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A MASS PERSONALIZATION FRAMEWORK FOR KNITTED FOOTWEAR

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Abstract: *The footwear industry has been one of the pioneers of Mass Customization (MC). However, MC trials in footwear have been far from success due to high expenses, long production times, and not being able to meet customer needs. Mass Personalization (MP) of knitted footwear may address these issues and provide the necessary leverage for the industry. This study investigates the MP opportunities with digital knitting and custom fit footwear in the pursue of an MP framework for knitted footwear. In this regard, personalizing parameters for knitting and custom fit are identified, and their dependencies are laid out, to be used in the proposed MP framework for footwear.*

Key Words: ***Mass Personalization, Knitted Footwear, Digital Knitting, Footwear Customization, Design Automation***

1. INTRODUCTION

Footwear has ever been a tool for self-expression, and customization in footwear dates back a long time with handcrafted shoes by artisans. With mass-production, footwear is standardized, and consequently, fit and comfort related problems have arisen Several foot-related problems are originated from the poor fitting of shoes [1]. On the other hand, customizing shoes is a very long and costly process. It is reported that consumers are willing to pay only 10 to 30% more for a personalized shoe [2].

Footwear is a very competitive and large industry, which produced 23 billion pairs in 2015 [3]. Therefore, to differentiate in the market and to answer diversifying customer needs, the Footwear industry has been eager to employ Mass-Customization (MC) and Digital Manufacturing tools. However, it is difficult to mention any significant success so far. Even an industry leader as Adidas could not sustain its MC platform MiAdidas, which was running since 2000. MiAdidas got closed in 2019, stating that the future of the footwear personalization is in co-creation, and they are working on user participation on a deeper level [4]. 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 [5].

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 [6]. 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 Mass-Personalization (MP) in footwear.

MP approach promises to provide higher user involvement in design while aiming to reduce the labor in the process. Instead of providing options as in MC, MP involves users in the design phase and allows true self-expression. Besides, by employing digital manufacturing and on-demand production, it dramatically reduces the need for stocks. Digital knitting fits perfectly within the MP scenario. Therefore, combining the MP approach with digital knitting for footwear may provide both higher customer satisfaction and the necessary leap for the industry.

This work aims to explore the personalization opportunities that digital knitting presents to footwear and to identify both knitting and custom fit parameters that define the personalized product. For this purpose, parameters to be used in an MP scenario are identified. It is also investigated how these parameters interact with or depend on each other. The preliminary framework proposed here is expected to be the foundation of the parameter-based MP model for knitted footwear. The long-term research aim is to establish a design methodology for MP to provide a set of guidelines and tools to support designers in developing product templates that are personalizable in an automated manner.

2. METHODOLOGY

The work in this paper is based on two steps of extensive literature reviews and the adoption of the results for the proposed framework. The first step is a literature review on footwear customization and related technologies in foot measurement and digital knitting. Based on the outcomes of the literature reviews, a previously proposed MP model is adapted for the MP framework of knitted footwear.

In the second part, another literature review was carried out on the parametrization of footwear sizing and knitting. The results were used to define design parameters and their interdependencies to construct the Seed Design, which is at the core of the proposed framework. Finally, the design parameters were clustered on a dependency matrix.

3. PROPOSED FRAMEWORK

3.1. Background

3.1.1. Mass Personalization Model

The Mass Personalization model adopted for the proposed framework can be seen in Fig. 1 [7]. Within this model, a user-modifiable product template, a seed design, is developed. The seed design is composed of a particular design space that has predefined and assured ranges of variables. The design process is then completed by the user, where the product is individualized within the predefined design space. The aim is to automate the process of obtaining personalized products, defining the seed design once, and then the co-creation is repeated by each customer.

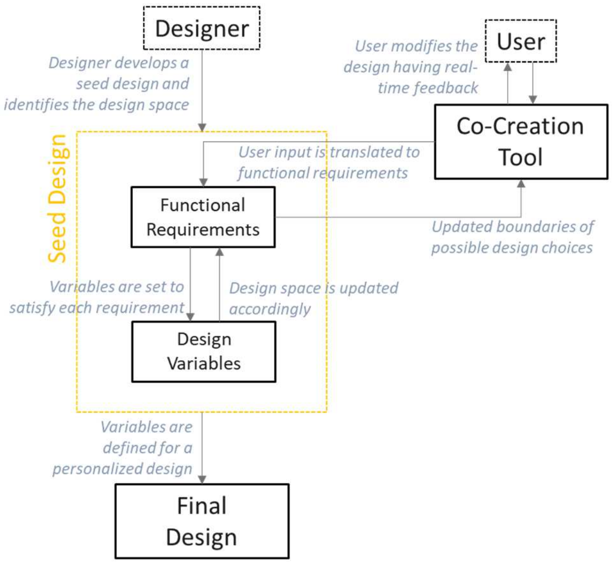

Fig. 1. *Adopted model of Mass Personalization*

To automate the design process, the relationships between the requirements by users and design variables are investigated and laid out. In addition to these relationships, conditional restrictions are defined for dynamic design space. Since the design choices specified by the user possibly affect the boundaries of the design space for the following requirements, a dynamic interaction between the seed design and the user is necessary. This implies that by each design choice made, consequences on further choices become evident. Once all the design choices are made, the personalized final design is generated.

This model entails the identification of personalizing requirements and mapping these onto relevant design variables. The interdependencies of the variables and the requirements are to be examined to generate a valid design solution. Dynamic design space is achieved by predefining the ranges of the variables in a conditional way, which consequently defines the ranges of functional requirements. A final design is achieved by iterating the variables following each input from the user.

3.1.2. Personalization in Footwear

Mass-customization in footwear has been thoroughly studied considering many aspects, such as from design to supply chain [8]–[10]. Opportunities, obstacles, and enablers of using Additive Manufacturing in MC have also been investigated [11]. The trend in footwear MC is towards systems with more customer involvement in the process. A very recent study of Shang et al. [12] 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 [13]. 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 service.

3.1.3. 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 [14]. 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 [15]. 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 [16]. One step further towards the perfect fit is models examining the changes in the foot shape over time [17]. All these methods can be employed for different levels of 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 [18]. These methods provide a foundation for the design automation of personalized fit.

3.1.4. Digital Knitting

Digital knitting technology promises many opportunities for personalized fitting. A methodology to produce personalized functional compression garments using body scanning and digital knitting has been introduced [19]. Extending it to a more functional personalization case, Underwood [20] 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 [6] explaining how to develop flat-knitted shaped uppers based on ergonomics and also demonstrated functional and decorative knitting structures to use in a knitted upper (Fig. 2). Taking this a step further is possible by automating the design personalization in an MP application. As an initial step, knitting aspects, opportunities, design options, and parameters are discussed thereinafter.

In machine knitting, in terms of manufacturing, materials, or design, there are undoubtedly many more parameters than the ones explained in the following sections. The parameters pointed here are the ones possibly to be employed in the given MP framework and focused on knitted footwear. Broadly categorizing these parameters, they are at three levels: yarn parameters at the material level, stitch parameters at structure level, and machine parameters at the manufacturing level.

Fig. 2. *Flat-knitted upper developed by Lu* [6]

3.2. MP Framework for Knitted Footwear

In the proposed framework for knitted footwear MP (Fig. 5), a seed design is devised as described before, and it is composed of a shoe last and three main shoe parts. Foot measurements of the user are parameterized through the shoe last design, and this provides the ergonomic fit input to the three shoe parts. Therefore, digital shoe last parameters and their relations to parameters of the shoe parts are needed to be identified.

For aesthetical or functional personalization, only the upper is considered. For this purpose, knitting-related parameters defining the upper are needed to be identified and interdependencies of these parameters to be laid out. It is essential to mention that there are numerous possibilities that AM presents to the aesthetical personalization of the insole or the midsole. However, since the focus in this work is given to knitting in footwear, only parameters related to personalized fit is considered for insole and midsole.

To complete the MP model, foot measurements and aesthetical or functional requirements by the user should be mapped onto the design parameters to develop a personalized design solution algorithm. However, this requires a defined scenario where possible user requirements for personalization are identified. Identification of these requirements is not covered in this paper and left as follow-up work.

3.3. Seed Design Development

Seed Design is at the core of the proposed framework, and therefore it is further investigated in this section. The components of the Seed Design for knitted footwear case are identified, and related design parameters are listed below.

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 [21]. 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 (Fig. 3). A similar case also exists for 3D printed soles and insoles.

Fig. 3. *Components of a traditional shoe upper (left)* [21] *and a Flyknit upper (right)* [22]

Therefore, in the context of this work, the shoe structure is divided into three main components: upper, insole, and midsole (Fig. 4). Shoe last is also considered here since it is essential to shoe design and manufacturing. In this context, it is considered as 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.

Fig. 4. *Main shoe components*

3.3.1. Insole and Last Parameters

Custom-fit insoles are commercially available, and the parameters used by orthotic specialists are well-defined. As seen in Fig. 6, parameters for a personalized insole are forefoot cushion height, arc height, heel raise, medial, and lateral heel wedges [23].

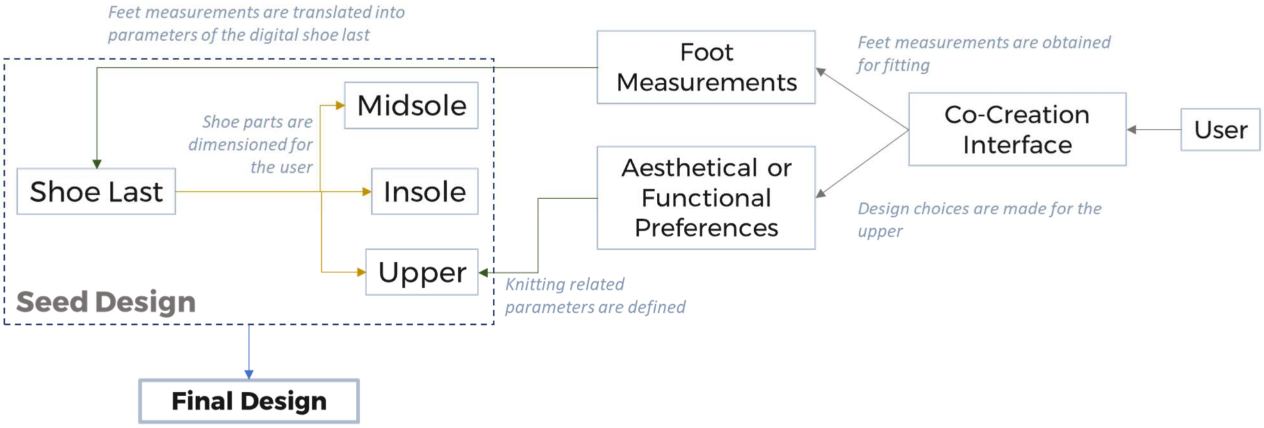

Fig. 5. *Proposed MP Framework for Knitted Footwear*

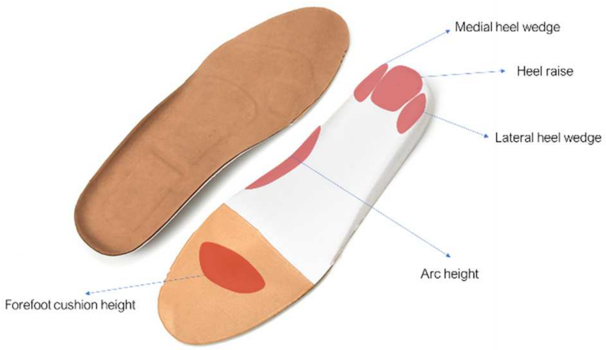

Fig. 6. *Parameters for custom insole making*

Shoe lasts contain the information both for the design and the sizing/grading of the shoe. The parameters used for sizing and grading (Fig. 7) are also well-established and could be used for custom shoe lasts as well. The main parameters to define the fit of the last are stick length, ball, waist, and instep girths [24][25]. These parameters are relevant to sizing the upper. For the size of the insole and midsole, the last bottom parameters are relevant. These parameters are bottom length, ball, waist, instep, and heel widths [5].

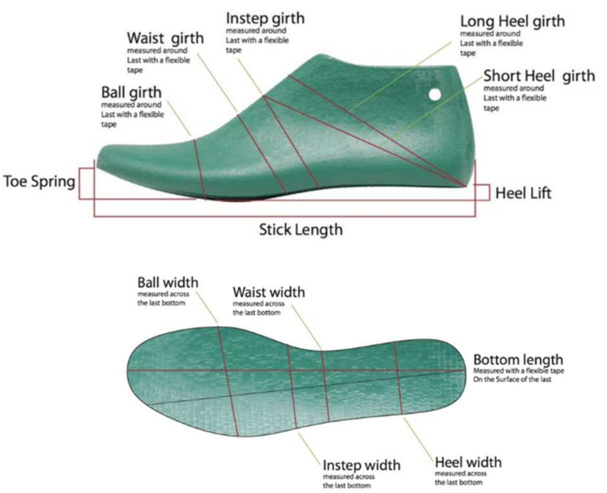

Fig. 7. *Shoe last parameters* [26]

3.3.2. Knitting Parameters for Upper

Knitting Machine Parameters

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 [27]. Today, improvements in CAD for knitting allow quick changes in the design and requires less expertise to operate. Therefore, digital knitting gains more attraction as it provides customized and on-demand production.

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 [28]. Although being more rare, four-bed knitting machines also exist and used in whole garment process for knitting complex fabrics seamlessly [29]. 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 mostly used for such applications. Whereas, double-bed flat machines can also knit tubular fabric by each bed knitting a single fabric piece [28]. 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 [30]. 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 5 and E 14 [31]. The number of carriers simply defines how many different yarns can be used in the knitted fabric [28]. In summary, manufacturing related parameters are the gauge options and the number of carriers available in the knitting machine.

Yarn 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 it is very well established. The selection of yarns available for knitting machines comes in great variety, and thus provide wide options for design personalization.

Yarns possess several different characteristics according to the fibers it is composed of and the way it is spun. They significantly differ with their mechanical properties or the sensory quality they provide [32].

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 with personalization and user interaction [33]. Lund [34] 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.

- **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 [32]. 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 [32], [35], [36]. 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 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 and visual properties [37], aesthetical personalization possibilities are infinite by changing the yarn material or creating combinations of them.
- **Color:** Very few yarns preserve their original colors, and mostly, they undergo processes of scouring, bleaching, and dyeing [38]. 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 with the number carriers the knitting machine used has. Using different color yarns is the simplest way to design individualization. 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.
- **Thickness:** Yarn thickness (count) 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 different measuring systems used [37]. Yarn thicknesses are available in a range depending on the material [39]. An interval of yarn thicknesses can be knitted with a given machine gauge, as exampled in Table 1. Therefore, yarn thickness selection is limited by the machine gauge, and for a given gauge, it affects the stitch density. Yarn thickness may have both functional and aesthetical personalization use. As an example, it may be employed to define the weight or thermal properties of the knitted shoe.

Table 1. *Typical yarn count ranges for particular E gauges* [31]

Gauge (E)	Yarn Count (NeK)
12	2/26 to 2/42
8	2/14 to 2/22
5	6/14 to 6/18
2	8/7 to 8/9

- **Layout:** 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 the knitting design and technology are also giving room to the MP of the 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.

Stitch Parameters

Stitches are the basic building units of knitwear structure. There are several stitching techniques, and using these in combination with varying densities allows creating unique knit patterns and designs.

The stitch parameters relevant to the MP study are stitch type, density, and layout.

- **Stitch Type:** Knit and purl stitches are the main stitch types, and basic knit structures such as plain, rib, interlock, and purl are composed of these [41].

To diversify the design possibilities, other stitch types such as drop, tuck, and float may be used [42]. For surface texture designs, weave, tuck and slip stitches are mainly used. Also, lifting and cable stitches are used for surface textures [36]. Each stitch type has a different density due to the specific technique.An example of how different stitches may be used to create knit patterns and surface textures seen in Fig. 8. Employing different stitch types provides many personalization possibilities, both structural and visual.

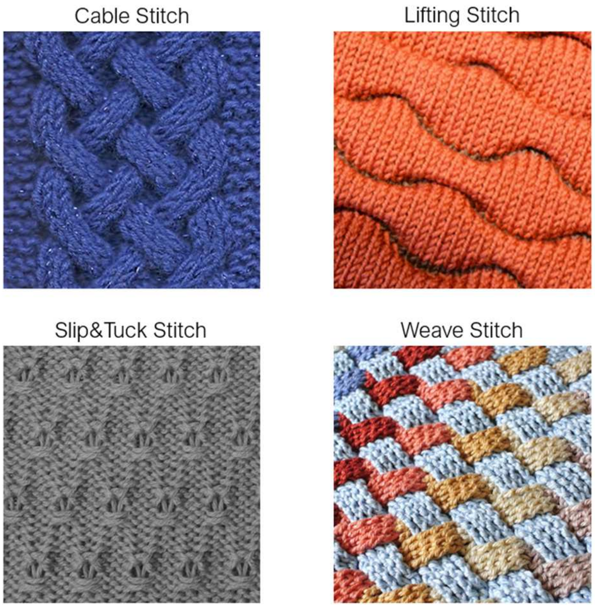

Fig. 8. *Textures and patterns created by different stitch types*

- **Stitch Density:** Stitch density is the number of stitch loops in a given area of fabric. It is often measured by multiplying the number stitches in a course (horizontal row of stitches) by the number of wales (vertical column of stitches) in a unit area of fabric. It is very much dependent on the machine gauge, as that sets the number stitches in each course. However, besides gauge, the yarn thickness also affects the stitch density. As the yarn gets thicker, the fabric gets denser and vice versa. Varying stitch density may have several different uses in a personalization scenario, both aesthetically and functionally. For instance, in a knitted shoe upper, functional features such as breathability or waterproofness may be regulated via stitch density. The same principle would also apply for the weight of the shoe. Stitch density, alongside yarn material and thickness, might be used for defining how lightweight is the shoe. Besides these, it can also be employed solely as an aesthetical element. This might be done by varying the density uniformly throughout the knitted upper or by using different stitch densities on the same knitted piece for decorative purposes (Fig. 9).

Fig. 9. *Different stitch densities on the same knitted fabric* [43]

- **Stitch Layout:** Stitch layout has the same principle as the yarn layout, while one defines the structure and physical patterns; the other defines materials and graphical patterns. The layout of different stitch types can be seen in Fig 10. It is possible to obtain unique designs and patterns by organizing these different stitch techniques. In combination with other stitch parameters, it is possible to obtain genuinely bespoke designs.

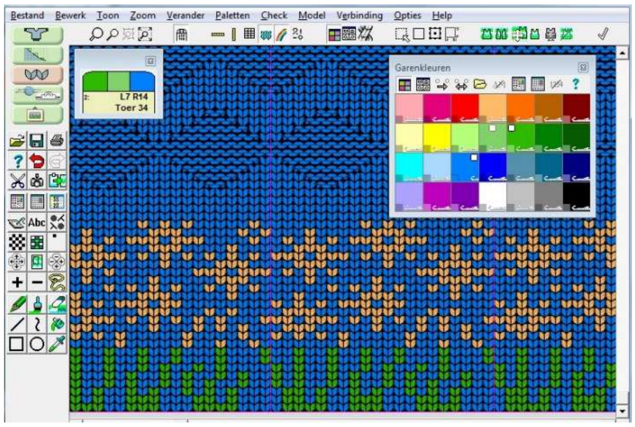

Fig. 10. *Yarn and stitch layout on a knitwear design software* [44]

4. DISCUSSION

An overview of the mentioned design personalization parameters can be seen in Fig 11. While yarn and stitch parameters are defining functional and aesthetical features of the knitted upper, the size of it is defined by the last parameters. The last bottom parameters define the size and fit of the midsole. While the fitting of the insole is set by the regarding parameters, the size of it is also defined by the last bottom.

The personalized fit parameters may either be used in a perfect fit scenario or closest fit by using existing sizing and grading tables. This depends on the defined MP case; however, the latter would be a more straightforward method. It should be noted that shoe last also transfers the styling of the shoe, and that is preserved with changing sizes. Different shoe styles in one seed design would not be practical. The dependency matrix of the design personalization parameters can be seen in Table 2. The matrix is to layout the dependencies of the parameters and enables a solution to the complex system. The parameters are clustered on the matrix according to their domains. The dependencies are stated directionally, as the parameter on the left row affects the parameter on the column right top. Fitting related parameters are clustered together since they act as a whole to affect the yarn and stitch layout, consequently the size of the upper. Color and thickness options depend on the yarn material. The stitch density also has a secondary relation to yarn material due to the thickness. Yarn thickness affects the stitch density within a given gauge. Also, stitch type affects the density as different stitching techniques have different densities. Finally, stitch density influences the stitched layout, since it changes the number of stitches in a given area

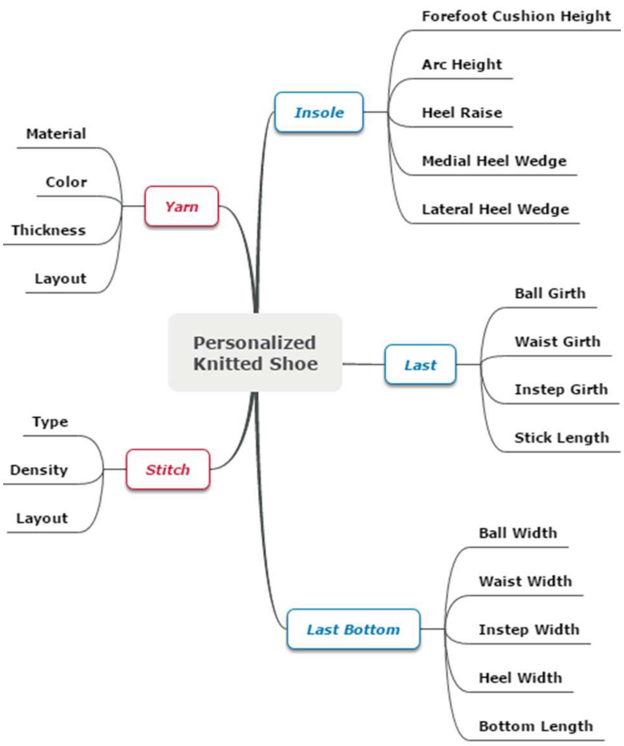

Fig. 11. *Overview of the design personalization parameters*

Table 2. *Dependency matrix of design personalization parameters*

		Custom-fit			Yarn				Stitch		
		Last C.	Last B. C.	Insole C.	Material	Color	Thickness	Layout	Type	Density	Layout
Custom-fit	Last Cluster							x			x
	Last Bottom Cluster										
	Insole Cluster							x			x
Yarn	Material					x	x			x	
	Color										
	Thickness									x	
	Layout										
Stitch	Type									x	
	Density										x
	Layout										

In order to construct a design space and a design solution algorithm for a footwear MP case, the range of each parameter should be defined. Some parameters get a numerical value within an interval, such as stitch density, while other parameters as yarn material have a set of options. In either case, using the dependency matrix, a personalized design solution can be iterated. In this dependency matrix, only the dependencies are shown, but not their amount or conditionals. These would be shown in a specific MP case where the design space is defined.

5. CONCLUSION

In this work, opportunities that knitting provides for footwear personalization are reviewed, and knitting design parameters to be used in an MP scenario are laid out. Also, methods related to foot measurement and parametrization is covered, and related custom fit parameters are explained. Finally, the dependencies of these parameters are presented.

The focus is on what is possible to manipulate in a knitted footwear design template. It is possible to provide endless options by changing the parameters mentioned here. Of course, it is not practical to employ all the mentioned parameters and full ranges of them. A certain design space should be identified according to the specific MP scenario, customer profile, and possible needs or desires.

The outcome is the first step towards the creation of an MP model for knitted footwear. As the next step to this work, possible user needs, or requirements, are to be identified, and the relations between user requirements and the design parameters should be laid out in a similar matrix as Table 2. Once the parameters to be used and their ranges are also identified, the design space where users can operate in co-creation is defined. Finally, using the dependency matrices, an algorithm can be built to automate design personalization. In order to test these concepts and build an MP model for knitted footwear, a specific case study will be devised as a follow-up to this work.

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