying requirements through its design variability, and the algorithm behind adapting the design according to specific requirements. Finally, in 3.4, envisioned user co-creation scenario illustrated how the user contributes to the design interactively, and how the seed design is completed into a personalized design.

Presented design methodology for MP includes adoptions from existing methods and tools and introduces new ones based on the theoretical arguments found in the literature. Therefore, it is necessary to demonstrate its applicability in practice. For this purpose, the next two chapters present case studies that apply the methodology to two genuinely diverse products.

4

CASE STUDY I: KNITTED FOOTWEAR PERSONALIZATION

Footwear is arguably one of the products that have to answer to personal needs the most. It significantly contributes to the comfort and ergonomics of walking and affects even performance in sports. Besides its functionality, it has ever been a tool for self-expression. Hence, personal footwear is nothing new; bespoke shoes date back a long time with handcrafted shoes by artisans. Evidently, the cost of an artisanal product is higher than a mass-produced counterpart. Thus, handmade bespoke shoes have narrowed down to a niche market, while the mainstream footwear has become more standardized, affordable and a fast fashion product with mass production. This has transformed the perception of the product as well; research suggests that the customer willingness to pay for a personalized shoe is only 10 to 30% more than a mass-produced one [85]. However, there is high interest in footwear personalization; a major reason is a need for proper fit and comfort. Standardized footwear with mass production results in a poor fit, which is found to cause several foot-related problems[86]. Another motivation for personalization is that footwear is also a fashion product and provides an opportunity for self-expression to customers.

The footwear industry has been one of the pioneers of MC, aiming to offer affordable custom shoes. However, MC trials in footwear have been far from success due to high expenses, long production times, or not being able to meet customer needs. But the advancements in production and manufacturing technologies may change this. Knitting and 3D printing are emerging in the footwear industry, with the advantages of providing new design possibilities and ease of manufacturing. Besides, the flexibility they provide may allow meeting customer needs better and more efficiently. Therefore, MP in footwear presents the potential to provide the desired uniqueness and fit to the customers, with near mass-production efficiency.

In this chapter, the DfMP methodology introduced in the previous chapter is applied for footwear personalization, focusing on two digital manufacturing technologies: 3D printing and digital knitting. The personalization opportunities that these technologies provide are explored. A simple shoe construction composed of a knitted upper and a 3D-printed sole is studied to develop a seed design following the proposed development steps. Then, the user co-creation process is exemplified over the developed seed design. The study is finalized with the results of interviews with experts of relevant domains, that evaluate the design process, tools, footwear context, and overall implications of the study. Parts of the content presented in this chapter has been published in *Design Science* [36], and *Proceedings of MCP-CE* [4].

4.1. CONTEXT

Footwear is a very competitive and large industry; according to World Footwear Yearbook, since 2010 the production increased by 20.5% to 24.2 billion pairs in 2018 [87]. To differentiate in the market and to answer diversifying customer needs, the footwear industry has been eager to employ MC and digital manufacturing technologies. However, it is difficult to mention any significant success so far. Even an industry leader such as Adidas could not sustain its MC platform MiAdidas, which was running since 2000. MiAdidas got closed in 2019, stating that the future of footwear personalization is in co-creation, and they are working on user participation on a deeper level [88]. Significantly higher costs of customized shoes might be another reason for the failure. It is necessary to establish automated design and manufacturing systems in the footwear industry to reduce costs [89].

Knitted footwear is trending more and more in the industry recently. Adopting knitting in shoes creates an excellent opportunity to reduce waste material and labor needs [90]. It is possible to produce a complete shoe upper seamlessly by knitting machines. Besides these advantages, the flexibility of knitting machines and the availability of various yarns show a great promise to enable MP in footwear.

4.1.1. PERSONALIZATION IN FOOTWEAR

MC in footwear has been thoroughly studied considering many aspects, such as from design to supply chain [91–93]. Opportunities, obstacles, and enablers of using Additive Manufacturing in MC have also been investigated [94]. The trend in footwear MC is towards systems with more customer involvement in the process. A very recent study by Shang et al. [95] proposed a social manufacturing system for the footwear industry, which involves customers, in this context prosumers, in the complete life cycle of the personalized product. There is limited research on user co-creation, experience, and service design aspects. One very detailed analysis of the co-design of sports footwear has been done by Head & Porter [96]. They proposed a personalized running shoe service composed of a co-design toolkit and store assistance for data acquisition. About 75% of the participants in the user study were reported to be willing to prefer such a service.

PERSONALIZED FIT

Bespoke shoes have a long history, and footwear has been one of the pioneers of MC. Therefore, both foot measurement and custom fit methods are well-developed and defined. Thus, foot measurement methods needed for personalized fit are briefly mentioned below. The initial step of ergonomic fit is foot shape modeling, which has been approached in numerous ways; through 1D anthropometric measurements or 2D, 3D, and 4D modeling. A recent study explained how 1D anthropometric data could be used to provide individual fit through parameterized body models generated by statistical shape models [97]. Another approach has been employing a 2D foot outline and foot profile to predict foot shape, which resulted in an average error of 1.02 mm [98]. Both previously mentioned methods have the motivation to provide a more affordable alternative to 3D laser scanners. For 3D foot shape modeling, point clouds are obtained by surface scanners dedicated to foot measurement [99]. One step further towards the perfect fit is models examining the changes in the foot shape over time [100]. All these methods can be employed for different levels of the personalized fitting. As the complexity of the method increases, the need for dedicated tools and experts arises. Data acquisition may be made directly by users for 1D or 2D methods, while 3D or 4D modeling needs expert assistance and tools such as 3D feet scanners. The method to be used is according to the specific MP scenario, but in any case, these provide the starting point of the data acquisition and parameterization. Since shoe sizing is done through shoe lasts, foot measurements need to be converted to a shoe last design. Several methods linking foot measurements or models to shoe last design have been reported [101]. These methods provide a foundation for the design automation of personalized fit.

4.1.2. DIGITAL KNITTING

Conventionally manufactured shoes are composed of numerous components in different materials. Every single component undergoes different processes, and they are assembled in a labor-intensive process [102]. This is where Digital Manufacturing creates a substantial advantage. While a traditionally produced shoe upper might have about 20 components, it is possible to manufacture a one-piece upper by digital knitting (Figure 4.1). A similar case also exists for 3D-printed soles that may incorporate different components like outsole, midsole, or insole.

(a) Traditional shoe upper

(b) Knitted shoe upper

Figure 4.1: Comparison of traditional and knitted shoe uppers [4].

Digital knitting technology promises many opportunities for a personalized fit. A methodology to produce personalized functional compression garments using body scanning and digital knitting has been introduced [103]. Extending it to a more functional personalization case, Underwood [104] proposed a parametric design approach to obtain 3D shapes employing different material behavior with digital knitting machines. Application of similar work to shoe uppers done by Lu [90] explaining how to develop flat-knitted shaped uppers based on ergonomics and also demonstrated functional and decorative knitting structures for a knitted upper. This shows the potential of knitting to provide personalized fit, aesthetics, and function through the shoe upper.

KNITTING MACHINES

Knitting machines and their main principle of operation date back to as early as the 16th century, while computerized knitting machines were introduced in the 1980s [105]. In older machines, knitting patterns are arranged by punch cards, and changing the design is a time-consuming task [106]. Today, improvements in CAD for knitting allow quick changes in the design and require less expertise to operate. Knitwear CAD tools[1] define the design in a pixel-by-pixel form; and each pixel contains a stitch type along with the used yarn. As the design tools for knitwear become more available along with digital knitting machines, modifying the yarn layout for different graphical or structural patterns gets rather straightforward. These recent advances in knitting design and technology also enable the personalization of knitwear.

There are two main types of knitting machines according to the number of needle beds on the machine: singe-bed (single jersey) and double-bed (double jersey). While single-bed machines have the needles working in one direction, double-bed machines have two beds of needles working in opposite directions, which allows knitting double-knit or rib fabric [107]. Although being more rare, four-bed knitting machines also exist and used in the whole garment process for knitting complex fabrics seamlessly[2]. Besides the number of beds, knitting machines can be categorized according to the shape of beds as flat and circular. Circular knitting machines can produce continuous knit tubes and are mostly used for such applications. Whereas, double-bed flat machines can also knit tubular fabric with each bed knitting a single fabric piece [107]. Both flat and circular knitting machines are currently being used for producing shoe uppers. However, since double-bed flat machines are both more common and provide more design freedom in the scope of this work, the rest of the arguments are based on these machines.

Knitting machines have several distinct features from each other. Nevertheless, the most relevant ones to mention in a personalization case are gauge (tension) and the number of carriers. Machine gauge implies the density of needles on the bed. While some machines have a single gauge, some others provide multiple gauge options by employing techniques such as half-gauging or using multiple yarn ends [108]. Multiple gauges allow the varying density of stitches on the fabric. The importance of the gauge is that it both affects the selection of yarns that can be used and also the knitting density. The gauge is commonly expressed as the number of *needles per inch* (npi) on the *English System* (E). The most common gauge values for flat machines are between E

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[1] An example knitwear CAD software: DesignaKnit, http://www.designaknit.nl/.

[2] https://www.shimaseiki.com/product/knit/feature/

5 and E 14 [109]. The number of carriers simply defines how many different yarns can be used in the knitted fabric [107]. In summary, manufacturing-related variables that can be used to create variability in the fabric are the gauge options and the number of carriers available in the knitting machine. In machine knitting, in terms of manufacturing, materials, or design, there are undoubtedly many more variables than the two mentioned. The parameters pointed out here are the ones possibly to be employed in the given MP framework and focused on knitted footwear.

In older machines, knitting patterns are arranged by punch cards, and changing the design is a time-consuming task [40]. However, as the design tools for knitwear becomes more available along with digital knitting machines, modifying the yarn layout for different graphical or structural patterns became rather straightforward. These recent advances in knitting design and technology are also giving room to the personalization of knitwear. As seen in Fig. 10, a knitwear CAD design is in pixel-by-pixel form, and each pixel is a stitch showing the type of stitch by shape and yarn by color. It is possible to obtain diverse graphical patterns by modifying the layout of different color yarns or adding different material yarn as an ornamental element.

4.2. SEED DESIGN DEVELOPMENT

This case study explores the development of a seed design for a two-component shoe, consisting of a knitted shoe upper and a 3D-printed sole (Figure 4.2). The reason for choosing these two technologies is that they both provide design personalization opportunities and the manufacturing flexibility needed for design variations with mass efficiency.

Figure 4.2: Prototype of knitted footwear with 3D-printed sole (size EU37B).

In this case, the starting point is a concept design. The base architecture contains the main features of the upper, sole, and shoe last. Shoe last is also considered here since it is essential to shoe design and manufacturing. In this context, it is considered the bridge between foot measurements and shoe components. Therefore, a parameterized digital shoe last is employed in this model as a stepping stone for a personalized fit. It should be noted that shoe last also transfers the styling of the shoe, and that is preserved with changing sizes. For instance, when the style in the base architecture is trainer shoes, the seed design can not vary to trekking shoes. Similarly, certain form elements, such as the form of the sole are also contained in the base architecture. The form of the upper is also a generic feature that is only scaled for sizing, but the structure of the upper varies. The variable features of seed design here are the sizing of the sole and upper for a personalized fit; and functional and esthetical features of the upper. These variable features of the seed design are explained in the development steps below.

4.2.1. PERSONAL REQUIREMENTS

In the first step of the design process, the identification of top-level PRs requires broad descriptions of the specific CNs. For personalized footwear, these are identified as comfort and self-expression. The top-level PRs corresponding to these are personalized fit and shoe upper properties for comfort and upper appearance for self-expression. These three top-level PRs correspond to ergonomic, functional, and aesthetic features to be personalized in the shoe. To also exemplify the generic features, the shoe style might be given. The style, of trainer shoes in this example, is predefined on the shoe last design, which may be considered as the mold in the footwear context.

Figure 4.3 shows the decomposition of PRs and the corresponding DPs. Flexibility, weight, permeability, and heat resistance are the lower-level PRs that define the functional features of the shoe upper. Graphical pattern and knit pattern are the lower-level PRs defining the visual appearance of the upper. The decomposition of PRs is done concurrently with DPs. For instance, requirements on upper properties are decomposed based on the features that knitting parameters can control.

The PRs framed in Figure 4.3 are selected as convenient levels to get the user input. These are mapped to the co-creation domain, to be expressed as design personalization options in the co-creation process. personalized fit and graphical pattern are decomposed one level further to be satisfied by the selected DPs. These lowest-level PRs are not directly mapped to the co-creation domain, since allowing the user to individually control these do not present any benefit.

4.2.2. DESIGN PARAMETERS

The identified DPs are shown in Figure 4.3. Yarn material, count, and knit pattern selections fulfill the comfort properties of the shoe upper. Yarn color and knit pattern fulfill the upper appearance needs. The Knit pattern is used both as a PR and a DP. Because it has both an aesthetic value and a structural function. In this case, it is assumed that there is a supply of yarns providing stable behavior, and the knitting machine is able to produce some patterns that behave substantially the same.

The fit requirement is fulfilled by the shoe last dimensions. The shoe last design can be modified for personal fit via sizing and grading parameters [110]. These parameters define the geometry of the sole and the upper. The sizing is defined by the length, and the grading is by the girth measures of the user's feet. The length and girth values are obtained from the foot measurements of the user.

The DPs selected to fulfill the PRs are explained in more detail below.

SHOE LAST PARAMETERS

Shoe lasts contain the information for both the design and the sizing and grading of the shoe. The parameters used for sizing and grading the shoe last are well-established and

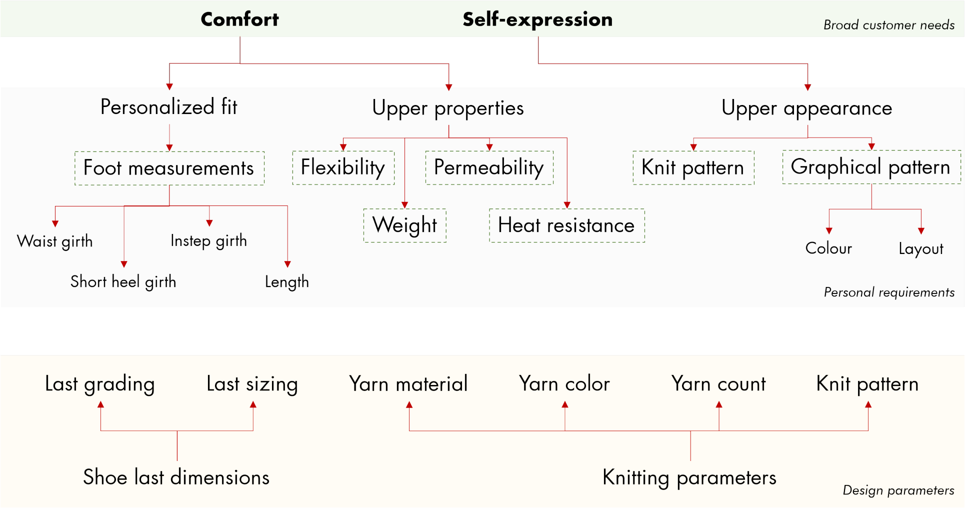

Figure 4.3: PR and DP decomposition for knitted footwear personalization. The PRs that are mapped to the co-creation domain are in rectangles with dashed lines.

can be used to create custom shoe lasts [89, 111, 112]. The main parameters to define the fit of the last are waist, instep, and short heel girths, and the stick length (Figure 4.4). These parameters can be varied according to the feet measurements for a custom fit, and the upper and sole can be scaled accordingly. The shoe last parameters, last grading, and sizing, shown in Figure 4.3 correspond to three girth parameters and the length parameter respectively. This is to avoid confusion since the same terms are also used for customer feet measurements.

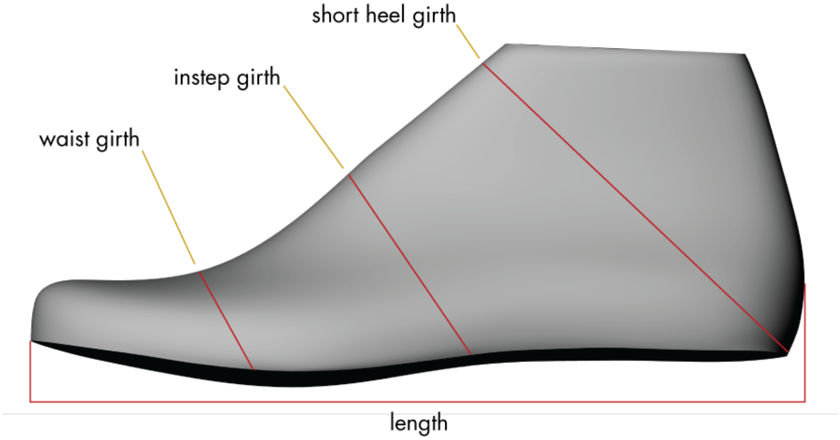

Figure 4.4: Shoe last design parameters for sizing and grading.

Besides containing the style and fit information, last is also an essential tool in shoe manufacturing, to assemble the parts of the shoe together. In this context, it is used as an intermediary digital tool to connect the feet measurements to upper and sole sizing. This study does not go into the detail of the parameters defining the size of the upper and sole, as they are simply scaled together with the last. Such parametric connections between the last and shoe parts are also provided by commercial footwear design software[3].

KNITTING PARAMETERS

In comparison to other Digital Manufacturing techniques, one significant advantage of knitting technology is on the material side, since yarn making has a long history, and is well-established. The selection of yarns available for knitting machines comes in great variety, and thus provides wide options for design personalization. Yarns possess different characteristics according to the fibers it is composed of and the way it is spun. They significantly differ in their mechanical properties or the sensory quality they provide [113]. With the advancements in yarn production and materials, digital knitting promises fascinating features and potential applications. Using textile sensors with conductive yarn may lead the way to several opportunities for personalization and user interaction [114]. Lund [115] reviewed in detail several types of conductive yarns, their properties, and their potential functional use cases. The primary parameter related to yarn selection is the material. Within the selected material, yarns come in different colors and thicknesses. Another yarn-related parameter is the layout of different yarns in the fabric, which may provide great variations of functionality. However, this is a complex parameter that requires extensive work to explore. Hence, this is not covered in this work; each upper can get one type of yarn material and thickness, but different colors of this may be used.

- **Yarn material:** The properties of the yarn are determined by the fibers it is composed of. While some yarns use a single kind of fiber, there are also composite ones to deliver the desired balance of properties [113]. In the context of this work, yarns are considered on a more macro scale, and the consideration is on the commercially available yarn cones. According to the source of fibers, yarns may be categorized as natural or man-made yarns. Natural yarns are also divided within as animal-based and plant-based. Common animal-based yarns are wool, hair or silk. Main plant-based ones are linen and cotton. Man-made yarns are composed of regenerated and synthetic fibers. Regenerated ones are derived from natural resources, such as viscose and acetate. Synthetic yarns are made from petrochemicals, and the most common ones are acrylic, nylon, and polyester [113, 116, 117]. More to this broad categorization, there are several subtypes of each mentioned yarn material, and there are also yarns with mixed fibers. Therefore, a wide selection of yarns is available commercially. Yarn material selection is very critical and may contribute to all three domains of personalization. Materials come with diverse mechanical, functional, or sensorial properties. For instance, fit and comfort may be regulated by employing elastic yarns, and the elasticity of the knitted upper may be set according to the customer. Using antibacterial yarns might be an option in the functional domain. As each yarn material has a different texture

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[3] https://atom-shoemaster.com/en/

and visual properties [118], esthetical personalization possibilities are infinite by changing the yarn material or creating combinations of them.

- **Yarn color:** Very few yarns preserve their original colors, and mostly, they undergo processes of scouring, bleaching, and dyeing [119]. Therefore, since yarns are dyed, virtually any color is possible. There is already a wide range of different colored yarn cones commercially available. However, the number of colors that can be used in knitted fabric is limited by the number of carriers the knitting machine used has. Using different color yarns is the simplest way to design personalization. Any graphical pattern may be applied to the knitted upper, only limited to the number of yarns and stitch density or resolution in this case.
- **Yarn count:** Yarn count (thickness) is uneven and difficult to measure since it is structured with different-sized fibers in a twist. Therefore, it is instead described as weight per unit length in direct measuring and length per unit weight in indirect measuring. There are several measuring systems used [118]. Yarn thicknesses are available in a range depending on the material [120]. An interval of yarn thicknesses can be knitted with a given machine gauge. Therefore, yarn thickness selection is limited by the machine gauge, and for a fixed gauge, it affects the stitch density. Yarn thickness may have both functional and esthetical personalization use. As an example, it may be employed to define the weight or thermal properties of the knitted shoe.
- **Knit pattern:** Stitches are the basic building units of knitwear structure. There are several stitching techniques, and using these in combination with varying densities allows the creation of unique knit patterns [117, 121, 122]. There are several established knit patterns that are widely used in knitwear [105]. Custom patterns may provide more tailored solutions; work in this direction was presented by Popescu et al. [123] on the automated generation of knit patterns to create 3D geometries. However, there is more research needed to obtain custom patterns to tailor the functional properties of the fabric. In this work, established knit patterns are considered for the knitted upper.

The dependency matrix in Figure 4.5 shows the PRs and DPs selected for the seed design and the dependencies between PRs and DPs. While some dependencies shown on the matrix represent the correlation between the corresponding PR and DP, some others represent hierarchical dependencies. These are explained further in Section 4.2.5.

4.2.3. CONSTRAINTS AND SOLUTION SPACE

To define the solution space, the DP ranges go through the constraining steps. Initially, all DPs start at the largest intervals possible within the given base architecture of the seed design. For instance, the sizing and grading parameter ranges are bounded with the anthropometric foot data [112].

The second step is checking the interdependencies between DPs. A simple example of this is the limited availability of yarn color and count options for a selected yarn material. In the third step, process and cost constraints are applied. Since a knitted upper is in the design proposal, the knitting parameters depend on the digital knitting machine.

	Last sizing	Last grading	Yarn material	Yarn color	Yarn count	Knit pattern
Waist girth		X				
Instep girth		X				
Short heel girth		X				
Length	X					
Flexibility			X			X
Weight					X	X
Permeability			X		X	X
Heat resistance			X		X	X
Color				X		
Layout	X	X				X
Knit pattern						X

Figure 4.5: Dependency matrix between PRs and DPs. X stand for dependency.

Figure 4.6: Kniterate digital knitting machine.

In this example, a Kniterate[4] digital knitting machine (Figure 4.6) is considered. For instance, the range of yarn counts that can be used is limited by the machine gauge, and also the number of colors that can be used at the same time is limited by the number of

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[4] https://www.kniterate.com/

Table 4.1: The ranges of DPs for the solution space.

Last size	EU38 to EU45
Last grading	A to G
Yarn material	Polyester, nylon, spandex (PU), wool, linen
Yarn color	10 color options
Yarn count	Nm6 – Nm2/12, Nm6.5 – Nm2/13, Nm7 – Nm2/14
Knit pattern	Single knit, half-cardigan rib, Half, Milano rib, Double knit interlock, Single-pique, crossmiss interlock

carriers in the machine [4].

The final step of the constraints is to limit the DPs which will define PR ranges in the initial design space. This step is according to CNs and the co-creation scenario. For instance, the number of knit patterns offered is limited to avoid over-complication for users. The boundaries of shoe sizes offered can be considered at this step as well.

Once all constraints are applied, the final ranges of DPs are obtained. These ranges, shown in Table 4.1, define the solution space.

4.2.4. DESIGN SPACE

Once how much DPs can vary is identified, these are used to define the ranges of corresponding PRs, hence the design space for the user (Table 4.2). The PRs of fit are directly connected to the last dimensions, and the size and grading intervals in Table 4.1 are translated into corresponding metric units. The ranges of PRs regarding upper properties are obtained through the combinations of the DP options seen in Figure 4.8. The max and min sum of coefficients for each PR define its range. For instance, the highest heat resistance can be obtained by wool yarn with Nm7 – Nm2/14 having a single knit structure. The sum of the coefficients of these is 3. Likewise, the lowest heat resistance can be achieved by any material except wool, Nm6 – Nm2/12, and half-cardigan rib or single-pique structure. The sum of coefficients, in this case, would be 1. Therefore, we can conclude that for heat resistance, the range is 1 to 3, and input within this interval can be taken. The same is applied to the other PRs as well and shown in Table 4.2. These ranges shown in the table define the initial design space. It is important to highlight here that the interdependencies of PRs are not considered for these ranges. For instance, it is not possible to obtain both the highest flexibility and the highest heat resistance at the same time, due to the coupled dependencies. These dependencies are considered by the solution algorithm during the co-creation process.

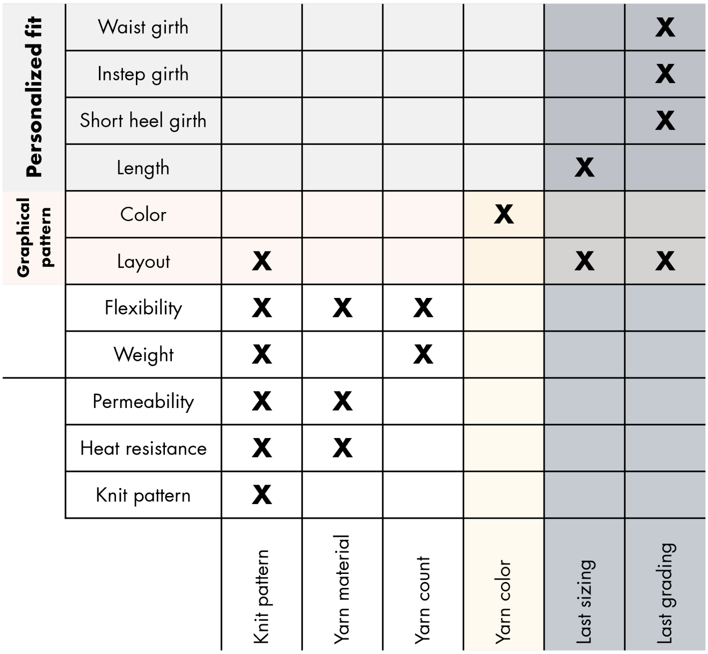
4.2.5. DESIGN SOLUTION

Before devising an algorithm to manage the co-creation process, the dependency matrix is analyzed, and reorganized if necessary. For this purpose, the dependency matrix in Figure 4.5 is rearranged into the form in Figure 4.7. The length and girth requirements are clustered together since they are all related to fit. The last parameters are also clustered as they are interdependent and fulfill the personalized fit cluster together. Similarly, graphical pattern requirements are clustered, since they are both interdependent,

Table 4.2: Final ranges of PRs forming the initial design space.

Waist girth	217 to 277 mm
Instep girth	239 to 299 mm
Short heel girth	331 to 391 mm
Length	238 to 285 mm
Flexibility	0.2 to 2
Weight	0.4 to 2
Permeability	0.6 to 3
Heat resistance	1 to 3
Color	10 options
Layout	User input
Knit pattern	6 options

and also they are not controlled by the user individually.



		Knit pattern	Yarn material	Yarn count	Yarn color	Last sizing	Last grading
Personalized fit	Waist girth						X
	Instep girth						X
	Short heel girth						X
	Length					X	
Graphical pattern	Color				X		
	Layout	X				X	X
	Flexibility	X	X	X			
	Weight	X		X			
	Permeability	X	X				
	Heat resistance	X	X				
	Knit pattern	X					

Figure 4.7: Dependency matrix between PRs and DPs. Clusters are shown with colored background. X stand for dependency.

The dependency between the graphical pattern cluster and the last parameters is related to dimensions. The last parameters define the size of the upper where a graphical pattern will be applied. Hence, this size information is a prerequisite for a graphical pattern input. Therefore, the fit of the shoe should be determined before the graphical pattern on the upper. A similar hierarchical dependency exists between graphical pattern and knit pattern as well since the knit pattern affects the layout. Thus, the knit pattern has to be determined before the graphical pattern. Consequently, the knit pattern has a dependency on the order of fulfillment, but eventually, it is fulfilled by an independent DP (yarn color).

After reordering the matrix, five PRs and three DPs on the lower left of the matrix are coupled. Fulfilling these five PRs requires an iterative solution. Considering the hierarchical dependencies, the personalized fit cluster has to be fulfilled the first, and the graphical pattern cluster has to be fulfilled the last.

As stated before, yarn color, last size, and grading are independent parameters and get direct input from the customer domain. On the other hand, the options within the range of yarn material, count, and knit pattern have different effects on the PRs. These effects are shown in Figure 4.8. The effects of different knit patterns are deducted from previous research on their mechanical properties [124]. For the other parameters, their effects are assumed to be proportional to their material properties[5]. Such assumption is made for the sake of simplicity; however since the materials are in the yarn form, their behavior might be different, and for an application case, the properties of these yarns can be determined more precisely through experimentation. To bring the coefficients to a common denominator, they are expressed as a value from 0 to 1. These ranges are mapped back onto PRs to define the initial design space in the next step.

Flexibility	0	0.2	1	0.4	0.4	0	0	0	0.8	1	0.8	0.6	0.6	0.2
Weight	0	0	0	0	0	0.2	0.6	1	0.2	0.2	0.4	0.6	0.8	1
Permeability	0.2	0.2	0.6	1	0.6	0.2	0.6	1	1	0.4	0.8	0.4	0.2	0.4
Heat resistance	0.6	0.6	0.6	1	0.6	0.2	0.6	1	1	0.2	0.8	0.4	0.2	0.4
	Polyester	Nylon	Spandex	Wool	Linen	Nm6 – Nm2/12	Nm6.5 – Nm2/13	Nm7 – Nm2/14	Single knit	Half-cardigan rib	Half-Milano rib	Double knit interlock	Single-pique	Crossmiss interlock
	Yarn material					Yarn count			Knit pattern					

Figure 4.8: Normalized relative effects of DPs on PRs.

EXAMPLE DESIGN SOLUTION PROCESS

An example design solution process is shown in Figure 4.9. The process starts with the user's foot measurement input. Firstly, the available shoe sizes are iterated for the given foot length. Afterward, the grading is iterated to match the user input with the obtained size. At the end of this process, 41.5C is found as the best fit, and the design space is updated with this information. As a second input, permeability=1 is given. DP selection function chooses the yarn count parameter to be iterated first. At the end of the iteration, Nm7 is set for yarn count and this fulfills the permeability requirement. Updating the valid design space again, now it can be seen that the weight and heat resistance have narrower ranges, since the yarn count is set. The next input is heat resistance=2.2. The DP selection function picks the yarn material and the iteration function picks wool as the most heat-resistant material. However, at this point, the heat resistance=2, and the PR is

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[5] Material properties are collected from http://www.matweb.com/index.aspx.

not fulfilled. Therefore, the DP selection function runs again and picks the knit pattern this time and the iteration results in half-cardigan rib and single-pique as equal options to reach 2.2. At this point, all DPs are set, except the two options left for the knit pattern. Therefore, flexibility and weight have only one possible value in the updated valid design space. The final input is for the knit pattern, and single-pique is chosen. In case the user is not satisfied with the final output, the input for any PR can be set again to reach other trade-offs. On this occasion, the DPs chosen are reset, and the iteration process starts again. The final personalized design in the example is a 41.5C size shoe with Nm7 wool yarn having a single-pique structure. The graphical pattern is not included in the iteration, as it is independent and can be fulfilled directly at any step after sizing and grading.

4.2.6. USER CO-CREATION PROCESS EXAMPLE

To illustrate the user experience throughout the co-creation process, an example user journey is shown in Figure 4.10. It is important to note that this is not covered within the proposed design methodology, and is only provided as an example to give an idea of how the co-creation process might look in the front end.

The example journey starts with acquiring the foot size data of the user. Through the photos of the feet, the size of the user is determined. Following that, the user decides on the functional properties of the upper in steps 4 to 6. With the four sliders, the user controls the functional properties of the knitted fabric, and within the images below, chooses a knit pattern. From step 4 to 5, the user moves the first slider and defines the permeability. Then, as seen in step 5, the other three sliders get more restricted due to the dependencies, and three of the knit patterns fade out for the same reason. A similar case happens from step 5 to 6 as well. Here, the user sees the consequences of the previous decision and may continue this process and make trade-offs between the functional properties. Once a suitable trade-off is reached, in step 7, the user defines the graphical pattern of the knitted upper. Consequently, the co-creation process reaches the end and the system generates a personalized design for the user.

4.3. EXPERT EVALUATION

In order to get feedback on both the content and the implications of the study, experts from different fields related to the study were interviewed. The aims of the evaluation are

- to gather reflections on the design process;
- to measure the validity of the content in terms of footwear and personalization;
- to get feedback on potential implications for industry and users;
- and to collect suggestions for further improvements.

4.3.1. METHOD

Five experts were contacted for the interviews. The profiles of the experts are presented in Table 4.3. They were informed about the subject and the semi-structured interview topics beforehand with a project brief (A.1).

The interviews were conducted separately, and each interview took approximately an hour in total, composed of two main parts. All the interviews were held remotely, and the presented material is available in A.2. In the first part, the mass personalization concept was introduced and the goals of the study were explained. Then, the highlights of the proposed mass personalization methodology were presented. Following that, the content of the knitted footwear study was explained in detail, covering all the topics explained in this chapter so far.

After the brief, the second part was a semi-structured interview, where the interviewees were asked to comment on different aspects of the project, as outlined in Table A.1. There are five aspects provided applicability, feasibility, potential, user experience, and comparison with existing applications. The experts were asked to comment on the benefits or limitations, and whether they have further remarks on the study based on the provided aspects. The experts were asked to comment freely, preferably from their own perspectives.

Table 4.3: The profile of the experts participated in semi-structured interviews.

	Expertise	**Current Role**
Expert 1	Footwear Technology&Mass Customization	Head of Research&Innovation
Expert 2	Knitting&Footwear Design	Senior Knitwear Developer
Expert 3	Knitting Design&Technology	Knitting Specialist
Expert 4	Ergonomics	University Professor
Expert 5	Mass Personalization	Innovation Lead

4.3.2. RESULTS

The highlights of the comments are provided in Table 4.4, with the same structure as obtained during the interviews. The complete transcription of the comments is available in the appendix A.4.

Table 4.4: Summary of the interviews.

	Applicability
Benefits	**E5:** The use case is very clear and similar to some commercial technologies, except for the functional personalization part and the coupled case of upper, where there is the novelty. This would be implemented in the footwear industry, especially considering sports shoes. **E4:** The dependency matrix, and the design and solution space connections are valid, and the algorithm is sound. The matrix and the algorithm are generic enough to cope with future additions, as tech advances. Hence, the methods are scalable and future-proof.

Limitations	**E4:** There should be more constraints to be considered for the whole process. It is not clear whether a functional shoe can be made since the methods are not tackling the whole development process. The complexity of shoes in terms of mechanical, dynamic, and heat loads are further points to be considered.
Remarks	**E1:** It is realistically applicable, and acceptable by the end-user, as long as the system running behind is set properly in terms of the framework. **E2:** Functional personalization of the knitted upper may be supported further by including parameters such as knitting gauge and stitch length, which would provide more design freedom. **E2/3/4:** Orthopedic applications would be a suitable addition to achieve higher personalization. The functionality of the insole and sole can be personalized according to weight distribution and stepping. The insole can be integrated into the sole by 3D-printing those together.
	Feasibility
Benefits	**E1/4:** It is technically feasible up to the point of having algorithms controlling the entire process. Considering the constraints, dependencies, the matrix arrangement, and tuning them into an algorithm has potential.
Limitations	**E1:** It is important to connect the whole personalization to the manufacturing processes. For instance, when the personalization process is done, a set of data that can run a knitting machine is needed. **E3**: It is technically possible in terms of knitting, depending on the type of the machine used. However, it is complicated to automate the process of connecting the design to the knitting machine, which requires a lot of expertise. **E5:** It will still take quite some time to implement, since footwear is very focused on mass production, and even in customization cases you can change some colors, but the shoe is more or less the same. This case will get more complicated when more parts of the shoe are included. The challenge will be to make the production suitable and to bring down the complexity of shoes to really tailor it to the individual customer this way. **E2:** The knit pattern choices are questionable. Mostly double knit structures are preferred for shoes since they would hold the foot in place better. Besides, applying graphical pattern to the chosen knit patterns is not easy. The best knit pattern for this purpose would be jacquard.
Remarks	**E4:** Feasibility in terms of user aspects depends on not asking for too much input from the users.

	E2: The costs might be adjusted based on the knit structure and material used. Some patterns take longer to knit, which affects the cost eventually. The same applies to the number of colors, or different yarns, used at the same time. Most of the machines can carry three yarns at once while adding a fourth yarn would double the knitting time. This can be considered a manufacturing constraint. Showing the cost change to the customer could be an addition.
	Potential
Benefits	**E1:** Knitted upper and 3D-printed sole are the perfect combination for personalized shoe construction. Streamlining the process by automating knitting programming and 3d printing is very promising. The presented personalization framework and the user involvement in design add value. Such simple shoe construction is advantageous, which would be easily assembled by gluing it out on an apparatus. If all the residual problems are solved, these kinds of shoes have a future; since they are simple to make, easy to assemble, and compatible with different scenarios such as localized production or compact manufacturing plants. **E5:** Custom designs are labor-intensive; you need a designer to create an individual design. Using the algorithm and automating the design flow can really create a scalable solution for unique products. You can create endless variations of just one single shoe. This is the new way of creating and selling products, and it will surely increase in the upcoming years. **E2/5:** The greatest potential is in the functional personalization of the knitted fabric, which is really an added value and very innovative. Alongside adjusting the functionality to one's needs, the graphical side is a nice added value as well. **E3/4:** The biggest potential is in democratizing fashion or giving it back to people, where you can make your own designs. We come from times when the shoes were fully personalized, then we got away from that, and now we can return to that.
Limitations	**E1:** One limitation is whether 3D printing can provide functional or resistant soles as traditional methods, though the technology is moving fast in that direction. **E2/3:** Even if all the design automation is achieved, there will be still manual labor in the process. So, you can never compete with fast fashion, as personalized shoes just cannot be made at the same speed. Thus, it is important to identify a market in which such a product would fit. However, if the fully automated scenario would be realized in the future, there would be surely a big business potential.
Remarks	**E3:** For a business case, some simplifications may be necessary, both to make it more cost-efficient and also to simplify the design options based on the user profile.
	User Experience

Benefits	**E1:** One important element is engaging the customer in a fun way. The interactive process here is like a game; you change something, and you see the effect. It is like targeting a certain outcome and being happy when you achieve what you had in mind. One possible issue with user satisfaction is whether the shoes would meet the expectations as presented, in terms of fit, functionality, or appearance.
Limitations	**E3/5:** The functional aspects might be confusing. The customer should be guided and supported during the design process. People may not be aware of what they are changing, for options such as knit patterns. Adding more visual information explaining how different materials or structures behave might make it easier. Also, customers may want to see different fabrics, to feel or touch them. Including this may improve the user experience.
Remarks	**E2/3:** There would be many people interested in this, as *fashion doesn't fit*. But, the positive user experience is on the condition of having a great fitting shoe, and how long it would take to deliver them. People are used to getting ready-made shoes the next day. If it is possible to really measure the needs of customers, then it may be worth the wait. **E2:** If the customers already know what functionalities they want, the decision-making process is simple. Maybe users want to customize the shoe for fitting or functionality. But designing side is more difficult for users. Graphical pattern options may be restricted, such as changing colors on pre-given graphics or only changing the pattern in a certain way to make it easier, then maybe only allowing more freedom with guidelines to users who want to get creative. It is also possible to include sort of artist editions, where someone else designs for you. **E4/5:** The expertise of the user is very important; the only challenge will be to not make it too complex. The users might be about the functional aspects mentioned, which is positive, but it is important not to give them too much, or ask for too much input for personalization. **E4:** The social and psychological factors should be considered as well, which can be investigated with these methods. The co-creation process is promising, but the ease of the process should be facilitated to avoid choice stress, and cultural and gender aspects should be considered while designing the co-creation process to elevate the impact of personalization.
	Comparison to Existing Applications
Benefits	**E1:** The winning point here is combining fit, aesthetics, and function in a way that is unique. In a classical customization example, the user is given the size option and the choice of a few selected parameters. There is no interconnection with a functional effect that you achieve when changing the design.

	E3: In comparison to the existing examples, there is definitely a higher level of personalization. The ability to completely define graphics on the shoe creates a lot of freedom. There is an advantage in cases such as a personalized fit is needed or a shoe for a special occasion is wanted. **E5:** 3D printing and 2D/3D scans are also used by existing examples, but what is really different is the functional personalization of the upper, which is an added value. Considering the different functionalities and parameters changing, digital knitting is very interesting, and it fits well in Industry 4.0 scenario.
Remarks	**E4:** It is a niche somehow. It allows you to express yourself through shoes, and it draws attention when you are on the move.

4.3.3. DISCUSSION

The applicability of the design process and the tools used in it are acknowledged in general, while still pointing out the necessity of setting a working system behind the algorithm. Solving coupled and functional personalization cases, and using an algorithm to automate the co-creation process while ensuring a reliable output were two important highlights of the methodology, and the benefit and novelty of these are also pointed out by the experts (1,4,5). There are also concerns about whether a real functional shoe is possible with the presented study, as it only covers the possible design variations. Hence, this is a point to be ensured in the base architecture of the shoe. An important suggestion is to increase the level of personalization by also tailoring the insole and sole orthopedically. This is surely feasible with 3D printing, also including the advantage of consolidating the two parts. For instance, this can be introduced by varying the density or type of lattice structures throughout the sole. However, this would require a thorough study to implement in the seed design, and the necessary data of the user should be acquired by professional means. Another significant suggestion is to improve the functional variation of the knitted upper by introducing additional parameters. This is possible by using more advanced knitting machines. More parameters would surely provide more freedom since in the current scenario only three parameters control the functional properties. This is also important to note for the scalability of the process as digital manufacturing technologies advance.

While there is a consensus on the technical feasibility in terms of manufacturing and design variety, having a seamless connection in-between is stated to be critical. The difficulty of this is especially pointed out for digital knitting. While it is more straightforward to transfer a design to 3D printing, digital knitting requires more work for the automation of manufacturing personalized designs. A challenge in terms of assembly might also arise as the number of components increases, besides the common use of conventional production in footwear. A suitable production and simple shoe are stated as critical for feasibility. The main advantage of knitting is reducing the number of components and simplifying the design. The least number of components in the shoe would be surely optimal for the feasibility. An important question is raised on the choice of knit patterns regarding the suitability of footwear and the ease of graphical pattern application. This is a case-based decision, depending on the priorities. If the variety of graphical pattern is primary, then only a single knit pattern can be used. If functionality is the priority, then the graphical pattern variation may be limited in favor of knit pattern variety. Introducing more knitting parameters would also help to compensate for limiting knit pattern. A critical comment is on the cost variations; the choice of patterns and number of yarns used in one fabric may affect the cost significantly. Here the options would be either reflecting the cost to the customer or limiting the case by introducing this as a manufacturing constraint. While the initial may result in a negative experience, the latter would limit the design options. In this case, it should be evaluated whether the design changes creating significant cost increase are still valued by some users.

The potential of digital knitting and 3D printing in footwear personalization is supported by experts. Specifically, the potential of knitting to provide varying functionalities is highlighted. While the simplicity of the proposed shoe construction is acknowledged, the manual labor in the production is seen as a potential drawback to competing with mass production. But besides the increasing manufacturing costs, the cost reductions due to on-demand production, such as not having stocks, should be taken into account as well. Moreover, manufacturing automation would surely make personalized products more affordable. The functionality and resistance of a 3D-printed sole are also seen as a limitation. This depends on the material and process used, but the increasing interest will surely lead to the development of more suitable materials. In terms of the design process and the framework, the main advantages are seen in the given design freedom to the user and the automation of the process to generate personalized designs. Though stating that for a business case, the design and the user involvement may need simplifications.

The experts foresee the interactive co-creation process to be a pleasant experience for the user and find it to be attractive to provide personalized fashion. However, considering the overall experience, the importance of the final product meeting the expectations of the user are underlined. The importance of considering the expertise and profile of the users while defining the extent of personalization is also strongly highlighted. Both the visual and functional design of the product might be challenging for some users. The overall suggestion to improve the experience is to provide more guidance to users in the process and allow them to understand the different functionalities better. There are surely many aspects to consider regarding the user experience, on top of what is presented in this study. The proposed methodology deals with only the back end of the co-creation process to facilitate it. Designing the front end of user co-creation should come as a supplementary process, which also provides input to the size and dimension of the design space.

In comparison to the existing applications, the main advantages are seen in tailoring the fit, aesthetics, and function together, and providing more freedom than traditional customization options. While the usage of 3D printing, knitting, and foot scanning in existing applications as well, the novelty and added value are seen in tailoring the functionality of the upper. Knitting is getting increasingly popular in footwear in the past years, though its use for customization or personalization is not common yet. As also highlighted by the experts, further advancements in connecting knitting design to manufacturing codes, and in the automation of the on-demand footwear production will promote such personalization cases in the footwear market.

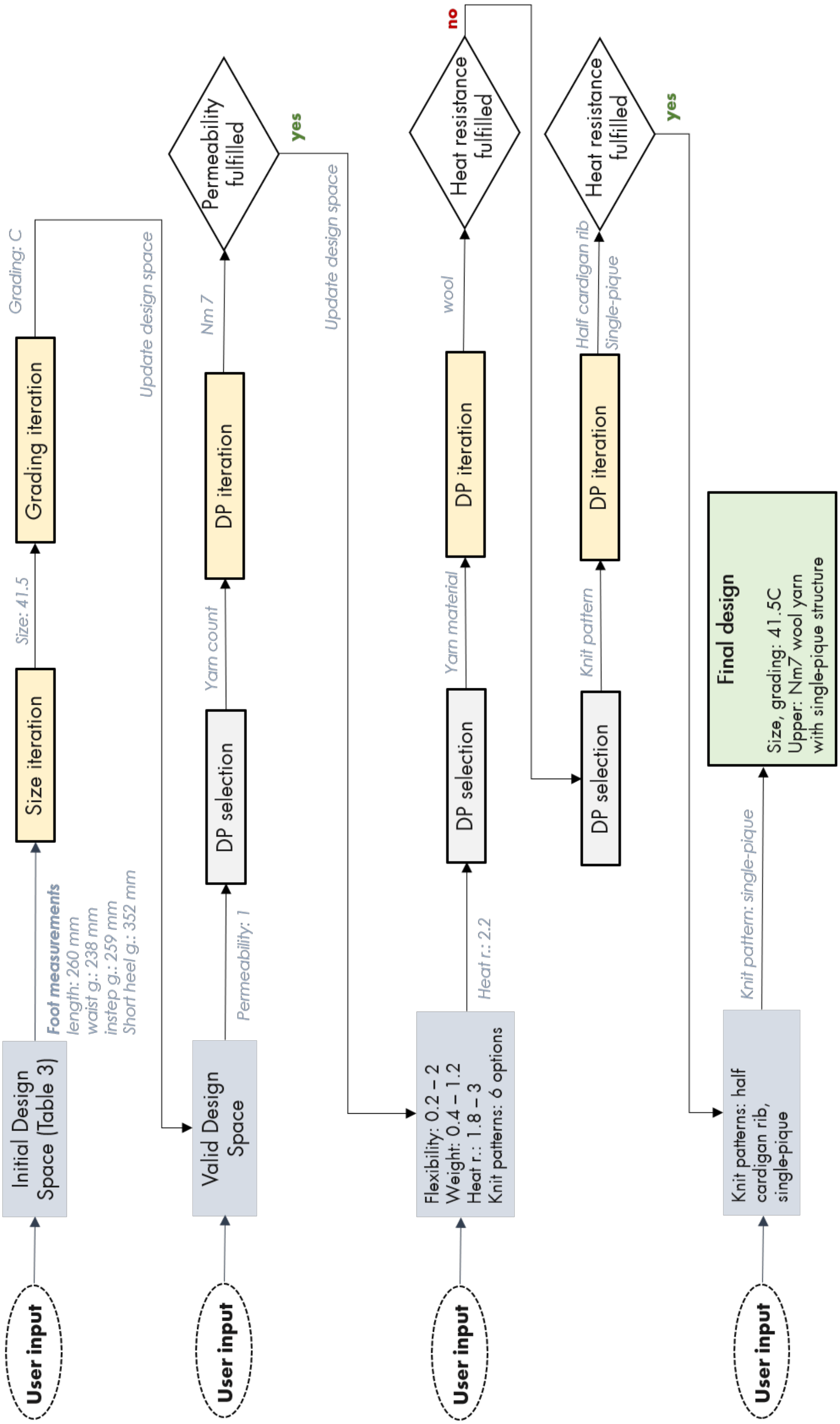

Figure 4.9: Design solution example for knitted footwear personalization.

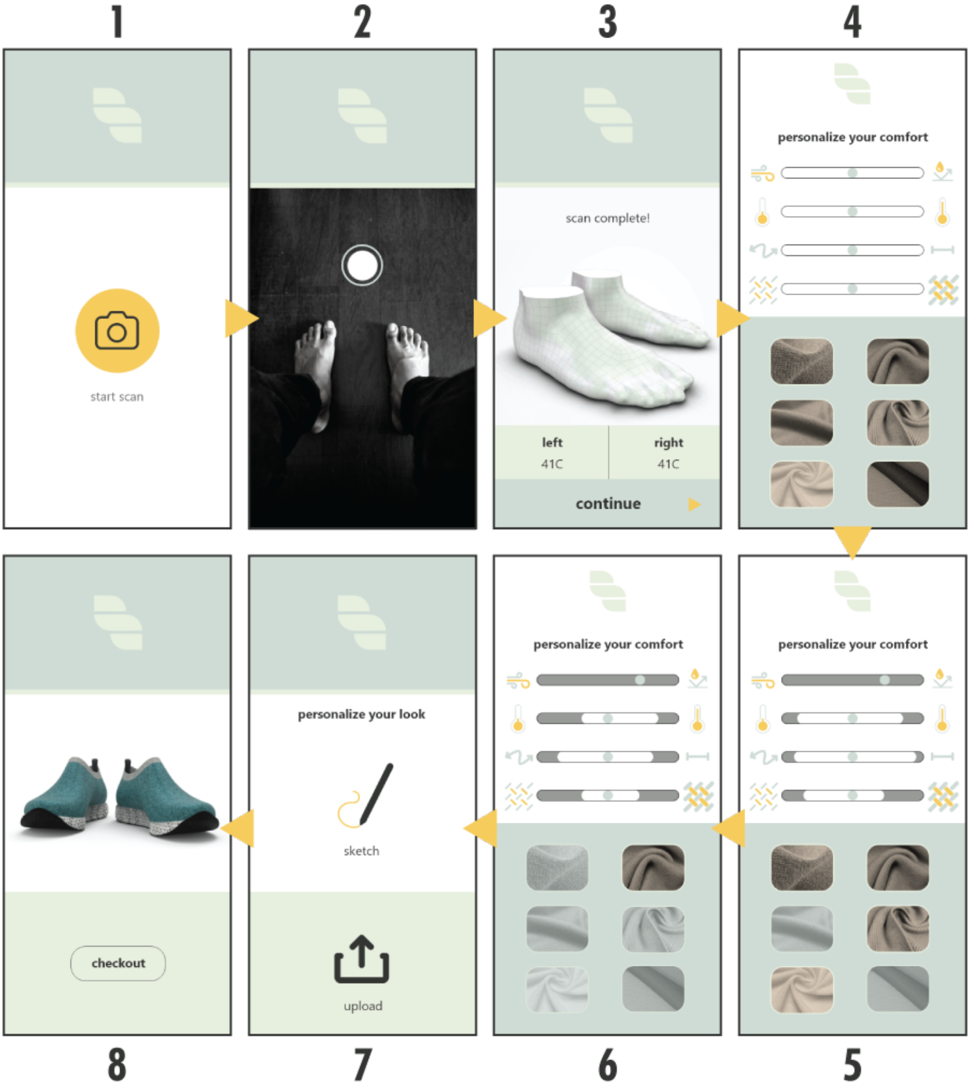

Figure 4.10: Co-creation process example on a user interface.

5

CASE STUDY II: SAXOPHONE MOUTHPIECE PERSONALIZATION

This chapter illustrates the proposed methodology for the personalization of 3D-printed saxophone mouthpieces. The present study showcases a valuable example of a coupled design between different performance indicators of the mouthpiece and its design. It is significant to demonstrate how consolidated functions can be managed to tailor products for customers. An experiment process supports the case study to identify the relationship between the performance and design of the mouthpiece. Finally, a user study concludes this chapter, to verify the experiment results and the effectiveness of the proposed co-creation scenario to meet the specific needs of customers. The majority of the content presented in this chapter has been published in *Acta Acustica* [125], and *Proceedings of Design Conference* [126].

The saxophone mouthpiece (Figure 5.1a) is the interface between the player and the instrument, where the vibration of a reed attached to the mouthpiece produces the sound. It is safe to say that in terms of acoustics, the mouthpiece is the most essential part of the saxophone; by not only producing but also shaping the sound. Hence, the design of the mouthpiece greatly affects the performance of the instrument. The choice of a mouthpiece is a very personal decision, depending on playing habits, the music genre, or the playing environment. As a result, there is an everlasting quest of finding the most suitable mouthpiece among saxophone players. Due to this demand, there have been several design iterations introduced by instrument makers, and today there is a range of different designs available in the market. There are also a number of artisans modifying existing mouthpieces to help players to reach closer to the desired performance. Thus, there is an existing demand for the personalization of saxophone mouthpieces, and tailoring it to the specific needs of players would certainly be an added value. Besides having a certain demand for personalization, the saxophone mouthpiece is a product with a rather simple design with high value. This makes it a very suitable candidate for personalization and on-demand production by AM.

(a) Traditional mouthpiece

(b) 3D-printed mouthpiece

Figure 5.1: Saxophone mouthpieces.

5.1. CONTEXT

5.1.1. MOUTHPIECE DESIGN

The saxophone sound is produced by the oscillation of a single reed as the air flows through the internal cavity of the mouthpiece [127]. The volume and the internal geometry of the mouthpiece have been shown to affect the input impedance of the instrument and hence the resulting sound [128, 129]. Moreover, small design changes on the mouthpiece may significantly affect the oscillations of the reed and cause playability, intonation, or timbre differences [129–131]. For instance, wider tip openings result in higher thresholds of oscillation [132, 133], requiring higher blowing pressure to start a tone. Furthermore, it has been shown via both experimental measurements [134] and physical modeling [135, 136] that reed stiffness dynamically increases when the reed closes, hence the reed–mouthpiece interface might affect the oscillation threshold and other playing parameters. Introducing changes in the mouthpiece geometry, though, might lead to either meeting the players' individual desires or generating counterproductive results (e.g. affecting the tuning of the instrument).

Saxophone mouthpiece design has transformed since the invention of the saxophone, and several iterations from the original design exist today [137]. These changes in the mouthpiece design have been proven to provide distinct tonal characteristics [131, 138]. The key design aspects in mouthpiece structure are shown in Figure 5.2.

Both the description and perception of tone quality are subjective. Hence, it is difficult to describe the tonal characteristics and standardize them. There is an effort in psychoacoustics to relate the perceptual descriptions of saxophone sound to acoustical dimensions [139]. The formant-like structures in the frequency spectrum of the saxophone sound are considered to be defining its tonal characteristics [140], such as, e.g., "brightness", which may be assessed using the spectral centroid [141].

Other than the tone quality, there are also performance-related aspects of the mouthpiece that rely on its design, such as pitch, loudness, equality of registers, flexibility, and ease of playing [130]. A steady pitch and good intonation throughout all registers are usually standard expectations from a mouthpiece. However, expectations regarding loudness, flexibility, and ease of playing aspects are likely to differ, because of playing

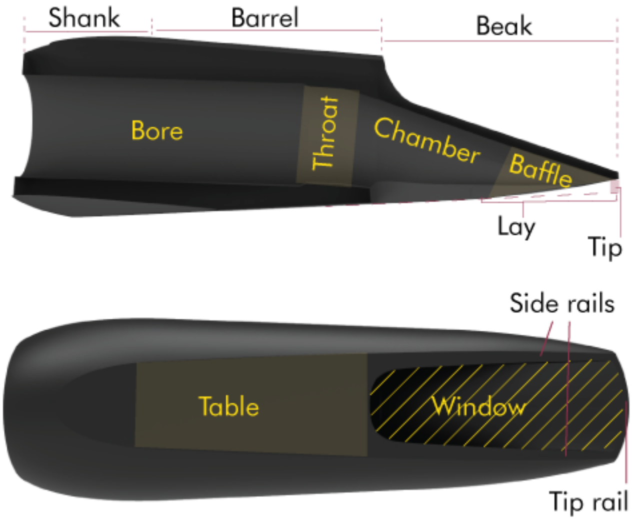

Figure 5.2: Saxophone mouthpiece design aspects.

habits, music genre, or playing environment [131].

The shape of the internal cavity (throat and chamber for the saxophone) is found to change the tone color and harmonic spectra of woodwind instruments [142]. On top of the change in tone quality, Teal [130] describes how mouthpiece dimensions and shape affect also loudness, flexibility, and ease of playing. He further lists the effective parameters as tip opening, lay length, baffle height, tip rail width, chamber size, and shape. Similarly, Pinksterboer [143] identifies tip opening, lay length, baffle shape, and chamber size as important parameters affecting sound and playability. Baffle height is particularly associated with the brightness or darkness of the tone [144]. In addition, variation in tip opening is found to alter the control, loudness, and projection of the mouthpiece. Analyzing and iterating the original design by Adolphe Sax, Celentano [137] identified chamber size, tip opening, table size, and window size as the important parameters for playability and timbre. By examining the characteristics of the airflow through the mouthpiece, Lorenzoni [145] demonstrated the effect of the inner geometry on the airflow, and hence on the produced sound.

5.1.2. MOUTHPIECE MANUFACTURING

Saxophone mouthpieces are most commonly made of hard rubber or various metals and are rarely found in wood, porcelain, or glass. The majority of the commercially available saxophone mouthpieces are manufactured with conventional methods. Although the manufacturing is mainly by subtractive machining today, finishing is still done by manual labor in most cases. This is a major driver of the high cost of mouthpieces. Regarding this, AM could provide substantial ease of manufacturing and reduction of costs, besides providing the necessary flexibility to tailor the design for each player.

The applications of AM for various wind instruments have already been demonstrated for various purposes, including restoration of ancient instruments, personalization, or innovation [146, 147]. An example of an innovation case is shown by Hang, 3D printing a single-component mouthpiece with a built-in reed [148]. 3D printed custom mouthpieces are also available commercially[1]. Recreation of the original mouthpiece design by Adolphe Sax is also an excellent demonstration of the restoration value of AM [137]. As an attempt to alter the properties of the mouthpiece, Lorenzoni [149] proposed novel designs of baffle and throat, which would have been very challenging with traditional manufacturing methods.

5.1.3. MOUTHPIECE PERSONALIZATION

The mouthpiece is a very personal product, both in terms of playability and produced sound. Therefore, players have different expectations and desires when choosing a mouthpiece. To be able to provide the desired features in the mouthpiece, the effects of the design changes need to be determined. This requires an understanding of the results of the design changes precisely. The traditional approach taken by manufacturers and artisans to improve or tailor the mouthpiece features is based on trial-and-error and iterating the changes in the design aspects [150]. Mouthpieces today exhibit a wide range of designs, some being quite different from the original design by Adolphe Sax, as the manufacturers iterated design changes based on players' feedback over the years [137]. These mouthpieces are sometimes further modified or fine-tuned by artisans to meet the players' demands. However, given that design aspects and their changes have no standard, the evaluation of these changes is very subjective, and it is challenging to tailor the mouthpiece to the desired performance. Besides, the lack of objective measures results in misinformation about the mouthpiece design, such as the common false belief of the mouthpiece material's effect on sound[130].

Perception of tone quality is very subjective, and it is likely to be defined by different adjectives by listeners[151]. The same subjectivity applies to producing sound with the mouthpiece and its associated playability since the vocal tract of the player has an essential role in these[152–154]. Therefore, the same mouthpiece cannot guarantee the same sound when used by different players. Besides, conditions such as different music styles (e.g. classical or jazz) or playing environments may require different performances from the mouthpiece[143]. As a result, players have different needs and expectations, which makes the mouthpiece a very personal product.

5.1.4. MOTIVATIONS FOR THE STUDY

The saxophone mouthpiece design is still to this date an artisanal work based on experience and trial-error. Over time, each manufacturer differentiated their mouthpieces with a certain aspect of the design, such as the exceptional window design of Jody Jazz or the high baffle design of Dave Guardala. Eventually, there has been an accumulation of knowledge about the design variables and their effect on the sound and playing experience. However, since the design has been based on intuition and often with changing multiple parameters, the relative effect of each parameter is not clear and there are several misconceptions. An example of this could be the common misapprehension about

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[1] Syos custom 3D-printed mouthpieces: https://www.syos.co/en/blog/acoustics/how-is-saxophone-mouthpiece-customization-possible.

the effect of material on sound. Therefore, besides the subjectivity in sound perception, a major challenge in this study is about defining the relative effect of design parameters on sound characteristics.

5.2. SEED DESIGN DEVELOPMENT

The starting point is an existing mouthpiece in this case, from which the features of the base architecture are derived. For instance, the overall dimensions of the mouthpiece, how it fits the saxophone, and how the reed is positioned are some elements of the base architecture. There are also some variable design features of the seed design that provides personalization. These are explained in Section 5.2.2 below.

To acquire base architecture features, a Yanagisawa ebonite alto saxophone mouthpiece (#6 with 1.83 mm tip opening and 22 mm lay length[2]) has been chosen due to being a well-established design and having design parameters at average values. The process starts with 3D scanning of the mouthpiece to obtain its dimensions precisely. A Konica Minolta VIVID 9i laser scanner is used for the 3D scanning, which has 0.03 mm Z-Depth and 0.145 mm X&Y resolution. Since the scan data is a point cloud, it is processed by PolyWorks software to be converted into a mesh model. Following this, the mesh model is converted into a parametric model by the Scanto3D module of SolidWorks. To define an interval for each parameter and dynamically control these, the Grasshopper module of Rhinoceros is used,

5.2.1. PERSONAL REQUIREMENTS

The needs of players are primarily related to how the instrument sounds, and also how they can perform with the mouthpiece. Hence, the personal needs of a player with a mouthpiece can be broadly grouped as desired sound and compatibility with playing habits. Based on these, Top-level PRs from the mouthpiece may be grouped into two categories: sound features (timbre attributes) and playability aspects (Figure 5.3).

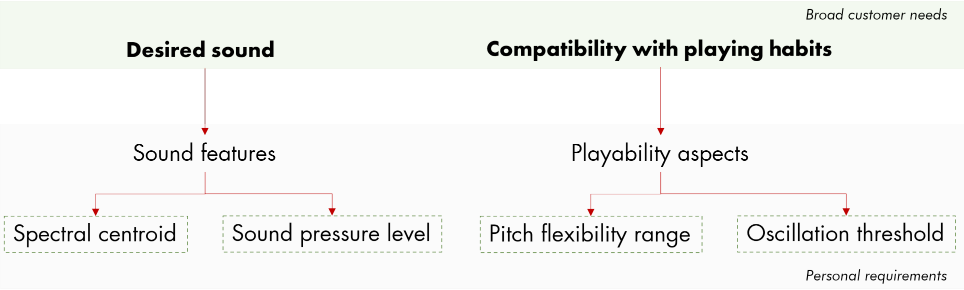

Figure 5.3: CNs, and PR decomposition for mouthpiece personalization. The PRs to get user input are in rectangles with dashed lines.

The sound features are usually very subjective and the perception of these is studied in psychoacoustics [151]. Especially in terms of defining the saxophone sound, or in general describing timbre, there are several descriptors identified in psychoacoustics

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[2] Yanagisawa mouthpieces: https://www.yanagisawasax.co.jp/en/saxophones/view/529.

[140]. However, these are based on the sound perception of the listener (player or external listener), hence very subjective. As quantitative measures are needed here, the features that are possible to be measured at the instrument are selected. One of the most distinctive descriptors of timbre is brightness, which is related to the energy at the high-frequency partials in the spectrum. For this study, brightness is the only timbre attribute considered. Another sound-related PR considered is the loudness of the produced sound.

The playability aspects are somewhat more tangible since they appear in the player-mouthpiece interaction. Two of the significant aspects for players are blowing resistance and flexibility on the instrument's pitch. Therefore, the mouthpiece features to be considered in this work, their explanations, and the means to be observed are as below:

- **Resistance** implies the difficulty of blowing into the mouthpiece, or in other terms, the ease of producing sound. For a fixed tip opening, the resistance of the mouthpiece is also dependent on the strength of the reed used. The resistance Resistance is assessed by considering the **oscillation threshold** [132], i.e. the blowing pressure necessary to start a sound.

- **Loudness** refers to the sound level of the instrument. Different loudness levels may be a desirable property for players. To exemplify, playing outdoors or in a marching band may require louder sounds, while the opposite may be valid for playing indoors. During the performance, loudness is controlled by the players' blowing pressure to achieve different dynamics [155]. Yet being a perceptual feature, in order to define a standard to compare the tested mouthpieces, loudness is assessed in this work by considering the external **sound pressure level** at a fixed blowing air pressure.

- **Brightness** is the most common tone color descriptor among players to describe how bright or dark is the sound produced. As different levels of brightness might be a personal preference, it may be more suitable or desirable for different music genres. Brightness is associated with the high-frequency content in the spectrum of a sound and can be assessed via its **spectral centroid** [141].

- **Flexibility**, also referred to as pitch flexibility [156] or flexibility of intonation [157], describes the possibility to adjust pitch. Saxophonists can alter the pitch of a fingered note in order to vary its intonation or perform pitch modifications such as pitch bending or glissando [154]. Higher flexibility might be a desirable property for a jazz player, while for a classical player, lower flexibility and a more sustainable pitch might be of more value. It can be measured by the **pitch flexibility range** between the highest and lowest pitch produced.

5.2.2. DESIGN PARAMETERS

The saxophone sound is produced by the vibration of the reed, which is excited by the air passing through the inner cavity of the mouthpiece. The parameters defining the inner cavity affect the airflow characteristics, and the parameters interfacing with the reed affect the vibration of the reed (Figure 5.3). Hence, these parameters, as shown in Figure 5.4, define the performance of the mouthpiece. These parameters vary among

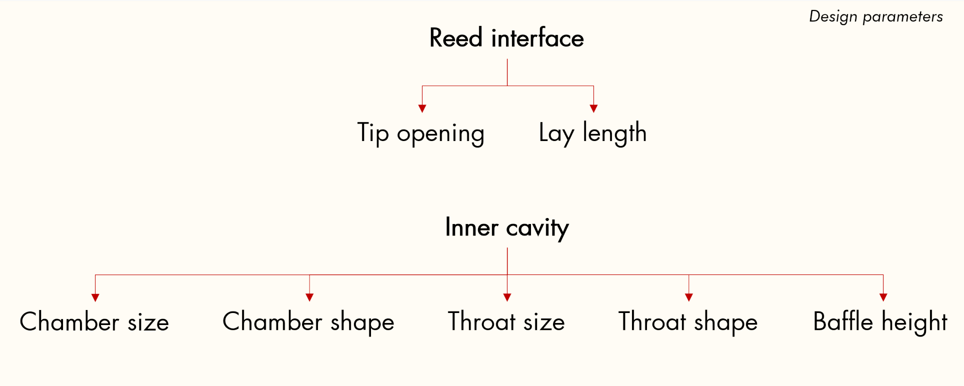

Figure 5.4: DP decomposition for mouthpiece personalization.

the existing mouthpieces, and it is known that they affect certain characteristics. However, there was no evidence on how and what they affect exactly. Since the proposed methodology requires quantitative relations between PRs and DPs, these were identified through a set of experiments in the previous study [125]. To assess the effects of design changes on resistance, loudness, and brightness, an artificial blowing machine was used to obtain measurements; for the flexibility, the measurements were done while a player is performing. The details of the experiment are explained in 5.2.4. The selection of DPs below includes all the major parameters identified in the literature, a few parameters were not included as it was not possible to account for their effects with the used experiment setup.

The design aspects used in the literature [130, 137, 143, 144] to produce saxophone mouthpieces (Figure 5.2) can be grouped as reed interface (table, lay, tip opening, tip rail, side rails), internal airflow (bore, throat, chamber, baffle), and player interface (beak) aspects. The design parameters used in this work are derived from the definitions in the literature, focusing on the reed interface and internal airflow aspects. Player interface aspects are disregarded because they would not result in an observable effect when tested in an artificial blowing setup. For instance, beak size does not directly affect the airflow or reed oscillation; however, it might affect the player's oral cavity and hence indirectly the airflow [130]. Furthermore, changes in tip and side rail thicknesses are significant when there is lip pressure change or tonguing exercise. However, since neither are present in the experiments, these parameters are excluded as well. One last reason to exclude a design parameter is the geometrical dependence between parameters: facing curve radius, lay length, and tip opening are dependent variables (Figure 5.5b). The facing curve is defined as circular and tangential to the window at the reed separation point, in accordance with common practice [130]. Geometrically, once two of the three parameters are set, the third is already fixed. Therefore, the facing curve gets excluded as it becomes redundant after setting the other two parameters. Attaining to these considerations, the design aspects and related parameters used in the experiment can be listed as:

- **Chamber size:** The chamber is the inner cavity between the baffle and the throat (Figure 5.2). The cross-section of the chamber is seen in Figure 5.5a. The chamber size is evaluated via the variable s_{chamber}, which is the shortest distance from the central axis to the chamber wall. Different chamber sizes are shown on the cross-sections in Figure 5.6.

- **Baffle height:** The inner part of the mouthpiece next to the tip is referred to as the baffle. Several baffle designs exist. The design adopted here is called a step baffle. The step baffle design has a triangular profile, resembling a stairway step. It starts from the tip rail and then drops into the chamber as shown in Figure 5.5c. The baffle height is defined with the variable h_{baffle}, as the distance of the baffle peak from the upper surface of the mouthpiece cavity, measured parallel to the tip-opening. Varying baffle heights are shown with different shades in Figure 5.5c. Other variables defining the baffle profile, b_1 and b_2, are kept constant.

- **Throat size:** The throat is the transition cavity between the chamber and the bore (Figure 5.2). The throat cross-section is seen in Figure 5.5a. The throat size is evaluated in the same way as the chamber size with the shortest distance from the central axis to the throat wall, s_{throat}. Varying throat sizes used in the experiment are shown in Figure 5.6.

- **Throat shape:** It is the shape of the cross-section, and it is defined with the variable r_{throat}, which denotes the fillet radius of the cross-section area corners. Varying throat shapes are shown in Figure 5.6.

- **Chamber shape:** It is also defined as the cross-section shape, the same way as the throat shape. The variable defining the chamber shape is r_{chamber}, which denotes the fillet radius of the cross-section area corners (Figure 5.6).

- **Window length:** The window is the opening between the reed and the mouthpiece. Its length l_{window} is defined as the length of the centerline from the tip to the table (Figure 5.5d).

- **Table length:** The table is the interface where the reed is fixed to the mouthpiece. Its length l_{table} is measured from the end of the window to the end of the reed (Figure 5.5d).

- **Lay length:** The lay length l_{lay} is measured as the distance between the tip of the mouthpiece and the point where the reed separates from the mouthpiece, in rest position and without lip force (Figure 5.5b).

- **Tip opening:** The tip opening h_{tip} is the vertical distance between the tip of the mouthpiece and the tip of the reed, in rest position and without lip force (Figure 5.5b).

5.2.3. CONSTRAINTS AND SOLUTION SPACE

To set the boundaries of the solution space, a list of previously suggested constraints is to be considered. In the case of the mouthpiece, there are a considerable number of designs

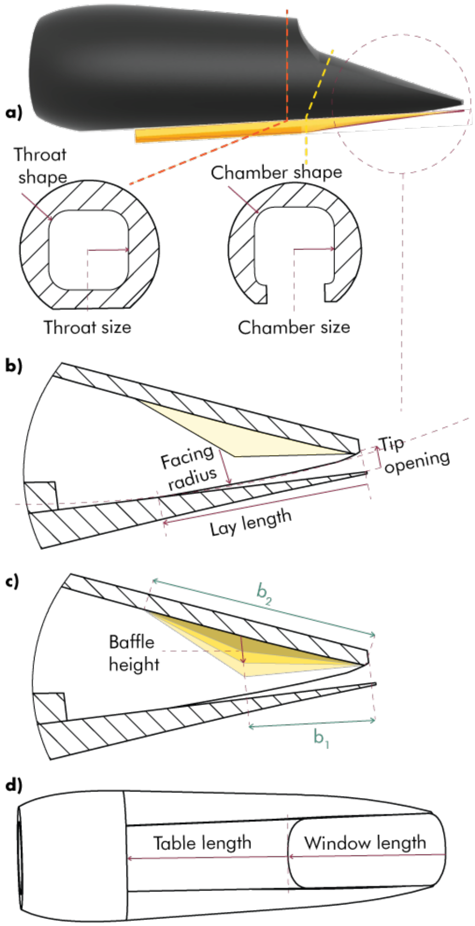

Figure 5.5: Design parameter definitions used in the study. The red circle in *a* highlights the location of the cross-sections in *b* and *c*.

available on the market. A survey of mouthpieces available in the market was carried out to have a reference for the variability of the parameters. This was done by considering the 100 most sold[3] alto-saxophone mouthpieces in a widely used online platform. For instance, the tip openings of these mouthpieces vary between 1.4-2.6 mm, and the lay lengths are between 17-25 mm, as shown in Figure 5.7. This is used as a starting point to set the range of these parameters. It is also important to note that the existing designs have discrete values within these intervals, and most of the possible combinations of different parameter values do not exist, as seen in Figure 5.7. Hence, there is a largely unexplored space of design possibilities, and consequently, unexplored performance characteristics. The proposed approach allows fine-tuning these parameters and exploring the complete solution space to tailor the performance of the mouthpiece.

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[3] as of February 2019; www.thomann.de

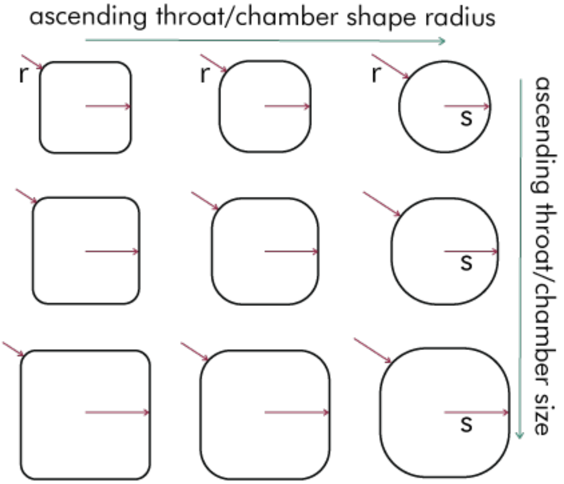

Figure 5.6: Throat and chamber cross-section shapes and sizes used in the study, ordered by ascending shape radius from left to right (r_{throat} and r_{chamber}), and ascending size (s_{throat} and s_{chamber}) from top to bottom.

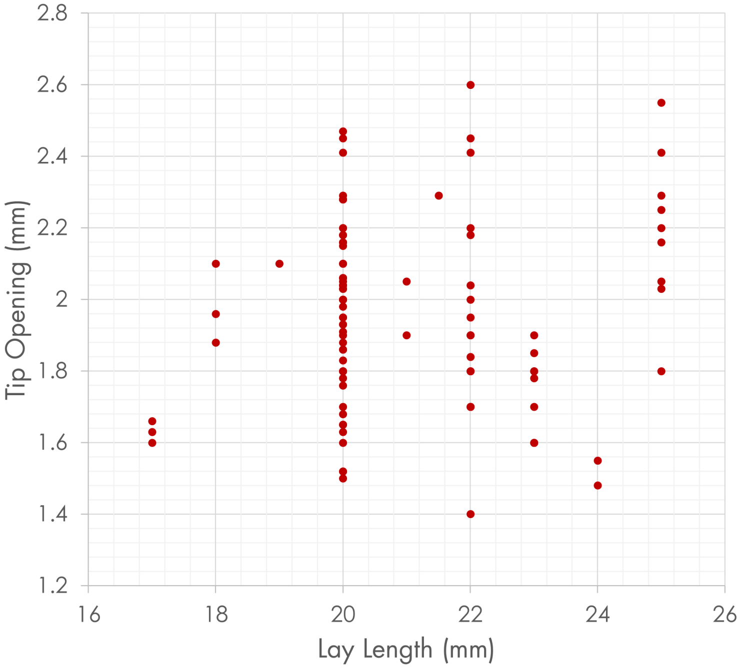

Figure 5.7: Tip opening and lay length values of 100 alto saxophone mouthpieces surveyed.

To constrain the design space further, the interdependencies of the DPs are checked. Continuing on the same two parameters, lay length and tip opening are dependent parameters, and extreme combinations of these are either unplayable or very uncomfortable to play. Therefore, these combinations are also eliminated.

In terms of manufacturing or feasibility, there are not any significant constraints in this case. This is since the product has a simple geometry, and the parameter changes are at a small scale. Nevertheless, there are still constraints regarding the basic design of the mouthpiece. For instance, the selected material should not be toxic as the product stays in contact with the player for a long time. Similarly, it should be resistant to moisture as it is significantly present while playing. There are surely more constraints to these to be considered for the basic design of the product. While the constraints here, and in the context of the methodology, are related to the possible changes in the product.

The final step of the constraints is related to the personalization scenario. In this case, the users of the product are rather experts, and hence they might benefit and appreciate the largest possibilities. For instance, if the user target was narrower, such as only beginner players or classical music players, the parameters could have been restricted further to avoid possibly undesired results. Once all constraints are applied, the final ranges of the DPs are obtained. These ranges form the solution space, within which a personalized design can be created.

5.2.4. EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF DESIGN CHANGES ON MOUTHPIECE FEATURES

To obtain the PR-DP dependencies, this experiment aimed to quantify the effect of mouthpiece design parameters on the playability and the sound of the instrument (hereafter features). Playability and sound criteria are defined by objective indicators extracted from the measurements obtained with an artificial blowing machine and one musician. These tests consider a set of 27 different mouthpiece designs configured according to the Taguchi method [34]. Analysis of the experiment results provides the quantitative relationships between mouthpiece features and design parameters (Section B.4).

As the literature study indicates that most of the design parameters affect multiple mouthpiece features [130, 134, 137, 138, 145], the decision on one design parameter will affect the decisions on other parameters. The most convenient way to analyze the effects of the design parameters is to change them one by one and observe the results.

METHODOLOGY

The approach taken in the present work, in essence, is similar to the traditional empirical method of artisans, but in a constructed way based on quantitative design iterations. To reduce subjectivity in the design changes, the design features and their interval of changes need to be defined parametrically. It is necessary to test the design parameters at different levels and analyze the variations they result in, to understand their behavior.

Firstly, the mouthpiece features to examine were selected, and following that, corresponding design parameters were identified. A commercial alto saxophone mouthpiece was used as a base design, and a seed design was created where parameters can be given a value within certain intervals. To understand the results of variations in design parameters, an experiment was devised to test mouthpieces with different design configurations, using an artificial blowing machine. The experiment setup and the procedure are explained in B.2.

EXPERIMENT DESIGN

To observe the effects of design parameter changes on the selected mouthpiece features, each parameter is to be tested at different levels, and the results are to be analyzed for the responses of the parameters. If the possible interactions are also included, all possible combinations of parameters should be tested at varying levels. However, a full factorial design would yield a very high number of cases to be tested, such as for nine parameters at three levels, the number of cases would be 3^9. Neither experimenting nor analyzing such a high number of cases is practical. Therefore, a fractional factorial method to analyze the main effects and the interactions of the parameters is needed. An experimental design following the Taguchi method simplifies the statistical design by employing orthogonal arrays, which reduces the variance for the experiment with optimum settings of control parameters [34]. The use of orthogonal arrays minimizes the number of runs in the experiments. For any given pair of columns in the orthogonal array, all combinations of parameter levels occur an equal number of times. The Taguchi method provides standard orthogonal arrays based on a number of factors and levels. In this study, there are nine parameters, and to observe any nonlinearity in the output, they are tested at three levels. The L27(3^{13}) orthogonal array of Taguchi can be used to analyze up to 13 parameters with three levels using 27 runs. Therefore, it is the most suitable orthogonal array for nine parameters at three levels, with a reasonable number of experiment runs. The parameter configurations for the 27 runs are presented in Table B.1 in Appendix B.1.

The levels of the parameters of the experiment are chosen within the ranges identified in the parametric mouthpiece model. Critical values such as maximum or minimum are avoided, thus each level is set in a way to prevent possible interactions between the parameters or unplayable combinations, which may show misleading results. Table 5.1 lists the design parameters and their level descriptions. The three levels of the parameters are combined to design the 27 mouthpieces as indicated in Table B.1.

Table 5.1: Parameter level descriptions. All units are in mm.

	Level 1	Level 2	Level 3
s_{chamber}	6	7	8.5
h_{baffle}	0	3	5
s_{throat}	6	7	8
r_{throat}	2	4	6
r_{chamber}	2	4	6
l_{window}	35	38	41
l_{table}	23	28	31
l_{lay}	18	21	24
h_{tip}	1.6	2	2.4

PROTOTYPING

Several 3D printing technologies have been tested and compared for manufacturing the mouthpieces. Due to the high accuracy, resolution and repeatability of the results, stereolithography was chosen as the manufacturing method. Since the design parameters considered to have a sensitivity of 0.1 mm, this is a limiting factor for certain technologies. E.g. mouthpieces manufactured by FDM technology had an inconsistency of up to 1 mm in repeated prints. Therefore, a Formlabs Form 2 3D printer has been used for the manufacturing (Figure 5.8). Post-processing of the prints has been done respectively in Form wash and Form cure modules. Standard translucent resin has been used for the prints. The machine is capable of printing 16 mouthpieces at a time, which lasts about 19 hours at 0.1 mm resolution. Post-processing steps took about another hour in total. The mouthpieces tested in the experiment are shown in Figure 5.9.

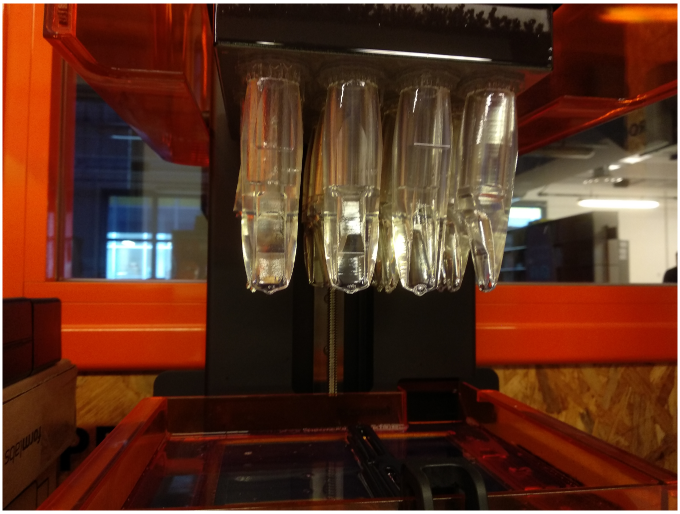

Figure 5.8: Prototyping of mouthpieces using a Formlabs (Form 2) 3D printer.

EXPERIMENT RESULTS

The data processing and statistical analysis are presented in B.3. The experiment results provided an indication of the relations between mouthpiece design parameters and features related to performance. The direction and the relative size of the parameter effects are deducible from the results, as seen in the plots in Figure B.6. The experiment results are discussed in B.4.

Based on the relationships obtained in the experimental analysis (B.4), the dependencies between PRs and DPs are identified. These relationships are adopted as a proxy to estimate the features of the mouthpiece. More specifically, the parameter configurations providing the extrema of each feature are deduced from the experiment results (for example the maximum brightness is expected when h_{baffle} is set at level 3, s_{throat} at level 2, and l_{lay} at level 3). The feature extrema form the boundaries of the scale, in which a feature can be configured, which implies the design space for the user. Relative to either end of the scale, the parameter values are iterated to obtain the desired performance.

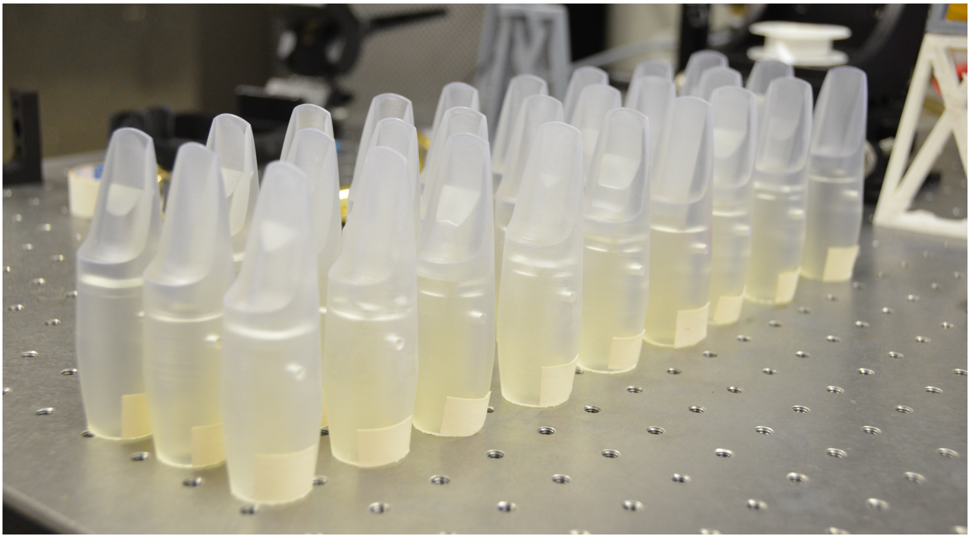

Figure 5.9: 27 different mouthpieces designs tested in the experiment.

5.2.5. DEPENDENCY MATRIX

The Figure 5.10 shows how each parameter affects PRs. As seen in Figure 5.10, there is a highly coupled case, where all PRs are defined by multiple DPs, and five of the DPs affect multiple PRs. Therefore, it is a complicated task to tailor the performance of the mouthpiece, and as the performance aspects are dependent on each other through the DPs, certain trade-offs may be needed.

5.2.6. DESIGN SPACE

The solution space set the boundaries of how the structure of the product may change. On the other hand, the design space includes possible personal requirements for the product. In this case, these are the four performance aspects. The solution space is mapped back onto these to set their ranges. To be more specific, the DP combinations providing the extrema of the given performance aspect give the largest range of the PR. For instance, the highest pitch flexibility is obtained with the largest baffle height and the smallest chamber size and tip opening. With the given DP ranges, the pitch variation interval (flexibility) can get a value between 41-129 Hz, according to the results of the previous study [125]. The same procedure is then followed for all the PRs to find what can be offered to the user, and this forms the design space. The design space initially provides the largest range of PRs. But since this is a coupled design case, PRs are dependent and the user can not simultaneously decide on all four PRs. Therefore, the user has to reach a trade-off considering personal priorities and can obtain the most suitable performance from the mouthpiece.

	Chamber size	Baffle size	Throat size	Throat shape	Chamber shape	Lay length	Tip opening
Pitch flexibility range	X	X					X
Spectral centroid		X		X		X	
Oscillation threshold	X	X			X	X	X
Sound pressure level	X	X	X	X		X	X

Figure 5.10: Dependency matrix between mouthpiece PRs and DPs. Independent DPs are shown with colored background. X stand for dependency.

5.3. EXAMPLE DESIGN SOLUTION THROUGH CUSTOMER CO-CREATION

This example briefly illustrates how the user co-creates the product through the interaction between the design and solution spaces via the solution algorithm behind it. Since the PRs are very technical and their values would not be meaningful to the users, they are renamed in the user language and sliders are provided for user input. In Figure 5.11, pitch flexibility refers to pitch flexibility interval; brightness refers to the spectral centroid; resistance refers to the oscillation threshold: and loudness refers to sound pressure level. In the user study of this example, benchmarking mouthpieces were given to the users to understand the scale and have a reference for their decisions [125].

A user co-creation scenario is shown in Figure 5.11. Step 1 shows the initial design space, where all four PRs have their largest ranges available. The first decision of the user is to set the pitch flexibility, moving the slider to the more flexible side. As the most effective DP, in this case, is tip opening, it is iterated to its lower limit; then passing to the second DP, the baffle height is increased, and a solution is found. In Step 2, it is seen that the design space and the default state of the PRs are changed. This is due to the DPs changed in the previous step. In this step, the user changes the brightness, and this requirement is satisfied by iterating the throat shape and the lay length, respectively. In the third step, four of the DPs are already set, and the remaining design space for the other two PRs is significantly smaller. In this case, the user changes the resistance, and this is satisfied by increasing the chamber shape. It should be noted that since the chamber shape is an independent DP, it does not affect the design space in the next step. In the last step, the user sets the loudness of the mouthpiece, and this is satisfied by iterating the throat shape first, as it is an independent DP. At this point, all PRs are decided by the user, and a design can be generated with the DP values at this instance. In the case desired, the user may continue looking for further trade-offs following the same process.

Figure 5.11: Interaction between design and solution spaces in a user co-creation scenario for mouthpiece personalization. The ranges of DPs are shown on the radar charts on the left side; their values vary from inner to outer heptagon, increasing towards the outer.

5.4. USER STUDY

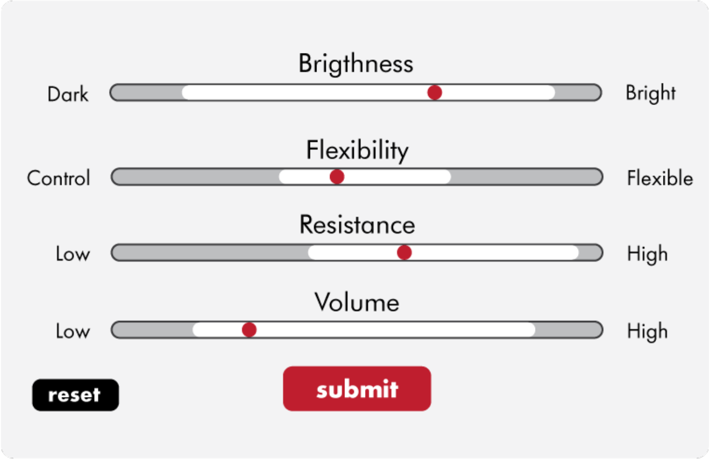

Figure 5.12: GUI used in the personalization process to collect the user preferences of mouthpiece features. White areas in the slider indicate the available range of the feature at that instant.

The experiment results demonstrated how design alterations affect the performance of the mouthpiece in a quantified manner. However, it is also important to understand how saxophone players perceive these performance changes and whether their perception is in accordance with the reported experiment results. For this purpose, a user study was devised to verify the results by employing the proposed personalization model. Besides, it provides an opportunity to test the co-creation scenario in the proposed design methodology.

The study was conducted with 5 participants at The Royal Conservatoire of Antwerp (Antwerp, Belgium). All participants were master-level saxophone students with minimum of 10 years of experience. The tests were performed with one user at a time, and each session took 40 to 60 minutes. The participants were informed about the experimental procedure and gave their consent to their anonymous participation in this study.

5.4.1. METHOD

The user tests were carried out in two phases (Figure 5.13). In the initial phase, players could test the mouthpieces, configure a personalized mouthpiece and get familiar with the mouthpiece feature changes. For this purpose, mouthpiece design configurations at levels providing the highest and lowest of each feature were manufactured. As explained previously, these configurations are deduced from Figure B.6 using the maxima and minima of the plots. These benchmark mouthpieces were used as a reference for the players to understand the boundaries of their design space for each feature. The GUI in Figure 5.12 was also presented to the players. They could use sliders to specify how they would prefer the features in a personalized mouthpiece for themselves. The parameters corresponding to the benchmark mouthpieces were presented at the extremities of the sliders. For each feature, players tested the benchmark mouthpieces several times and

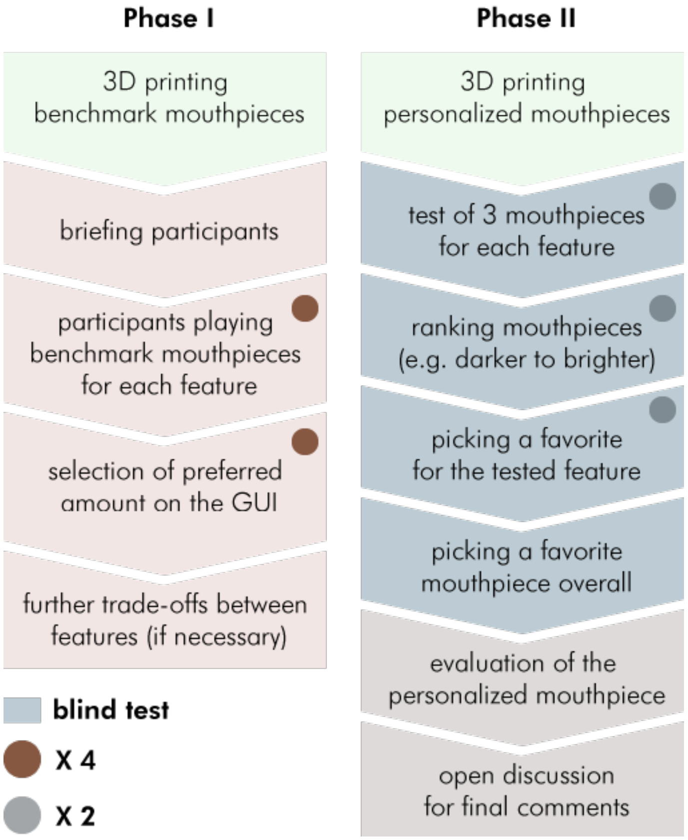

Figure 5.13: User study procedure.

specified a preference on the GUI. Each player was provided a new Vandoren V16 reed (strength 2.5) during the tests. In two cases where players could not perform comfortably with the provided reed strength, they were allowed to switch to a softer reed (strength 2). Since both of these cases were while performing with the highest resistance benchmark mouthpiece, players could still assess and compare the given mouthpieces in terms of resistance. It is further assumed that small changes in the reed properties would contribute in a similar fashion to changes across players (embouchure and vocal tract).

The second phase of the tests was performed after a personalized mouthpiece had been manufactured for each player. In this phase, players were presented with the previous benchmark mouthpieces and a new personalized one and performed a blind comparison. To avoid long exhausting sessions that could have influenced their judgments, they were asked for their choice of the two most important features and comparisons were done only for these two features. For each feature, they were given three mouthpieces to test and asked to rank these mouthpieces according to their judgment of how the mouthpieces perform a certain feature (e.g., from lowest to highest resistance). They were also asked to pick a favorite mouthpiece for each of the two features.

5.4.2. RESULTS

In the blind comparisons of mouthpieces for each given feature, 7 out of 10 times (i.e. 2 features and 5 players) users ranked the mouthpieces in accordance with the experiment results. Out of these 10 rankings, in 8 instances, the mouthpiece that participants picked as their favorite for the given feature was the participants' personalized mouthpiece. Brightness appeared to be the most important feature for all participants, as it was always ranked first.

After these two comparisons, they were asked to pick a favorite mouthpiece, again blindly, among all the mouthpieces tested. This was a selection among 5 mouthpieces, 4 for benchmarking, and a personalized one. At the end of the second phase, 4 out of 5 participants picked their personalized mouthpieces as their favorite in the blind test.

After the blind comparison part, the personalized mouthpiece was revealed to the participants. They were asked to play the personalized mouthpiece again and rate their satisfaction with each feature on a 5-point Likert scale (from 'very unsatisfied' to 'very satisfied'). Figure 5.14 presents the levels of satisfaction of the players with their personalized mouthpieces for each mouthpiece feature.

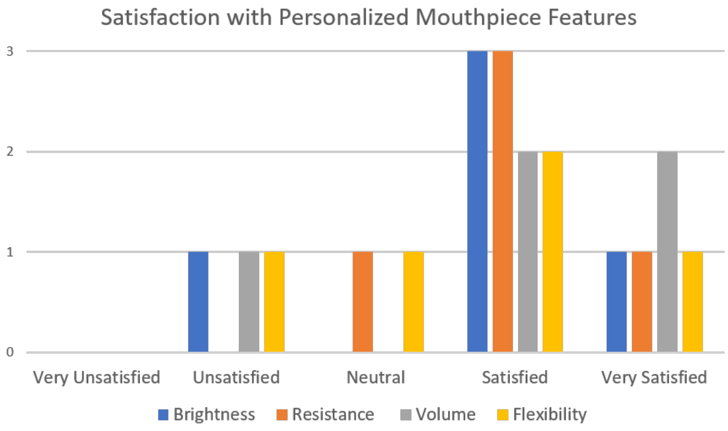

Figure 5.14: Survey results of players' feedback on the personalized mouthpiece features.

Participants also provided feedback on the personalization model. There was consensus about personalizing a new mouthpiece based on their current mouthpiece, instead of using benchmark mouthpieces. Moreover, they reported that they would also prefer to either choose the tip opening and lay length themselves, or set them at similar values to their current mouthpiece.

5.5. CONCLUSION AND REFLECTIONS

This study demonstrated the use of the proposed design methodology for personalized saxophone mouthpieces. It focused on personalizing the performance of the mouthpiece, which has valuable implications for players, and it presents a significant example to illustrate the benefit of the design methodology to solve such consolidated and coupled design cases. The personalization of the mouthpiece may also be extended to its aesthetics and ergonomics as well. Varying colors, textures, or finishing may be provided. It is also possible to personalize ergonomics with outer size, and shape, or by changing the bore size to fine-tune the fit to a specific saxophone.

To explore and quantify the PR-DP dependencies, this study employed an experimental investigation. Defining variety through the structure of the design may often require such experiments to understand the consequences of design changes. Therefore, the experiment here presented an important example for identifying PR-DP dependencies. DOE methods, such as the Taguchi design in this study, provide practical solutions to experiment in such cases with fractional experiment designs.

The experimental findings were then evaluated via a user study with five experienced saxophonists. The results of the user study show that participants were aware of changes in mouthpiece features and, in most cases, they were able to judge their changes demonstrated via benchmark mouthpieces during the sessions. Besides, they were also satisfied with the mouthpieces personalized in the proposed way. However, they also provided key insights pointing out room for improvement. As they stated, configuring a mouthpiece based on their current ones might make the process more easily graspable. Likewise, comments on the tip opening and lay length indicate that user habits should be more carefully considered in devising a personalization model.

6

EXEMPLARY APPLICATION ON DENTAL LIGHTS

Dental light is an essential tool in every dental practice. The primary use of a dental light is to illuminate the oral cavity of the patient, and hence to improve the vision of the dentist while operating. It should provide adequate illumination for the dentist without distracting shadows or disturbing the patient. Dental lights are produced as separate products, and according to the needs of the dental clinic, they are permanently mounted to other equipment, such as the dental unit (Figure 6.1), or directly to the room wall or ceiling. When choosing a dental light, it is important to consider its compatibility with the rest of the operatory lightning in the dental clinic, in terms of color temperature or light intensity. Compliance with the dental room design is also important, such as compatibility with the existing delivery system or the cabinet. Besides, the ergonomics should be considered as well, for the dentist to operate the light at different angles effortlessly. Therefore, there are diverse needs for a dental lamp; it should be suitable for the space it is installed, and it should serve the specific needs of dentists in terms of functionalities included and ergonomics.

This chapter presents a brief application example on a dental lamp from FARO S.p.A.[1], the company sponsoring this doctoral research. The current example is slightly different from the previous two case studies presented; while some 3D-printed components are varied through design, it is partially a configuration case with varying standard components. Besides, it is not necessarily a personal product, since it may need to address the needs of multiple parties. Yet, it is still evaluated within the proposed framework and elaborated with the same perspective, which may also demonstrate the applicability of the proposed methodology for configurability. In the following sections, the seed design for the dental lamp, the decomposition of PRs and DPs, and the dependency matrix are elaborated.

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[1] FARO is a historic Italian brand for lighting in the dental sector that has been designing and producing equipment for dental manufacturers, dealers, dentist, and laboratories for over 70 years. For further info: faro.it/en/.

Figure 6.1: A dental unit.

6.1. CONTEXT

Lighting is an important aspect of the design of any dental exam or surgery room. Selecting the right lighting equipment is a crucial part of the dental office design [158]. During exams, treatments, and operations, the lights utilized must be bright enough to produce a well-lit environment without making the patient uncomfortable [159]. It would be difficult for the dentist to obtain the desired results without seeing the region they are working on effectively, which possesses the risk of potential mistakes. The type of light source is found to have a considerable effect on the shade matching performance of dentists [160]. Working in such a confined space as the mouth requires dental lights to be moved to provide the best illumination in every condition. Besides improving the working condition of the dentist, lightning is also important to provide a safe and inviting environment to the patients. Since some patients may be nervous or afraid of the treatment, it is important to improve patients' confidence and make them feel at ease.

Dental rooms have different requirements depending on the treatments performed, the people engaged in different tasks and the kinds of patients treated [161]. Therefore, there are varying needs to consider while choosing a dental light. Evidently, the most prominent functionality is the illumination performance, which depends on the light source used and its properties. The needed illumination properties depend on several factors in the environment, such as the rest of the lightning, the amount of daylight, or even the color scheme of the walls [162]. Besides the lightning performance, depending on the tasks performed, certain additional functionalities may be beneficial or required as well. For instance, including a camera in the dental light allows keeping a record of the operations or using it for educational purposes.

The ergonomics of the light and where it is mounted are also critical considerations in dental light selection. Depending on the dental room design, there are different types mounted on the walls or the ceiling, on the unit or the cabinet, or on moving tracks. Since dentists work in relatively small environments usually, it is important to take into account the flexibility of the lightning to get different angles easily. The ergonomics of moving the light is largely the choice of the dentist based on the working style.

6.2. SEED DESIGN DEVELOPMENT

This example illustrates defining a seed design for a dental light. It consists of a number of 3D-printed exterior parts that have variable design features, varying and optional components, and a set of standard components.

Figure 6.2: ALYA Dental LED light from FARO.

The starting point in this example is an existing product, ALYA LED light[2] from FARO (Figure 6.2). Since this case is largely a configuration one, the base architecture includes a set of standard components, such as the electronics, arm joints, or reflectors. Besides, since it is a relatively large assembly, the interfaces between parts also remain fixed in the base architecture. This is especially the case for 3D-printed parts that may vary in form. Besides, certain generic features are contained in the base architecture; most importantly the lighting setup that includes the position and orientation of the light source and the reflectors.

The variability of dental light seed design is created through the design variability of 3D-printed parts, different arm configurations, and varying components for performance. These are elaborated on in the following sections.

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[2] https://faro.it/en/illumination-led-and-halogen/alya/

6.2.1. PERSONAL REQUIREMENTS

To begin with, identifying the top-level CNs, the broad categories of needs are shown in Figure 6.3. The main needs of the dental light are evidently related to its performance, primarily the lightning and other supplementary functionalities. As mentioned in the previous section, the suitability of the product for the dental room and other equipment is also an important consideration. In this case, a product within the budget may also be considered a need, since the design changes in the dental lamp may result in significant cost differences.

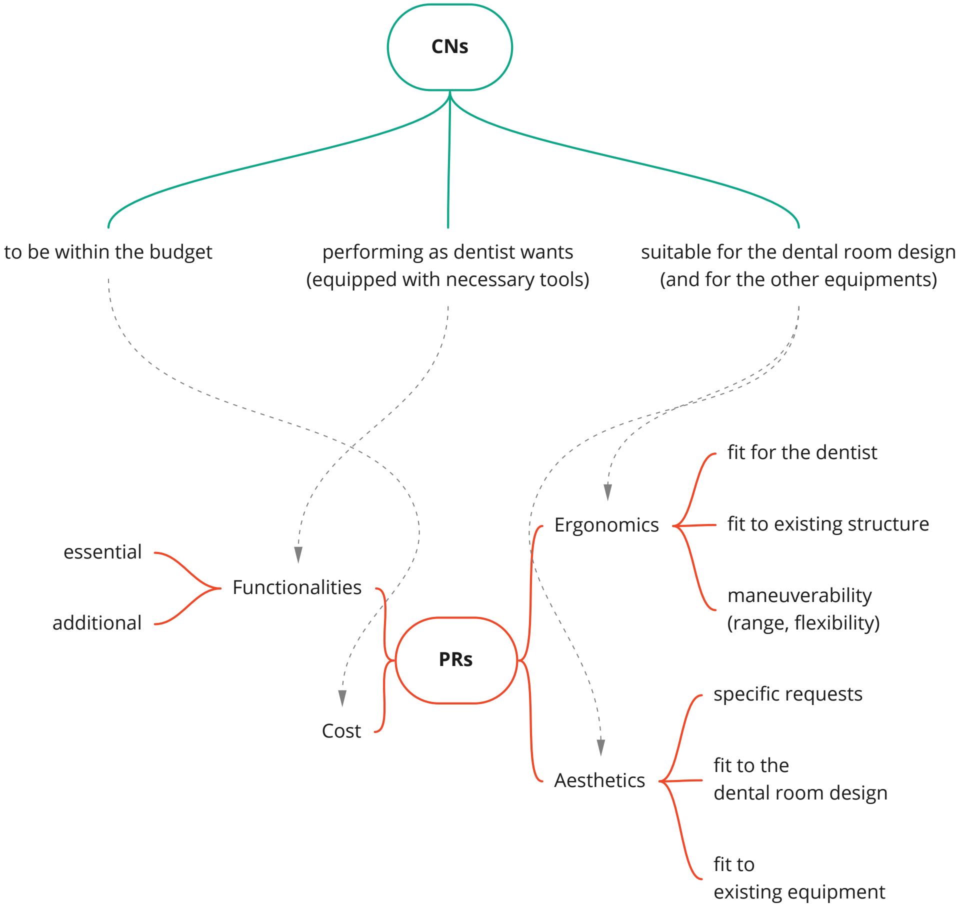


Figure 6.3: Top-level CNs, and decomposition of PRs.

The four top-level PRs corresponding to the CNs are shown in Figure 6.3; these are namely the categories of cost, ergonomics, aesthetics, and functionalities. In terms of ergonomics, the requirements are identified as fit to the dentist, fit to the existing structure, and the maneuverability of the dental light. Fit to the dentist refers to the ergonomic needs of the dentist while operating; fit to the existing structure implies the compatibility of the product with the rest of the equipment; maneuverability refers to the movement range or flexibility of the dental light. The requirements in terms of aesthetics may be the lamp to fit the dental room, the other equipment visually, or other specific requests. In terms of required functionalities, these are first decomposed into essential and additional ones. If these are to be decomposed further, an essential function is the lightning performance, and additional ones can be the ability to record the operation or resistance of the product to chemical aggression. All the mentioned PRs may be further decomposed, along with the DPs, to allow the expression of more specific needs. A final PR to mention is cost. In this case, the user may request to obtain a product within a certain cost range, or the user may drive the process by controlling the cost directly and seeing what design options are possible with a specific cost. The cost PR may be also decomposed further down to control the cost drivers more specifically. For instance, decomposing cost into the cost of functional, esthetical, or ergonomic features of the product would allow the user to control more specifically where to allocate the budget for the product.

6.2.2. DESIGN PARAMETERS

The DP identified to fulfill PRs, and their decomposition is shown in Figure 6.4. DPs in this case are component selections, optional components, basic design changes of 3D-printed housing parts, and varying lengths of arms. Starting from the most important, lightning is the first top-level DP. An essential choice here is the type of light source, which defines the light temperature and intensity. According to the needs, additional lighting may be provided through an arm light, ceiling light, or a second dental light (Figure 6.5). Another top-level DP is arm configuration. Here again, it is decomposed into essential and additional parameters. The essential setup is two arms with varying lengths and fixture parts according to the mount type. The mount type can be modified according to the existing equipment, or to mount in a position to the dental room directly (Figure 6.6). The arm lengths can be varied according to the ergonomic requirements. An additional configuration here is to use a duo joint (Figure 6.7) to allow the attachment of secondary equipment to the structure. Another ergonomy-related DP is the handle ergonomy. The design of the handle and the support parts (Figure 6.5) may be varied to fulfill the ergonomic requirements of the dentist. To control this variability, these parameters should be decomposed further to parameters defining the position and the geometry.

The functional features are a top-level DP that includes optional and additional functionalities. User interaction and device connection type are standard features of the product, but with the possibility of different options. The addition of a camera (Figure 6.5) or protective coating is supplementary features to be included if required. These also have certain options as exampled in Figure 6.4.

The top-level visual DPs include design changes of the housing parts which may possess certain variability thanks to 3D printing. Here the form, texture, color, or finishing of the parts may be varied to meet different aesthetical requirements. These DPs should be decomposed further to reach a level where the variability can be controlled by a design solution algorithm. These DPs may provide significant variability in the appearance of the dental light, and not necessarily by elevating the cost of the product.

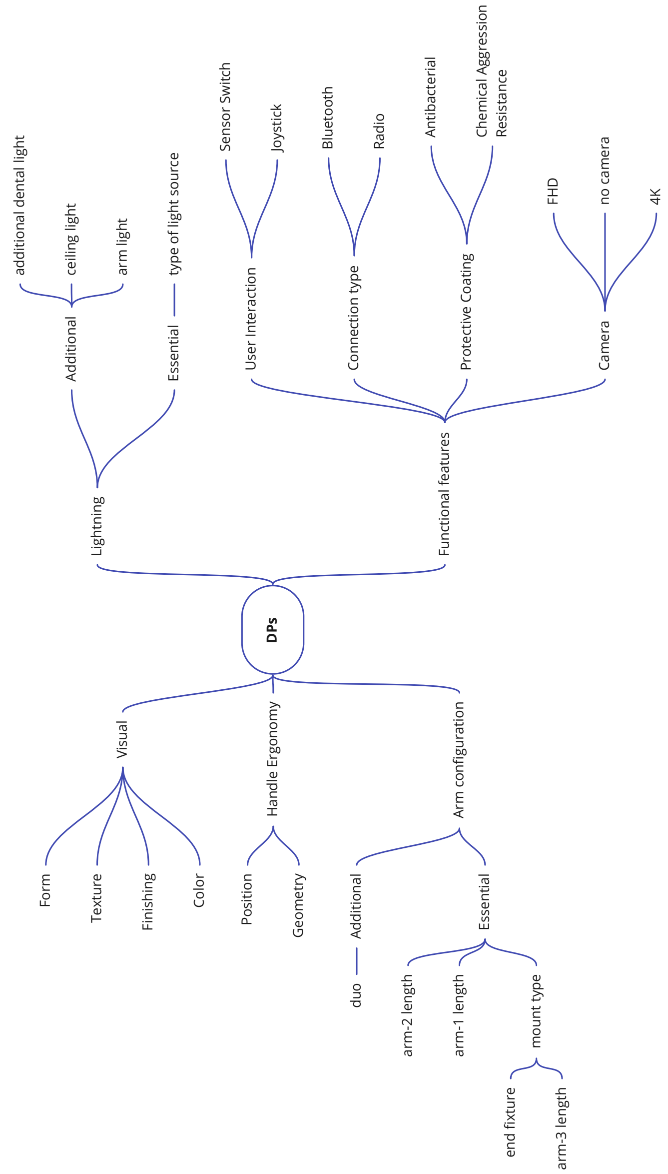


Figure 6.4: Decomposition of DPs.

6.2.3. DEPENDENCY MATRIX

The dependencies between PRs and DPs are shown in Figure 6.8. For the sake of simplicity, the PRs and DPs are not shown to the lowest level. However, PRs should be decomposed at least until a level where user input can be processed. Similarly, DPs should be decomposed until a level where the design can be sufficiently defined and controlled

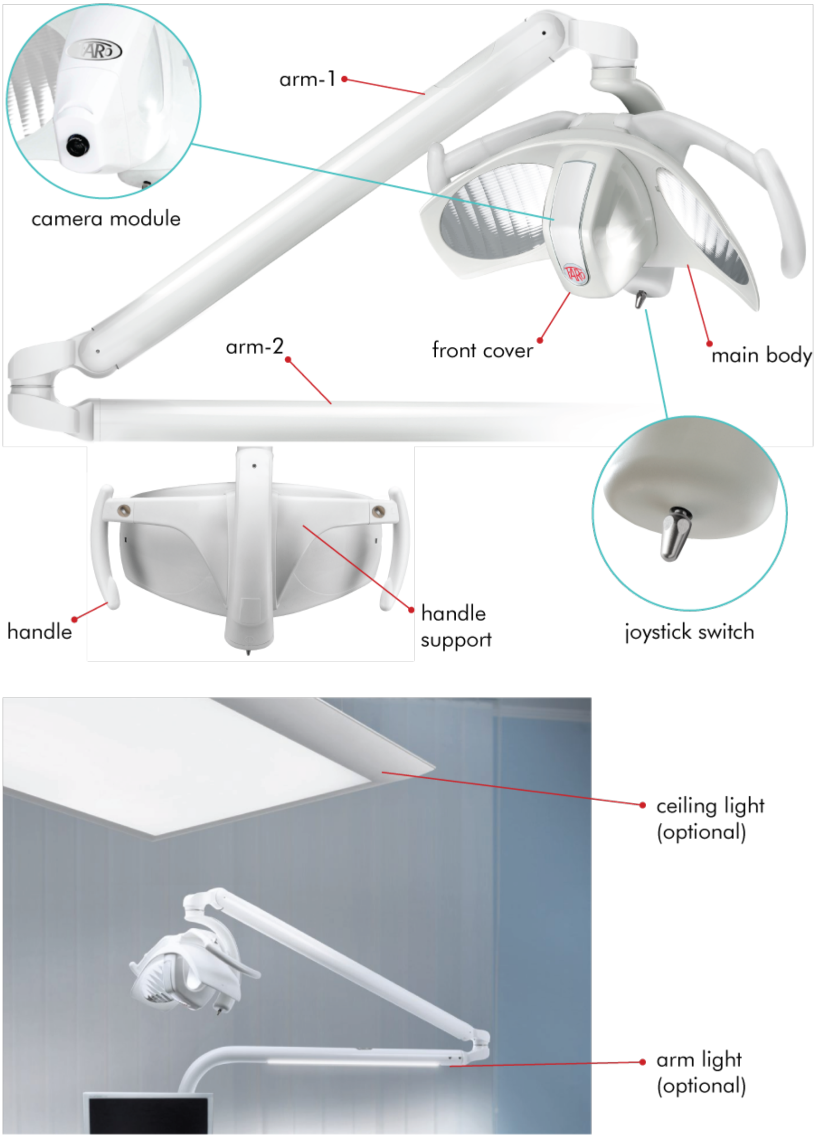


Figure 6.5: Varying components of dental light (above) and additional light options (below).

by the algorithm.

As it is seen in the matrix, especially the configuration options have a one-to-one

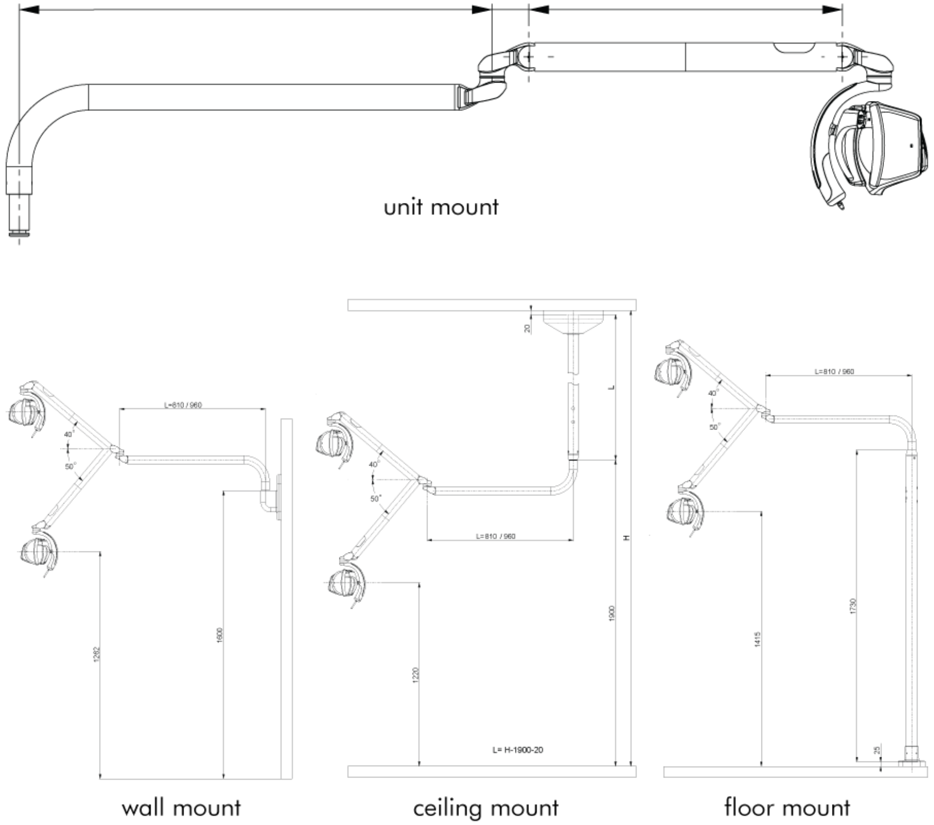
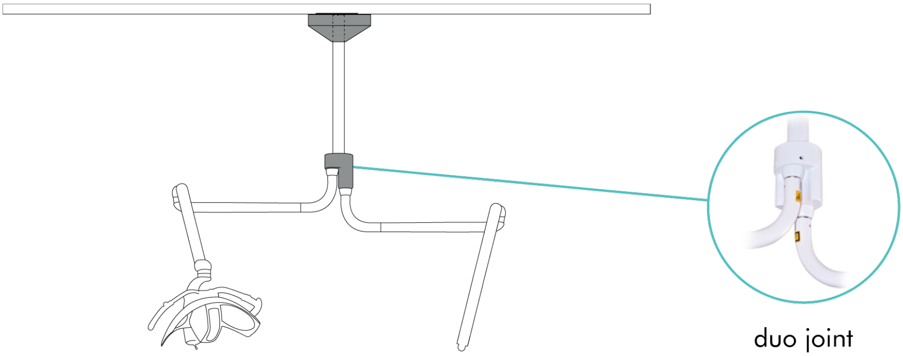


Figure 6.6: Dental light mount configurations.

mapping with PRs. Decomposing DPs controlling the design change of 3D-printed parts may reveal certain couplings in the design. While the cost seems as coupled with other PRs, it is more of a choice of the customer to drive the process through cost or other requirements from the product.

6.3. REFLECTIONS

This application illustrated exploring the possible variability of a dental light seed design. Categories of possibly varying needs are identified and expressed as PRs, and these are decomposed to more specific requirements to transmit the CNs to the design more precisely. The presented PRs shall be decomposed further to allow customer co-creation. For instance, it should be more evident how to elicit the lightning needs of the customer, such as whether there is a need for additional lighting or which additional lighting would be more suitable. As these PRs are decomposed, there might be many requirements to be set by the customer, which would result in a lengthy co-creation process. While a lengthy process is often discouraging for mass-market customers of consumer durables [4], a dental light is a professional product that the customer would be willing to invest



duo setup

duo joint

double dental light arrangement

dental light and screen

Figure 6.7: Duo arm setup (above) and configuration examples (below).

time and effort to get the most suitable product to the specific needs.

The DPs to fulfill the PRs are identified through a variety of essential and additional components, and design variability of arm configuration and 3D-printed housing parts. The DPs for component variety and for the arm configuration are already sufficiently defined. However, the design changes of 3D-printed parts should be structured further to define what exactly may vary in the design. The possible solution space also depends on the definition of these DPs, meanwhile, the solution space for the varying components and arm configuration is already exampled. Certain constraints should be taken into account for the solution space as well. Such as the variety of arm lengths should be limited considering the strength of the mount and the joints. Also, the design changes in the housing parts should not limit the movement of the light, or block the reflected light

Functionalities	Essential	X	X												
	Additional			X	X	X	X								
Ergonomics	Fit for the dentist							X	X	X	X				
	Fit to the existing structure									X	X				
	maneuverability									X					
Aesthetics	Fit to existing equipment											X	X	X	X
	Fit to dental room design											X	X	X	
	Specific requests											X	X	X	X
Cost			X	X		X	X			X	X				X
		Essential	Additional	User interaction	Connection type	Protective coating	Camera	Position	Geometry	Essential	Additional	Form	Texture	Color	finishing
		Lightning		Functional features				Handle ergonomy		Arm configuration		Visual			

Figure 6.8: Depencency matrix between PRs and DPs.

through the mirrors.

One important consideration is that the user contribution to design is driven by the requirements. For instance, rather than giving the option of what additional light sources to include, the user is provided a solution according to the lighting needs. While this both eases the decision-making of the user, it also allows for meeting specific needs better. In case the user is given control over the cost, it might be better to set the DPs that do not depend on cost first, in case these DPs are independent. Thus, the user may vary a cost input and see the possible design configurations of DPs that affect the cost. The options that Once the solution space is formed after applying all the constraints, a design space for the user can be formed as well. Based on the dependencies on the matrix, a solution algorithm can be devised to manage the variety and the customer co-creation process.

7

DISCUSSION

7.1. ANSWERS TO RESEARCH QUESTIONS

RQ1: How to define a seed design architecture that can contain consolidated parameters or functions, and provide design variety through manufacturing process flexibility?

As a solution to the research question, we introduced a seed design architecture that defines variety and commonality through design features that take its source from process flexibility. This variety bases on structural and material variations throughout the product that can provide continuous and intricate changes in the product to meet individual needs precisely. Besides, some common design features form a base architecture, which acts as a skeleton to the variability of the seed design. By defining design parameters in various forms at different levels according to process capabilities, this seed design definition may flexibly adapt from cases very close to configuration to cases that allow flexible and continuous variation of all possible requirements. Hence, the seed design can be very simple, or very complex based on the case or degree of investment. The main inspiration and supporting argument of this definition is the design optimization methods in DfAM, such as part consolidation, topology optimization, cellular structures, multi-material distribution, and so on. These methods already demonstrate various ways of design changes pushing the boundaries of AM process capabilities to reach a design goal within a given design space, while satisfying certain restrictions. The proposed seed design architecture uses similar means to *optimize* the design for each individual customer.

Catering for diverse personal needs requires a large product variety to be able to address the needs of each individual. A determining factor for the extent of variety is the means of defining it. The most common way is the PFA, which defines variety through modularity and scalability of components. The variety created in this architecture is limited by nature since it is necessary to trade off variety for the sake of lower cost and manufacturing complexity. The main idea behind PFA is to benefit the assembly flexibility in conventional manufacturing. Thus, shifting the context to digital manufacturing requires different considerations to exploit the process capabilities. Variability through process flexibility may allow not only larger but also more profound variety. Therefore, the proposed seed design architecture aims to exploit that, and goes beyond the capabilities within PFA. A demonstration of this is the case study on the saxophone mouthpiece, which illustrated a functional personalization case with a highly coupled design. It is a single-component product that delivers variety on multiple performance aspects. Hence, it is a strong case to illustrate the benefit of the proposed seed design architecture. The mouthpiece is characterized by a coupled design and as long as its architecture is not changed, modularization is not an option. In this case, the working principle of the mouthpiece makes the necessary architectural change to decouple the design virtually impossible. More in general, highly coupled designs require deep architectural changes to ensure modularity and consequent configurability. On the other hand, what is proposed here is to characterize the behavior of the system even in the case of a coupled design to assign the most suitable value to each DP to fulfill PRs.

The application of knitted footwear personalization demonstrated a diverse use of the seed design; comfort and self-expression needs correspond to all three categories of personalization, which is suitable to show the complete potential of the methodology. Besides, this case exampled the definition of design parameters in various forms, using the capabilities of two different processes. Although the starting point of the seed design architecture was AM, personalization of the knitted upper is important to show the scalability to other digital manufacturing processes. The case of the knitted upper is another example of a coupled design. Although the variety is more discrete in this case, it does allow the user to prioritize certain performance aspects that such product differentiation does not exist in the market according to the experts interviewed. An important note on the knitted footwear example is that although discrete knitting parameters resemble modular components, these are the building blocks of a single component that provide multiple functions. Even if these were to consider as component options, such coupled case would have no solution in PFA.

> *RQ2: How to structure different domains and their interactions in the process to define the variability of a seed design?*

To provide an extensive and intricate variability through process flexibility, the design process also needs to adapt to identify the means and working principles of such design variability. For that purpose, we proposed an adapted process for the decomposition of the domains that contribute to the seed design construct and provided explanations for each step. In addition to the commonly used domains, a co-creation domain also contributes to the process, since the increasing design freedom for the customer creates the necessity to consider the way of involving the customer more carefully. One use of this domain is to decide at what level the user will have control over the design. This decision bases on the co-creation scenario, such as the expertise of the user target. For instance, in the saxophone mouthpiece case, the users are very knowledgeable about the product, and often have a clear idea of how the product should perform. Therefore, giving more control over the design to such user profiles may be suitable. The knitted footwear example demonstrated another likely case; the domains are decomposed until reaching sufficient design definition, but the lowest level of requirements is not meaningful for the user to control. For instance, it is not worthwhile for the users to control the color of each knit, or similarly the instep girth measure. Both requirements can be obtained at a higher level by other means: e.g. an image for graphical pattern and a 3D foot scan for instep girth.

Another important point was to include manufacturing considerations in the process since the variability of the design is highly dependent on the process capabilities. In this regard, we included the process domain in the concurrent decomposition of functional and physical domains. The motivation is to identify the design parameters within the process limits or by getting inspired by the process capabilities. Explicit use of this is in the knitting case; the design parameters, and consequently lower-level requirements, are according to the flexibility that digital knitting offers. Hence, the process capabilities become the determining factor for what the customers can personalize in the product. While in the case of the saxophone mouthpiece example, there were already established parameters used by the commercial mouthpieces, and redefining these would require excessive work, if it is even possible or beneficial. In this case, the AM process allowed the variability that was not feasible with conventional manufacturing.

A crucial consideration in the proposed process is allowing design coupling during the concurrent decomposition of the domains in favor of more variety. Here the motivation is to provide the largest variability for each requirement at the expense of design complexity and let the customer prioritize the desired performance of the product. Hence, the customer gains more freedom on the prioritized product features, in exchange for more restrictions on others. Besides the more freedom where needed, letting the customer set the priority of requirements also contributes to solving the coupled case. The mouthpiece example demonstrated the benefit of this approach by providing a wide, but conditional, range of variability on each performance aspect. Combining this with the near-continuous variability, it became possible to explore a very large design space. The subjects of the user study also confirmed the large variability of the performance aspects. Besides, they had clear priorities among these aspects and were largely satisfied with the performance of personalized mouthpieces.

> *RQ3: What is the alternative to standard configuration structures that can facilitate customer co-creation over a seed design that potentially has continuous and coupled variability?*

The first step towards a personalized design is forming a solution space. While the traditional considerations of variety-commonality trade-off do not apply here, there are other considerations to take into account. to this respect, we proposed a series of constraints to filter the solution space. These constraints mainly aim to sustain the structural integrity and functionality, ensure manufacturability, and avoid choice overload. Not necessarily all constraints apply in all cases, but these are the suggested topics to consider to form a reliable solution space. For instance, while forming the solution space for the mouthpiece case, sustaining the functionality of the product enforced limitations on DPs, but no limitations in terms of manufacturing were necessary. A large number of different mouthpieces within this solution space were tested in the experimentation phase and later tested by the musicians who participated in the user study. One topic of the constraints to highlight is the scope of personalization, where the co-creation considerations contribute to the process again. The purpose of this is mainly to avoid choice overload considering the co-creation scenario, or user profile.

As discussed in Section 2.3, the traditional configuration structures have limitations in terms of navigating through a continuous and coupled solution space. In this regard, we introduced a design solution algorithm that, in the simplest terms, receives the customer requests as input, browses through the solution space, and generates a final design as output. Especially to address coupled designs, the algorithm uses a set of rules, user input, and iteration of DPs to reach a design solution. The main objective of the algorithm is to keep the valid portion of the solution space the largest by trying to use the least number of DPs to fulfill a given PR. The necessity and benefit of such a solution become evident in cases like the saxophone mouthpiece, where there are four requirement functions with seven unknowns (Figure 5.10). It is not possible to decouple this case, hence there is no way to approach it with a configuration structure. For the solution of such a case, the user has a key role; the algorithm finds a solution for each user requirement at a time. Therefore, the user sets the hierarchy of solutions based on personal priorities. Such priority setting is also necessary for the user control over design since it is not possible to set coupled requirements simultaneously.

Providing a product that answers to the specific needs of customers requires understanding those needs first. The most evident way of this is by allowing them to express their needs explicitly in the design. As discussed in Chapter 2, previous works also highlight the necessity of customers' active participation in the design process to achieve MP. In this respect, we structured a design process where the designer provides the means to facilitate customer co-creation. The proposed co-creation scenario is parallel with the seed design definition introduced, which is in a way an unfinished product with open parameters within certain limits. With the co-creation process, the user finalizes the product, rather than configuring it. This provides more design freedom to the user by allowing trade-offs between different requirements. The user is in the condition to make their own choices and priorities. In that perspective, the needs may, at least partially, remain latent. A user may even go beyond and satisfy a need that was not even intended to offer. Instead of a standard configuration structure, there is an iteration process to personalize the product. This results in a dynamic interaction with the user. The methodology includes a specific form of co-creation, where the user, in a way, negotiates with the algorithm behind to reach the desired trade-off. This both allows more design freedom to the user and also streamlines the personalized design generation in coupled cases. But, it is important to inform the user well about how the system operates. A lengthy co-creation process may discourage users [4]. Therefore, trying to find a balance between the adequate design freedom of users and the complexity of the requirement-parameter dependencies is necessary. In addition, In this process, the user does not have direct control over the parameters but does have control over the performance of the product. Therefore, the personalization process is driven by the requirements, and then parameters fulfill these. For instance, while the mouthpiece personalization case has dimensional parameters, what the user requests is not these dimensions, but the functionality provided by fine-tuning these all together. This is also where our proposal differentiates from the parametric design applications in the literature, which allow geometrical modifications directly without any performance considerations behind.

The key advantage of the MP paradigm is providing affordable personalization. In this sense, to achieve near-mass-production efficiency, both manufacturing and design processes should be able to flexible and adaptable. On the manufacturing side, digital manufacturing technologies provide this by integrating CAD systems with processes that do not require dedicated tooling. Hence, a final design can be manufactured on demand. However, such transition from design to manufacturing of the product was not evident in the process from customer needs to personalized design. A major reason is that previous work is mainly on PFA. In that case, there is no such challenge, since the transition from customer needs to final design takes place in a configuration structure that has pre-given options. To sustain mass efficiency, the system that facilitates customer co-creation should avoid additional labor for each customer. In that respect, two main considerations are streamlining the process from customer needs to design parameters, and generating reliable designs. The proposed design solution algorithm manages the communication between the customer and the design in a structured way to ensure both customer requests and design parameters are in the valid region of design and solution spaces. The dependency matrix adapted from DSM supports this by organizing the FR-DP dependencies according to provided considerations. These interdependencies of the seed design are the core information for the algorithm to manage the variability. Another support for the validity of the final design is the introduced constraints. Four levels of potential limitations aim to ensure the reliability of the solution space. While these constraints apply in the seed design development phase, the algorithm controls the validity dynamically in the co-creation phase, with respect to the interdependencies and user decisions. The user study on saxophone mouthpiece personalization demonstrated the application of this in practice. The algorithm was implemented with a user interface and CAD software. The users personalized their mouthpieces on the interface, and the resultant designs were 3D printed successfully.

> *RQ4: What guiding principles and tools can designers use when designing for MP to create and manage sufficient variety, and to address individual needs?*

The main gap we identified in the DfMP literature was the lack of prescriptive guidance and frameworks for designing physical products. To address this, we first introduced a DfMP framework that structures the design process and clarifies the roles of the designer and the user. This design process composes of a two-phase seed design development and a user co-creation phase. While the first phase of the seed design development is to create variety by defining the variability of the design, the second phase is to manage variety by devising the means of customer co-creation. We outlined the actions to take in this process on a pipeline and provided instructions and principles with supporting arguments for each action. Aiming for sufficient variety for individual needs, we proposed a seed design architecture, and a scheme structure and decompose design domains to enable exploiting process flexibility to create variety. To facilitate customer co-creation, the first tool proposed is the dependency matrix to organize the interdependencies that affect the solution space. Finally, we introduced an algorithm to manage the co-creation and demonstrated how it should interact with the user. Overall, the proposed methodology defined and prescribed a design process for MP. Following two case studies demonstrated the use and applicability in practical cases of two diverse products.

7.2. LIMITATIONS TO THE DESIGN METHODOLOGY FOR MASS PERSONALIZATION

The main limitations to the methodology overall concern how manufacturing aspects have been taken into consideration. As in line with the initial aim, the design methodology relies on digital manufacturing primarily. Hence, it does not explicitly consider having standard parts in the product. Whereas in practice, some products may be partially mass-produced with conventional methods. Besides, the functional integration here expectedly does not consider separating the seed design into different parts, which may make maintenance more difficult, and there might be recycling issues to consider. While the knitted footwear case contains two parts, this is not a result of the development process, but a pre-given condition. While it was explicit to have two parts in that example, for other cases more guidance on this matter might be useful. The application of dental light in Chapter 6 is valuable in this sense to demonstrate that the methodology is also applicable to cases that are closer to PFA with scalable and personalized components. This also highlights that in some cases, there is some overlap between MC and MP in practice. In such cases, we can consider a hybrid scenario between MC and MP. The proposed design methodology can complement product family design methods with personalized modules [59], or open architecture platforms [33, 68], by providing a solution to design personalized modules.

It is also important to note that we mainly target consumer durables which may gain value through personalization. In this sense, the two case studies in Chapter 4 and 5 represent well the target products, and how personalization adds value to them. Although the application of these two very diverse products supports the validity of the proposed methodology, they are still limited in number and do not represent the potential variety of applications completely.

Manufacturing considerations may also need further elaboration to streamline the process better from the design to the physical product. The main focus was on creating variability in design according to digital manufacturing process flexibility and capabilities. In the current form, the process domain contributes to the definition of DPs and their ranges. Hence, it has a significant influence on the design itself and to what extent it can be personalized. In the given case studies, generated personalized designs were ready for manufacturing. But, in cases where a more intricate variability is present, process variables may also need to adapt to the design. Another limitation worth mentioning exists in the user's real-time interaction with the design. The design space changes with each user decision, and in case these changes are too radical, the user experience might be affected undesirably. The design of the co-creation experience was out of the scope, but future work on this would be a valuable addition to the methodology.

Since the focus of the work was on creating variety, the commonality aspect in the proposed seed design architecture may not be sufficiently elaborate. Here the commonality is not necessarily to help reduce costs or ease the manufacturing and supply chain operations. It is to protect or preserve certain aspects of the product where the limit of product variety goes to absolute design freedom. This could be to ensure common functionalities of the product, preserve brand identity, or create a "family feeling". In this sense, defining a base architecture is a sort of setting constraints from the conceptual design phase. Hence, it acts as a skeleton to the design variability. The case studies example the use of base architecture in practice. For instance, the mouthpiece case starts with an existing design to adopt some design aspects, such as the interfaces with the saxophone and with the player, to ensure the minimum functionality. This can be interpreted as base architecture ensuring that the mouthpiece produces sound, while the variable design features define how it sounds.

While constructing a seed design, the relationships between PRs and DPs may not be immediately evident in every case. These relationships can be identified depending on how much one can invest in seed design development. While it is possible to linearize the relationships up to an extent to simplify the case, it is also possible to obtain a very precise map of how the product behaves with varying parameters through simulation or experimentation. The methodology makes a general claim on this, and linearization is not mandatory as far as one can invest in characterizing the design space in further detail. For instance, in the application of mouthpiece personalization, experimental characterization of the mouthpiece behavior as a function of the different design parameters was done, and in this case, the relationships were not linear. While the experimentation might be limited by the sample size; if it was possible, an accurate simulation might have provided a more detailed characterization. However, it is still important to note that the proposed algorithm assumes that it is possible with a reasonable effort to find the relationship between PRs and DPs. But it is clear that if the system is highly unstable, then it would be too complicated or too costly to build a detailed map for personalization.

In the case when the seed design needs an update, such as the introduction of a new DP or changes in the solution space, certain parts of the design process may need to be repeated. For instance, if the introduction of a new DP changes the dependency matrix, then the design process should be reconsidered starting from the constraints to account for possible changes in the solution space. However, introducing an independent DP, or removing an existing DP, would only require a simple update to the design solution algorithm.

A limitation revealed by the case study on saxophone mouthpieces is the difficulty to play a few mouthpieces. While these mouthpieces performed well with the artificial blowing machine, they required an air pressure that is difficult to produce for a real player. However, this issue did not appear with the mouthpieces used for benchmarking in the user study, which delivers the extrema of each performance aspect. This implies that it is not an issue related to the size of the solution space, but there might be a combination effect. More extensive experimentation may reveal such effects.

8

CONCLUSION

To the aid of designers and as a contribution to DfMP literature, this thesis presented a design methodology for mass personalization with a focus on digital manufacturing technologies. This chapter concludes the thesis by summarizing the key research outputs with respect to the main research objectives. Then a brief discussion on the research novelty and contribution follows. Finally, recommendations for future research based on observed limitations and potential improvements conclude the chapter.

8.1. CONCLUDING REMARKS

The research began with three main objectives (Section 1.3) towards a design methodology for MP. A brief outline of the research output referring to these objectives is presented below.

O1: *Determine the necessary product architecture that allows exploiting digital manufacturing capabilities in creating variety*

We proposed a new seed design architecture that contains variability through ranging design features in its structure. This variability definition takes its source from design parameters that may allow changes throughout the product at various levels according to the process capabilities. Such definition allows providing continuous and extensive variety to fulfill specific customer needs. We supported this definition with a domain decomposition structure and a design process to create product variety effectively while considering the design complexity due to intricate variability. Two case studies demonstrated the benefit of this architecture with large variability of various personalized product features.

O2: *Determine the ways of customer-design interaction to address specific needs and to fulfill these with the personalized product*

To facilitate customer co-creation, we introduced a design solution algorithm that manages the customer-design interaction while considering the interdependencies of the seed design. In the given co-creation scenario, the customer actively takes part in the design personalization process. In real-time, the customer negotiates the desired product features with the algorithm to reach a desirable trade-off with conscious and informed decisions. This helps to align the customer expectations with the final product, which may improve customer satisfaction in terms of the experience and the product. We also demonstrated this in practice with a user study, where the participants followed the proposed co-creation scenario to personalize the design, and later obtained the final products.

O3: *Develop prescriptive guidance and tools to be used in the DfMP process*

To help the implementation of the proposed seed design architecture and the co-creation scenario regarding the first two objectives, we provided a set of tools and guiding principles throughout the defined design process. With a DfMP framework, we first structured the design activity. Then, demonstrating the order of actions to take on a development pipeline, we disclosed a two-phase design process of creating design variability and devising the means to facilitate customer co-creation. Each phase included certain tools and directions helping to carry out the process. We also demonstrated the application of this design methodology on two different products in the case studies.

The main outcome of this research is a prescriptive methodology that aims at guiding designers to develop seed designs in the digital manufacturing context and to facilitate customer co-creation effectively to reach truly personalized designs. It includes the development and execution of a design personalization process by defining a seed design as the overarching architecture that ensures flexibility and adaptability to the user's expectations. The more customer-centric approach to the design personalization process aims to improve customer co-creation experience and satisfaction with personalized products. The methodology is applicable to the design of consumer durables where personal needs are present, personalization would have added value, and application to digital manufacturing is feasible.

Two case studies demonstrated how to apply the methodology to representative cases. In both cases, there is an existing demand for personalization, and both are based on existing RD topics that led to commercial solutions. Two very diverse products in these studies demonstrated the range of applicability of the methodology. The first case study on knitted footwear explored all three domains of personalization: the fit, appearance, and functionality of the product. Thus, it provided a good overview of the complete methodology. In addition to 3D printing, digital knitting was also present in this case to illustrate the usage of another digital manufacturing technology. The second case study was on 3D-printed saxophone mouthpieces, where the focus was on the functional personalization of the product. This was a very suitable case to demonstrate how multiple functions can be varied in a single part by fine-tuning its design. Hence, the benefit of the methodology became more evident, as there was also a coupled design case while tailoring the performance of the mouthpiece. As further support to the case studies, interviews with experts from various related domains followed the first case study to evaluate the design process, its implications, and its use in the footwear context. A user study concluded the second case study, both to evaluate the validity of the devised personalization logic on the mouthpiece and to understand users perceive and react to the proposed co-creation scenario. Finally, Chapter 6 presented an illustrative example of an industrial product to show the possibilities and considerations for companies to employ the methodology starting from existing products. While this application is partially a configuration case with component variety, it is still evaluated from the same perspective of the proposed methodology, which also demonstrates that the applicability can be extended to such cases as well.

Mass personalization aims to provide unique products and experiences for customers in an affordable way. Now It is more real and feasible than ever with advancements in manufacturing and industrial production. Further advancements in digital manufacturing technologies will enable more profound changes in the product architecture, thus more products will be the subject of MP and personalization will get more affordable. MP is compatible with on-demand smart manufacturing envisioned in Industry 4.0 and is expected to play a major role in the future of the consumer durables market. The manufacturing automation in the smart factory concept must be supported by design automation to truly enable personalization with mass efficiency. Designers should get acquainted with the MP process and the necessary perspectives for successful implementation in product development.

8.2. RESEARCH NOVELTY AND CONTRIBUTION

This thesis aimed to contribute to the design thinking related to product development for MP. The research addressed the gaps in the definition of product variety, customer involvement, and systematic design methodology for MP to exploit digital manufacturing capabilities effectively. The literature analysis revealed the limitations of existing methods and tools in realizing MP and the scarcity of design support dedicated to MP. The analysis concluded that the lack of a comprehensive design methodology at the intersection of MP and digital manufacturing is a major limitation of the MP paradigm.

The novelty of the thesis lies in developing a systematic design methodology for Mass Personalization of consumer durables to be realized by digital manufacturing technologies. The main novelties and contributions are as below.

- This research defines a design methodology that exploits manufacturing flexibility to create variety for product personalization, and actively involves customers in the design process to answer their specific needs. It covers a two-phase development process as defining a seed design with variability that can adapt to the CNs, and devising a system to manage the variability to facilitate customer co-creation.

- This research contributes to a novel framework for DfMP that defines the main contributors to the design process that is centered around the seed design architecture and assigns the roles of the designer and the user in the design process.

- A novel seed design architecture is proposed that defines commonality and variety through basic design features. The proposed architecture allows a near-continuous variety of designs to allow meeting the individual needs of customers better.

- The proposed methodology defines, decomposes, and connects different domains considered in the design process taking into account the case of near-continuous seed design variability, possible design complexity, and customer co-creation. It also contributes to guiding designers by a development pipeline, tools to use along with the development procedure, and providing support with key principles and insights on the different stages of development.

- The research proposes a novel solution to manage design variability by employing an algorithm, which is capable of dealing with coupled design cases and near-continuous variety.
- Furthermore, the proposed methodology contributes to customer co-creation by defining a co-creation method that actively involves the customer in the design with an interactive process of design decisions and trade-offs to reach the optimal solution.

8.3. RECOMMENDATIONS FOR FURTHER RESEARCH

The proposed methodology provides a foundation for DfMP from a product development perspective, where the designer is not only the product developer but also in a facilitator role for a customer design. Mass personalization is still an emerging paradigm, hence both advancements in the enabling technologies and changes in customer demands and expectations may require the design approach to be adapted accordingly. The use of the methodology will be more significant with the advancements like varying topologies, voxel-based multiple materials among the same component, or embedded 3D-printed electronics.

To provide the efficiency in on-demand manufacturing of mass-personalized products, the automation, and interconnectedness of systems are essential. While the proposed methodology provides the basis for a system that generates personalized designs automatically with user co-creation, this can be further connected to manufacturing systems to streamline the process from design generation to realization of the physical product. The suggested development process ensures manufacturable designs, but not necessarily manufacturing-ready data. Therefore, future research may address a tighter connection to the process domain to include manufacturing preparation considerations. Besides, design rules of specific processes may also be considered to evaluate the consequences of design changes, such as; certain designs may require additional labor or processes.

The design process for MP proposed in this thesis highly involves customers in a way that is different than the participatory design approaches well-known in co-design. While participatory design approaches involve customers in the initial phases of the design process to help meet their needs better, the intent here is to tailor a design to individual needs, which has been conceived upfront by the designer. To increase the customer involvement, and to spread it in more phases of the design process, a combination of these approaches may be considered. Participatory design approaches may be employed at the beginning of the design process to understand possibly varying needs, while the proposed co-creation scenario answers to the specific needs in the final design. It is also possible to extend this further along with the wider trend of customer involvement throughout the whole product life cycle, such as in manufacturing, maintenance, or repair.

Future work should also focus on designing the co-creation activity and projecting that onto the seed design development. Besides the value offered by the personalization of the product, the co-creation experience also presents value for the customer. Customers' satisfaction with the final product and engagement with the co-creation process is also related to the experience provided. The different contributors such as co-creation process, product personalization interfaces, user experience, and customer journey through personalizing a product may be considered together with a product and service design approach to provide the best processes and results for customers.

A

APPENDIX A

A.1. PROJECT BRIEF

The project brief provided to interviewees beforehand is present in the online appendix [163].

A.2. PRESENTED MATERIAL

The presentation used during the interviews is present in the online appendix [163].

A.3. EVALUATION TABLE

Table A.1: The table used to semi-structure the interviews with experts and categorize their comments.

	Benefits	Limitations	Remarks
Applicability			
Feasibility			
Potential			
User experience			
In comparison to existing applications			

A.4. INTERVIEW TRANSCRIPTS

The complete transcripts of the interviews are present in the online appendix [163].

B

APPENDIX B

B.1. MOUTHPIECE DESIGN CONFIGURATIONS USED IN THE EXPERIMENT

B.2. ACOUSTICAL EXPERIMENT SETUP AND PROCEDURE

For the acoustical assessment of the characteristics of the 27 mouthpieces (with the configurations in Table B.1), an artificial blowing machine was used [164]. Such artificial setups are commonly used in music acoustics to evaluate the physics of wind instruments independently of the player's actions [132, 165]. The artificial blowing machine allows adjusting the blowing pressure and lip position and provides repeatable conditions for the comparison of the mouthpieces. The used artificial blowing machine is based on the control of the air pressure in a 170 cm^3 plexiglass box representing the oral cavity of a player, as shown in Figure B.1a. This is achieved by the control of a proportional valve (SMC; type PVQ33-5G-23) at the air entrance to the cavity. The mouthpiece is inserted with the reed facing upwards, and the reed meets an artificial lip consisting of a metallic rod with a rubber cover, mimicking the lower lip of the player (see [166] for more details). The artificial lip is mounted on a translation stage, that allows to regulate and fix its vertical position. The valve adjustments and the data recordings are performed via an external PC with National Instruments hardware and software.

The mouthpieces were tested individually. For each test, the mouthpiece was attached to a saxophone neck (STAGG Alt Saxophone 77-SA) and inserted into the artificial mouth, as shown in Figure B.1a, so that the artificial lip rested on the reed at 10 mm from the mouthpiece tip. Only the neck of the saxophone was used, as this simplified changing mouthpieces while maintaining the setup configuration, as well as improved the stability of the setup and the positioning of the external microphone. This implies that a tone at around 410 Hz is obtained, which is within the playing range of the alto saxophone (138 Hz to 830 Hz). The same synthetic reed (Légère, strength 3), which is independent of humidity, was used for all mouthpieces. The acoustic pressure in the mouthpiece was recorded via a piezo-resistive pressure transducer (Endevco 8507C-2) inserted into the mouthpiece via a lateral orifice, at 5.7 cm from the tip, included in the 3D-print design. The acoustic pressure in the artificial mouth was measured with a pressure transducer (Technoterm 5400, with a resolution of 1 Pa). This artificial-mouth pressure value was used in a feedback loop as a control parameter to establish the pressure patterns to be used during the tests and regulate the settings of the air valve. A second piezo-resistive pressure transducer (Endevco 8507C-2) was placed at 5 cm in front of the saxophone's neck output to measure the external sound.

For the measurements concerning resistance, loudness, and brightness, an ascending pressure (1 kPa/s) was used to drive the blowing pressure in the artificial mouth, as shown at the top of Figure B.3. Notice that the pressure in the artificial mouth increases at 1 kPa/s before the tone onset, but faster during the transient. This jump is due to a change in the acoustic impedance at the tip of the reed when the reed starts to oscillate. The test was repeated three times, to ensure the soundness of the results and avoid any inconsistencies due to the experiment setup. This data is provided in Figure B.2. The mean value considering the three repetitions at each of the 27 mouthpieces is used in the analysis.

For the measurements concerning flexibility, a complete alto saxophone was used

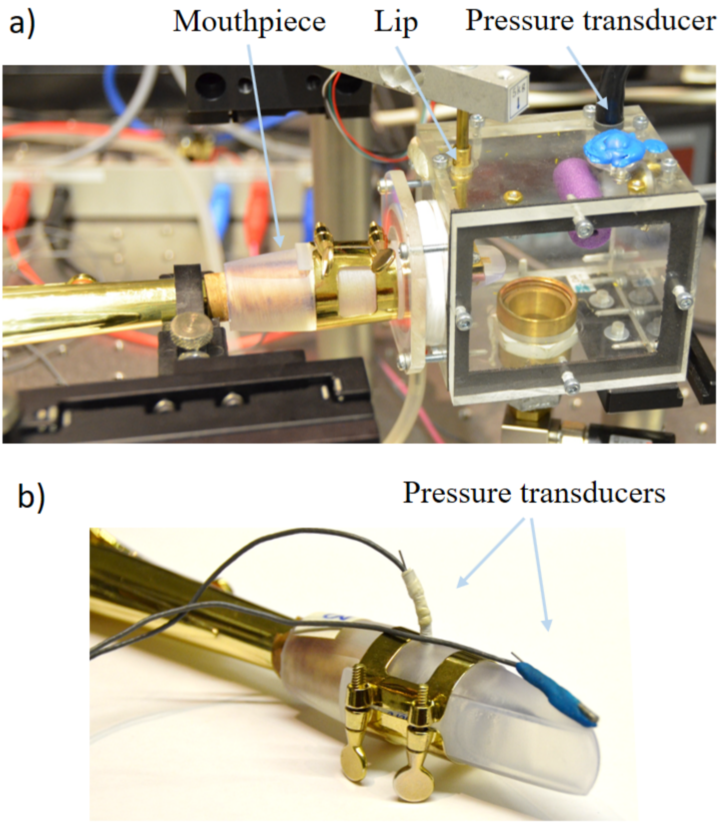


Figure B.1: a) The artificial mouth used to blow into a 3D-printed saxophone mouthpiece. b) Pressure transducers attached to a saxophone mouthpiece to measure pressure variations in the mouthpiece and in the mouth of a player.

(STAGG Alto Saxophone 77-SA). The mouthpieces were equipped with two pressure transducers (Endevco 8507C-2), as shown in Figure B.1b, to measure the mouthpiece pressure and the blowing pressure in a real playing configuration [155]. The same synthetic reed and neck as in the artificial configuration were used. For this task, the first author tested all mouthpieces in a blind test, where the mouthpieces were randomly assigned with a new numeration. The player performed pitch adjustments while fingering the tone C$\sharp_5$ (concert pitch E$_5$, 659.26 Hz) with all the mouthpieces. The test was repeated three times. The reported value is the widest pitch variation interval played.

B.3. DATA PROCESSING AND ANALYSIS

B.3.1. ACOUSTICAL CHARACTERISTICS EXTRACTION

In order to analyze the relationship between the 9 selected geometry parameters and the acoustical characteristics of every tested mouthpiece, four mouthpiece features have

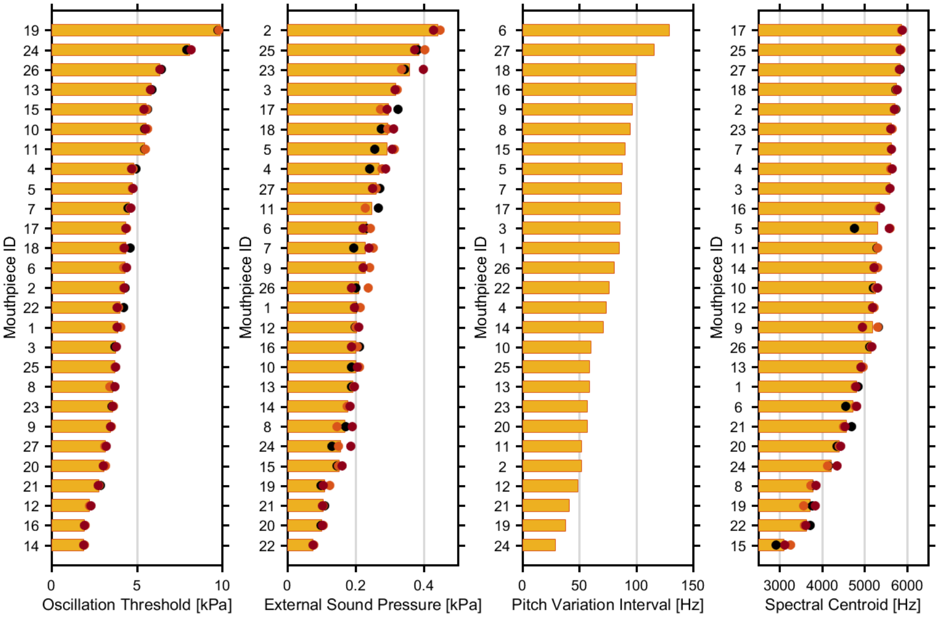


Figure B.2: Mean values for the four tested features on each mouthpiece (bars), with the indication of the three values of the repeated tests (dots). The standard deviations of the three measurements averaged along all mouthpieces are 0.08 kPa for the Oscillation threshold, 0.015 kPa for External sound, and 68.9 Hz for the Spectral centroid. Mouthpieces are ordered by descending feature values.

been tested. To do that, the recorded signals were processed, and the following features were analyzed:

- The difficulty of blowing into a mouthpiece to create a sound, i.e. the ‘resistance’ it provides when beginning a tone, is assessed by measuring the threshold of oscillation of every mouthpiece. The threshold of oscillation is obtained as the minimum air pressure in the artificial mouth (p_{mouth}) required to start a tone [132]. This is found as the artificial-mouth pressure value corresponding to a mouthpiece pressure amplitude of $p_{\text{mouthpiece}} = 0.5$ kPa at the tone onset (R in Figure B.3), a value that is above the noise level for all mouthpieces and right at the beginning of the oscillations.

- The ‘loudness’ of every mouthpiece is assessed as the external sound level that is achieved at a certain artificial-mouth pressure. Such measurement relates to the acoustic efficiency of the instrument since it considers the relationship between the input pressure and the output pressure across the system. For that, an artificial-mouth pressure of $p_{\text{mouth}} \in [12, 12.5]$ kPa was selected since at this level all mouthpieces would produce a sound in the stationary state. Within this interval, the average amplitude of oscillation of the external sound signal was calculated. This was obtained as the difference between the mean upper envelope and the mean lower envelope during the interval (L in Figure B.3).

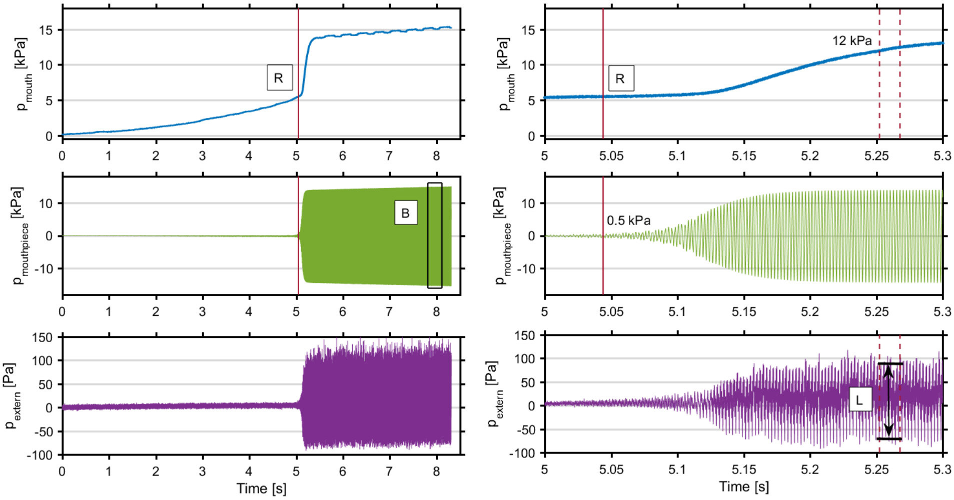


Figure B.3: Artificial-mouth pressure p_{mouth}, mouthpiece pressure $p_{\text{mouthpiece}}$ and external sound pressure p_{extern} when recording a mouth-pressure ascending ramp at 1 kPa/s. On the right side, zoomed view of 300 ms around the tone onset. R indicates the threshold of oscillation, considered to assess resistance (vertical red line indicates the first instant where $p_{\text{mouthpiece}} > 0.5$ kPa). B indicates the time interval of mouthpiece pressure used to compute the spectral centroid (Figure B.4), considered to assess brightness. L indicates the external sound amplitude considered to assess loudness, at p_{mouth} between 12 and 12.5 kPa. [Mouthpiece no. 10, first repetition]

- The ‘brightness’ of a sound is a perceptual feature that is related to the distribution of energy across the partials of its spectrum, and it is often assessed as the spectral centroid of the sound [141, 167]. The spectral centroid represents the center of gravity of the signal spectrum [168]. To extract the spectral centroid corresponding to the sound of the tested mouthpieces, a segment of 300 ms of the mouthpiece pressure signal recorded at the maximum achieved blowing pressure was selected for every mouthpiece (B in Figure B.3). In case the reed closed against the mouthpiece during the test (at a blowing pressure below 15 kPa), the selected segment is located before the release transient, i.e. during the steady part of the recorded sound and right before the sound ended. For the mouthpieces that did not close (because their extinction threshold was higher than 15 kPa, posing a safety risk) the selected segment is located at a blowing pressure of 15 kPa (see B in Figure B.3). Hence, this calculation considers that differences in the beating conditions might appear, which result in differences in brightness [169]. After *smoothing* the segment with a Hanning window and filtering it at 15000 Hz to reduce high-frequency noise, the first 35 peaks of its spectrum were used to compute a peak-wise spectral-centroid as in [168]. Figure B.4 shows the spectra of the sound produced by two mouthpieces that present low and high spectral centroids.

- To assess ‘flexibility’, the interval of pitch variation (I_{pitch}) was obtained as the frequency difference from the highest to the lowest pitch during the performance of

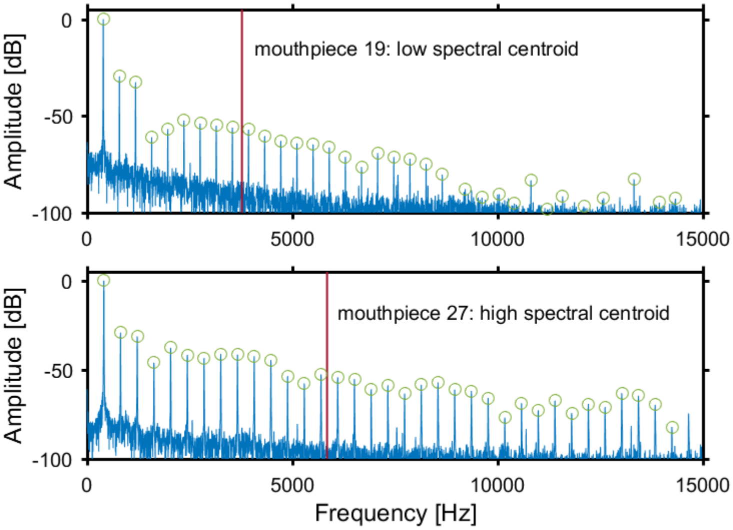


Figure B.4: Spectra of the mouthpiece-pressure signal comparing two mouthpieces with low and high spectral centroid (marked as a vertical line). The spectral centroid is calculated by considering the amplitude of the first 35 peaks of the spectrum (marked with circles).

pitch adjustments while fingering the tone C♯$_5$ (concert pitch E$_5$, 659.26 Hz), as shown in Figure B.5.

Notice that the available recorded data during the performance of the ascending ramp in p_{mouth} defined the manner in which resistance, loudness, and brightness were assessed, in order to obtain a standard procedure across all mouthpieces. A compromise was made to compare the mouthpieces at similar playing conditions: at the tone onset for resistance, at a certain blowing pressure in the steady-state for loudness, and at the maximum achieved blowing pressure for brightness. The four selected acoustical properties were then analyzed independently of each other as follows.

B.3.2. STATISTICAL ANALYSIS

The analysis of the Taguchi method is largely focused on orthogonal arrays and analysis of variance (ANOVA). The aim of the experiment was to determine which parameters have an influence on which features and at what amount. The influence of the parameters is observed on the main effect plots of data means (Figure B.6). The plots demonstrate the mean response at each level of the parameters. As each level of a parameter appears 9 times, the mean response of those 9 measurements is analyzed for the main effects. The validity of the main effects is verified with the statistical significance of every effect in the ANOVA analysis. The ANOVA results for the four experiment cases are presented in Tables B.2, B.4, B.6 and B.8 in the Appendix A. A stepwise model reduction is applied according to statistical significance criteria [170]. For the model reduction in the cases of oscillation threshold, spectral centroid, and pitch variation interval, a significance level of 0.05, i.e. a confidence level of 95%, is taken for the p-value. In the case of

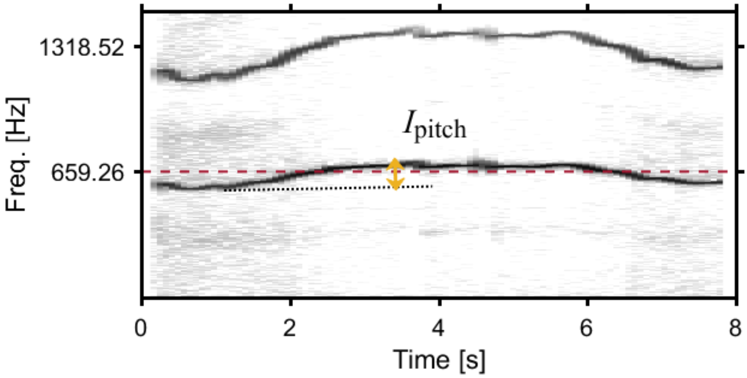


Figure B.5: Spectrogram of the mouthpiece pressure during the performance of pitch adjustments when fingering the tone C$\sharp_5$ (concert pitch E_5) showing the theoretical fundamental frequency (659.26 Hz; marked as a horizontal dashed line) and the first harmonic. The interval of pitch variation (I_{pitch}) is considered between the lowest and the highest fundamental frequency achieved during the task. [Mouthpiece no. 6, first repetition]

external sound level, the p-value threshold is taken as 0.15. At each step of model reduction, the parameter with the highest p-value is eliminated, and the ANOVA is repeated. The reduction is followed until all the parameters are within the taken p-value threshold. The ANOVA results after reduction are presented in Tables B.3, B.5, B.7 and B.9 in the Appendix A.

Based on the ANOVA results, the effective parameters for each mouthpiece feature, to be used in mouthpiece personalization, are determined. The statistically significant parameters for the four experiment cases are highlighted in Figure B.6. In the following section, the results of the analysis are discussed, and the effective parameters for each feature to be used in the mouthpiece personalization model are presented.

B.4. INFLUENCE OF DESIGN PARAMETERS ON MOUTHPIECE FEATURES

The influence of each of the 9 selected design parameters on the 4 tested mouthpiece features (i.e. on the extracted acoustical characteristics) is observed via main effect plots (Figure B.6). The obtained values of the 4 features for every tested mouthpiece are shown in Figure B.2, with the indication of the measurements obtained in the repeated tests.

Changes in l_{window} and l_{table} did not demonstrate any meaningful effect on any of the measurements. Besides, both had very low statistical significance values in ANOVA for all four features measured. Therefore, it is safe to conclude that these two parameters may be excluded in the resultant mouthpiece personalization model. Yet it is to be noted that this conclusion is valid within the scope of the experiment as well as within the tested values. These two parameters might still have an influence on other mouthpiece characteristics that are not covered in this work.

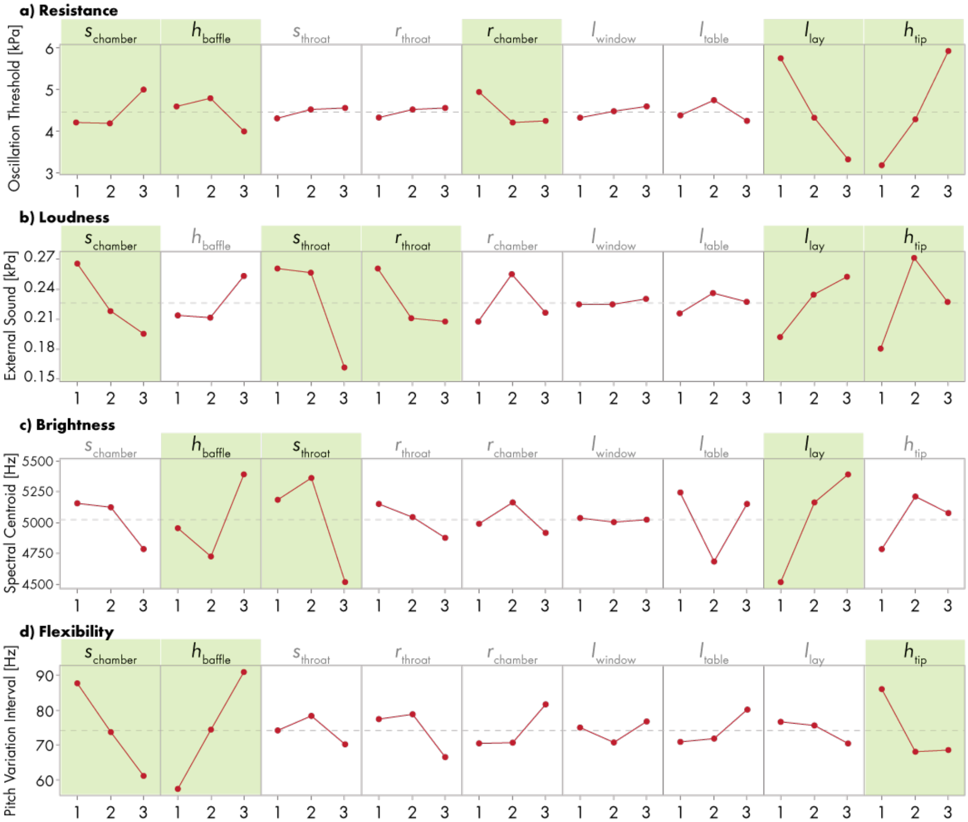


Figure B.6: Main effects plots of the mean of means for design parameters, showing the four experimental cases (resistance, loudness, brightness, flexibility). The horizontal axis represents the levels of parameters (1 to 3 levels correspond to ascending values, as in Table 5.1), and the vertical axis represents the mean response of 9 measurements at the given level for the measured acoustical characteristics. Statistically significant parameters after stepwise model reduction are written in bold and highlighted in green.

Resistance

The initial ANOVA results of oscillation threshold measurements are presented in Table B.2. Main effect plots for parameter means are in Figure B.6a. As seen in the plot, s_{throat}, r_{throat}, l_{window} and l_{table} do not present any significant effect on the oscillation threshold. These parameters also have very low statistical significance, as seen in the initial ANOVA results (Table B.2).

The model is reduced by eliminating the parameter with the highest p-value at each step until all the parameters are within the 0.05 threshold (Table B.3). As expected, s_{throat}, r_{throat}, l_{window} and l_{table} are not in the reduced model. The most influential parameters on resistance are h_{tip} and l_{lay}, both having a confidence level of 100%. This is very much in line with the literature review [130, 133, 137], since the oscillation threshold is proportional to the tip opening and to the reed stiffness [171]. The influence of the lay length relates to the modification of the vibrating length of the reed, as well as the way the reed curls upon the lay, and hence affects the reed stiffness [134–136]. The parameters tip opening h_{tip} and lay length l_{lay} define the airflow cross-sectional area between the player and the mouthpiece, hence directly related to airflow resistance. s_{chamber}, r_{chamber} and h_{baffle} showed similar effects to each other on the results, also appearing to be effective between two levels only (Figure B.6). These three parameters define the size of the inner cavity of the mouthpiece, which justifies their effect on the oscillation threshold [137]: the internal geometry of the mouthpiece affects the airflow characteristics and the output impedance of the mouthpiece [172], and hence it has an important role on the sound production [145]. As a result, one can conclude that the oscillation threshold is affected by h_{tip}, l_{lay}, s_{chamber}, r_{chamber} and h_{baffle}.

Loudness

ANOVA results on the mean response of external sound level are presented in Table B.4 in the Appendix A. After model reduction (Table B.5), only s_{throat} and h_{tip} remained as statistically significant.

The throat size s_{throat} appeared to be the dominant parameter for the loudness of the instrument, with a confidence level of 96% (p=0.004, Table B.5). s_{throat} shows an inversely proportional relationship to external sound level (Figure B.6b). s_{chamber} also shows a similar inversely proportional effect, from which one can reach a generic conclusion that reducing the cross-sectional area of the internal cavity may increase the loudness of the mouthpiece. Whereas, the tip opening h_{tip} demonstrated inverse trends on either side of level 2 (Figure B.6b). This indicates that the highest loudness is achievable with an average h_{tip} value. A probable reason for such behavior is that, with small h_{tip}, when high blowing pressure is applied to the mouthpiece, the reed closes against the mouthpiece, blocking the airflow. On the other hand, with large h_{tip}, playing the mouthpiece requires higher blowing pressure and hence it is more difficult to achieve louder sounds. Consequently, the external sound level is defined by the parameters s_{chamber}, s_{throat}, r_{chamber}, l_{lay} and h_{tip}.

The relationship between loudness and h_{baffle} is also included in the personalization model, even though it was above the p-value threshold (p=0.232 for h_{baffle} in the analysis of external sound level, at the second step of the model reduction). To build a reliable model, the subject matter knowledge is customarily used to interpret the results [170, 173, 174]. In this case, the motivation for including the h_{baffle}–loudness relationship is that the effect of baffle height on the loudness of the mouthpiece (also stated as power) has been reported by players [130] and manufacturers [175]. Furthermore, the impact of the baffle has been reported to produce observable changes in the mouthpiece impedance [176].

Brightness

Initial and reduced model ANOVA results for spectral centroid measurements are provided in Table B.6 and Table B.7 in the Appendix A, respectively. After the stepwise reduction of statistically insignificant terms, h_{baffle}, s_{throat} and l_{lay} were the remaining parameters. The lay length l_{lay} is the most prominent parameter, with a 91% confidence level. This correlation between l_{lay} and brightness has not been reported in the literature. It is however expected that changes in l_{lay} may affect reed beating and hence brightness

[135, 169]. Both the baffle height h_{baffle} and the throat size s_{throat} were expected to have an influence on the spectral centroid [150, 176], as seen in Figure B.6c, yet they have unexpected trends between levels 1 and 2. One potential source of this trend is the existence of an interaction between the parameters. In conclusion, l_{lay}, h_{baffle} and s_{throat} are found to be effective parameters on spectral centroid.

Flexibility

The measurement of flexibility is defined in this study as the interval between the highest and the lowest pitch achievable by the player without changing fingering (I_{pitch} in Figure B.5). The initial ANOVA results and eventual results after model reduction are presented in Table B.8 and Table B.9 in the Appendix A. s_{throat}, r_{throat}, r_{chamber}, l_{window}, l_{table}, and l_{lay} were eliminated at each reduction step as statistically not significant terms. They also demonstrate remarkably less effect on the main effects plot (Figure B.6d). h_{baffle} and s_{chamber} are the most influential parameters with 99% and 91% confidence levels, respectively.

The baffle height h_{baffle} and the chamber size s_{chamber} define the first cavity of the mouthpiece, significantly influencing the impedance at the beginning of the air column [172, 176]. In this study, both parameters show a similar trend: a wider cavity (low h_{baffle} and high s_{chamber}) results in a reduced possibility to adjust the pitch. The tip opening h_{tip} appeared to be influential only between levels 1 and 2. A probable explanation for this observation is the usage of the same reed (i.e. same reed strength) for all the experiment mouthpieces. Combining different reed strengths might imply differences in lip force, which would affect h_{tip} and would yield diverse results. Consequently, pitch interval is affected by the parameters h_{baffle}, s_{chamber} and h_{tip}.

Table B.1: Experimental layout using L27 orthogonal arrays

	Parameter level								
	s_{chamber}	h_{baffle}	s_{throat}	r_{throat}	r_{chamber}	l_{window}	l_{table}	l_{lay}	h_{tip}
1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2
5	1	2	2	2	2	2	2	3	3
6	1	2	2	2	3	3	3	1	1
7	1	3	3	3	1	1	1	3	3
8	1	3	3	3	2	2	2	1	1
9	1	3	3	3	3	3	3	2	2
10	2	1	2	3	1	2	3	1	2
11	2	1	2	3	2	3	1	2	3
12	2	1	2	3	3	1	2	3	1
13	2	2	3	1	1	2	3	2	3
14	2	2	3	1	2	3	1	3	1
15	2	2	3	1	3	1	2	1	2
16	2	3	1	2	1	2	3	3	1
17	2	3	1	2	2	3	1	1	2
18	2	3	1	2	3	1	2	2	3
19	3	1	3	2	1	3	2	1	3
20	3	1	3	2	2	1	3	2	1
21	3	1	3	2	3	2	1	3	2
22	3	2	1	3	1	3	2	2	1
23	3	2	1	3	2	1	3	3	2
24	3	2	1	3	3	2	1	1	3
25	3	3	2	1	1	3	2	3	2
26	3	3	2	1	2	1	3	1	3
27	3	3	2	1	3	2	1	2	1

Table B.2: ANOVA for oscillation threshold, R^2=94.69%.

Source	df	Seq SS	F	p
h_{tip}	2	35.2844	33.15	0
l_{lay}	2	27.907	26.22	0
s_{chamber}	2	4.0223	3.78	0.070
r_{chamber}	2	3.2857	3.09	0.101
h_{baffle}	2	3.1702	2.98	0.108
l_{table}	2	1.2113	1.14	0.367
s_{throat}	2	0.3686	0.35	0.717
l_{window}	2	0.3428	0.32	0.734
r_{throat}	2	0.2896	0.27	0.769
Residual Error	8	4.2579		
Total	26	80.1397		

Table B.3: ANOVA for oscillation threshold after model reduction, R^2=91.93%.

Source	df	Seq SS	F	p
h_{tip}	2	35.284	43.63	0
l_{lay}	2	27.907	34.51	0
s_{chamber}	2	4.022	4.97	0.021
r_{chamber}	2	3.286	4.06	0.037
h_{baffle}	2	3.17	3.92	0.041
Residual Error	16	6.47		
Total	26	80.14		

Table B.4: ANOVA for external sound level, R^2=83.93%.

Source	df	Seq SS	F	p
s_{throat}	2	0.054683	6.76	0.019
h_{tip}	2	0.036611	4.53	0.048
s_{chamber}	2	0.022128	2.74	0.124
l_{lay}	2	0.017281	2.14	0.180
r_{throat}	2	0.015429	1.91	0.210
r_{chamber}	2	0.011408	1.41	0.299
h_{baffle}	2	0.009452	1.17	0.359
l_{table}	2	0.001781	0.22	0.807
l_{window}	2	0.000196	0.02	0.976
Residual Error	8	0.032342		
Total	26	0.201312		

Table B.5: ANOVA for external sound level after model reduction, R^2=72.59%.

Source	*df*	Seq SS	*F*	*p*
s_{throat}	2	0.05468	7.93	0.004
h_{tip}	2	0.03661	5.31	0.017
s_{chamber}	2	0.02213	3.21	0.067
l_{lay}	2	0.01728	2.51	0.113
r_{throat}	2	0.01543	2.24	0.139
Residual Error	16	0.05518		
Total	26	0.20131		

Table B.6: ANOVA for spectral centroid, R^2=86.17%.

Source	*df*	Seq SS	*F*	*p*
l_{lay}	2	3654293	6.93	0.018
s_{throat}	2	3571621	6.78	0.019
h_{baffle}	2	2035572	3.86	0.067
l_{table}	2	1623841	3.08	0.102
h_{tip}	2	842065	1.60	0.261
s_{chamber}	2	767167	1.46	0.289
r_{throat}	2	337242	0.64	0.552
r_{chamber}	2	300289	0.57	0.587
l_{window}	2	4949	0.01	0.991
Residual Error	8	2108169		
Total	26	15245208		

Table B.7: ANOVA for spectral centroid after model reduction, R^2=60.75%.

Source	*df*	Seq SS	*F*	*p*
l_{lay}	2	3654293	6.11	0.009
s_{throat}	2	3571621	5.97	0.009
h_{baffle}	2	2035572	3.40	0.053
Residual Error	22	5983722		
Total	26	15245208		

Table B.8: ANOVA for pitch interval, R^2=83%.

Source	*df*	Seq SS	*F*	*p*
h_{baffle}	2	5033.9	7.68	0.014
s_{chamber}	2	3176.5	4.85	0.042
h_{tip}	2	1897.2	2.90	0.113
r_{throat}	2	812.1	1.24	0.34
r_{chamber}	2	718.7	1.10	0.379
l_{table}	2	500.1	0.76	0.497
s_{throat}	2	296.1	0.45	0.652
l_{lay}	2	190.7	0.29	0.755
l_{window}	2	174.5	0.27	0.773
Residual Error	8	2620.7		
Total	26	15420.5		

Table B.9: ANOVA for pitch interval after model reduction, R^2=65.55%.

Source	*df*	Seq SS	*F*	*p*
h_{baffle}	2	5034	9.47	0.001
s_{chamber}	2	3177	5.98	0.009
h_{tip}	2	1897	3.57	0.047
Residual Error	20	5313		
Total	26	15421		

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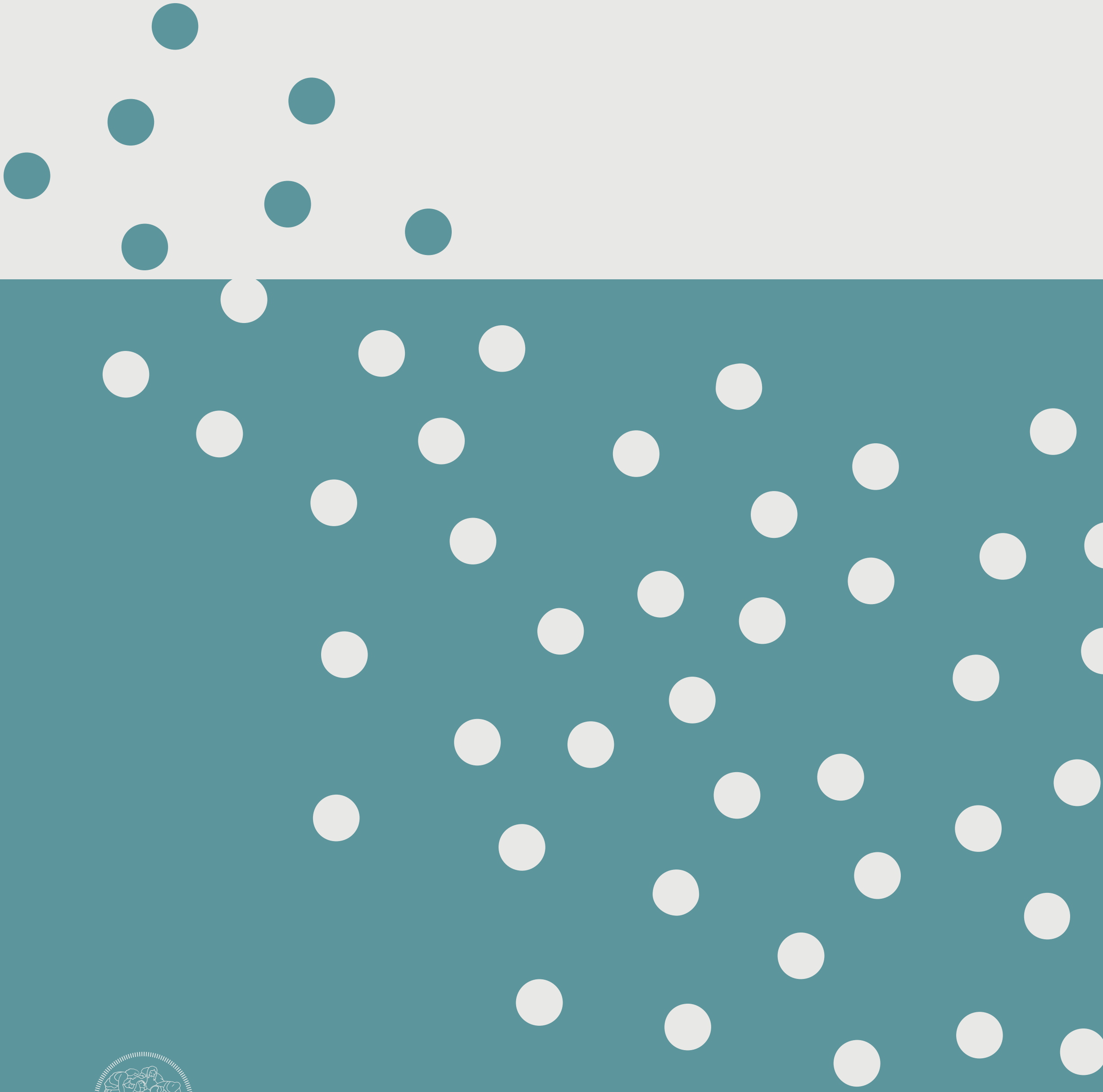

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