Smart, Sustainable and Socially Valuable: How Digital Textile Microfactories can Contribute to a Brighter Future

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1. Introduction

The traditional textile and clothing industry (TCI) is undergoing a significant and rapid transformation (Bebchuk et al. 2017, Berg 2022). This transformation is driven by factors such as volatility, velocity, variety, complexity, and dynamism (Boyle 2022, Brown 2022), necessitating the adoption of digital solutions (Wascinski et al. 2018). Here, digital networking across the entire value chain offers speed, individualization, efficiency, sustainability and high quality, with a strong potential for innovation and consumer interaction (Kiel et al. 2017, Winands et al. 2022). By establishing flexible production systems focusing on decentralized manufacturing as well as on-demand products, the TCI can shape new concepts that contribute to customer value, sustainability and even add to social entrepreneurship.

In order to promote such flexible production systems, Microfactories have recently been subject to research and development (Montes et al. 2019) which offer new possibilities for the TCI in the form of a Digital Textile Microfactory (DTMF). A DTMF is an end-to-end digitally networked development and production process for textile and clothing products (Winkler et al. 2022). Its digital backbone allows for speed, efficiency, high quality, and deep consumer interaction leading to a great innovation potential in a wide area of applications and business models. (Winkler et al. 2022)

Such DTMFs include a number of new technologies, such as digital textile printing or 3D knitting as an additive manufacturing technology. Digital Textile Microfactories thus show a new technological approach to clothing production, from a customer's body scan to the 3D simulation of the individual garment to digital printing and cutting or 3D knitting to the finished product (Artschwager et al. 2022). Using this smart approach, better sustainability could be achieved compared to traditional textile production.

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The aim of this paper is to systematically explore in which ways Digital Textile Microfactories can contribute to a brighter future by looking at their digital technologies and analysing their potential contribution to sustainability and social value. Section 2 reviews the basic concepts of DTMFs. Section 3 aims to explore in general the potential benefits of Digital Textile Microfactories, in terms of sustainability aspects and their impact on adding to social value. Section 4 will provide a comprehensive presentation of the recent digitally-driven technologies in the TCI used for DTMFs, with a special focus on digital textile printing and 3D knitting and elaborate on the specific sustainability potential of these two case studies. Finally, Section 5 focuses on discussing the findings, summarizing how DTMFs can contribute to a brighter future as a smart networked, sustainable and socially valuable way of textile production, and pointing to further research needed in order to detail and quantify the general potential described in this paper.

2. Basic Concepts of DTMFs

DTMFs have been in existence in various forms and characteristics for several years as a technical implementation. The first Microfactories were described in Japan in the 1990s (Mishima et al. 2002), and since then, the evolution of this manufacturing concept has resulted in a commercially feasible alternative to traditional manufacturing. The aim of this section is to introduce basic concepts of a DTMF which include its application settings and technologies.

2.1. Development of DTMFs

The textile and clothing industry has a long history of offshoring since the 1960s (Kunz et al. 2016), resulting in the development of intricate supply chains (Kunz et al. 2016). Despite the widely recognized advantage of low labor costs in developing countries (Bolisani/Scarso 1996, Kunz et al. 2016), there has been a notable shift towards reshoring in the industry starting in the 2010s. The motivations for reshoring are diverse and include factors such as the need for enhanced flexibility, greater control over the entire production process, commitment to environment protection, the closeness to customers and skilled labor, and more (Pal et al. 2018, Moore et al. 2018).

In the past years, the COVID-19 pandemic was another important issue which had a significant impact on different industries including the TCI. This unprecedent pandemic has caused disruptions in global value chains and complicated the transportation of intermediate products, resulting in significant losses for many multinational companies and a subsequent decline in global GDP (Kersan-Škabić 2022). This has further accelerated preexisting issues in the supply chain such as shortening of the value chain, refocusing on regional trade links instead of global value chains and reshoring activities (Kersan-Škabić 2022), bringing priorities such as digitalization to the fore (Zhao/Kim 2021).

Europe has a strong tradition of research and development, particularly in advanced manufacturing technologies (European Comission 2020). By bringing textile production closer to European centers of innovation, companies can benefit from the latest advancements, such as DTMFs which practice automation, digitalization, and sustainable manufacturing.

At present, DTMFs are used for three types of products: knitted fabrics, home textiles, and clothing made from textile surfaces (Winkler et al. 2022). They cover the entire development and production chain from customer to finished product, utilizing digitalization to optimize the complete process.

In contrast to traditional textile production workflows, which involve manual, labor-intensive steps from design to garment sewing (Lushan 2018), the DTMF is a model of the future that allows for competitive production of individualized products, with the potential for regional and on-demand production through the use of digitally networked and automated processes. This seamless digital networking of production steps enables optimal material and energy consumption, faster processing times for orders, and high flexibility to quickly respond to market needs.

Moreover, the implementation of DTMFs can potentially address challenges such as counterfeiting and socio-ecological concerns through digitaliization in product development and local production.

2.2. Technologies

The emergence of DTMFs is a response to the digitalization of value chains in Industry 4.0 or Textile 4.0. DTMFs use digital technologies to create value across various stages of the textile and apparel industry. The aim is to cater to individual customer demands, small quantity requirements, and savings in product development by integrating various value-adding stages.

Simulating the garments together with the customer for virtual fitting generally offers significant advantages. DTMFs' new technology approach even goes one step further in this context. It links the 3D simulation of apparel directly with production. The solution enables a complete, digital process chain from the initial body scanning, through 3D simulation and design, to digital printing/cutting or 3D flat knitting up to the final product. Technological solutions for simulation, textile design and marker-making, digital printing, single-layer cutting, automated knitting pattern generation and 3D flat knitting are integrated. Figure 1 shows two possible workflows of production lines in DTMFs.

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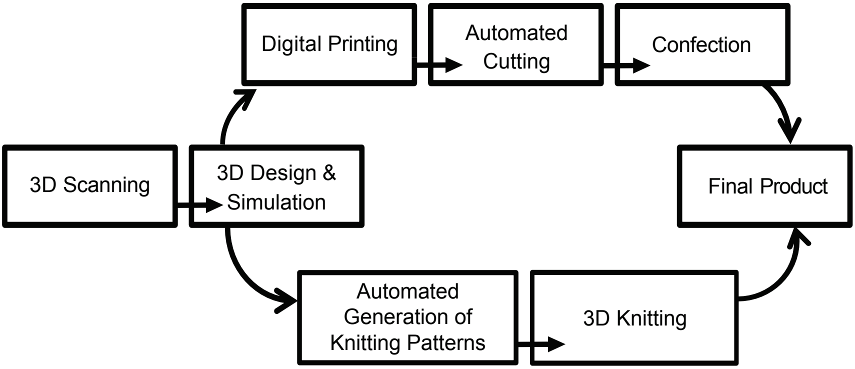

Figure 1: Digital Textile Printing and Knitting:
Two possible workflows of production lines in DTMFs

2.3. Business Models and Settings

Business models for DTMFs can utilize the benefits related to the new technologies. Hence, typically DTMFs can be used to address individual customer needs, to produce and reproduce small series fast, or to make sampling and prototyping more efficient (see also Section 3.2. for details).

DTMFs can be configured in different ways to support various application areas. Apart from being used in a "Fab Lab/ Technology Centre" setting for open purpose use, there are different settings for a commercial use of a DTMF. The first setting is the "Factory-in-Shop," which is located in a retail or selling environment that prioritizes customer interaction and has a fast turnaround time for production. The second setting is the "Standalone Factory", which has the capacity to scale up production and offers fast and flexible on-demand production, such as high-speed printing using multiple printers. The third setting is the "Factory-in-Factory," which is a dedicated workplace in a textile or garment factory for specific production jobs, such as sampling or producing lot-size one items (Winkler et al. 2022). Finally, the fourth setting is the "Virtual Factory", in which assets could be geographically as well as organizationally widespread due to their digital connectivity and communication.

The utilization of the first three settings enable the integration of a DTMF as a unified process, encompassing all production steps in a centralized location. On the contrary, the fourth setting allows for the production of digitally networked samples across various countries, utilizing specific elements of the integrated DTMF concept (Artschwager et al. 2022).

3. DTMF's Potential Contribution to Sustainability and Social Value

The TCI is faced with ecological, economic and social challenges of sustainability and is recently pushed to develop customer-oriented and sustainable value chains. Wherever sustainability aspects are significant, DTMFs provide good arguments in all three dimensions of sustainability because of their digital backbone (Tilebein 2019b).

The objective of this section is to show in general the potential of DTMFs to change the textile value chains in a sustainable way. In addition, different forms of positive impacts that a DTMF could make in local society are considered in this section justifying its capability of adding to social value.

3.1. Ecological Dimension of Sustainability

With respect to ecological and environmental aspects, the DTMF contributes to the current trend of ecological sustainability in production. The reduction of carbon footprint, waste, and material resources are central goals in this context.

Implementation of a DTMF process causes reduction of transport and logistics, compared to conventional processes, along the value chain, thereby decreasing the carbon footprint (Tilebein 2019a). The DTMF has a significant impact on reshoring, which involves relocating production closer to where products are purchased. By bringing production closer to the customer, the distance products need to travel is reduced, resulting in lower transportation distances, logistics costs, and environmental impact.

Moreover, in the case of larger series production, virtual engineering used in a DTMF plays a crucial role in minimizing transportation and production costs, particularly during the collection development phase. Through virtual engineering, designers can collaborate remotely, eliminating the need for physical transportation of prototypes and samples. This not only reduces costs but also reduces the carbon emissions associated with transporting materials and products. Additionally, even in cases where DTMFs act as partners in geographically widespread business ecosystems, the use of virtual communication and data sharing can significantly minimize transportation needs (Tilebein 2019a). By leveraging digital technologies, DTMFs can stay virtual for as long as possible, sending data files instead of physical products. This approach reduces the reliance on physical transportation, further lowering carbon emissions and environmental impact.

DTMFs offer significant opportunities for reducing overproduction and waste, promoting a more sustainable production process. Several key factors contribute to waste reduction in DTMFs:

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- Prototypes and simulations: DTMFs utilize simulation technologies to create prototypes on-site, replacing the need for numerous physical prototypes (Tilebein 2019a). This reduces the number of physical models required and contributes to waste reduction.
- Enhanced supply chain efficiency: Digital technologies employed in DTMFs enhance supply chain efficiency, minimizing instances of wrong deliveries and damaged goods. This optimization reduces resource consumption and mitigates waste generation.
- On-demand production: DTMFs minimize overproduction and the generation of excess inventory by producing goods on-demand leading to a significant reduction in waste generation.
- Implementation of virtual fitting and shopping advice: DTMFs can integrate virtual fitting and shopping advice, often powered by artificial intelligence (Tilebein 2019a). These tools empower customers to make informed purchasing decisions, thereby reducing the need for product returns and eliminating associated waste generation.
- Individualized made-to-measure products: DTMFs demonstrate potential in the production of individualized made-to-measure products, particularly in fashion and health textiles. This customization approach meets customers' expectations and lowers the number of product returns and respective waste generation resulting from issues such as poor fit or insufficient functionality (Tilebein 2019a).

Overall, DTMFs play a pivotal role in carbon footprint, material and waste reduction by minimizing transportation needs and overproduction, optimizing resource utilization, implementing virtual technologies, and producing tailored products on-demand. These practices contribute to a higher efficiency in material resource and energy use, thus enhancing ecological sustainability of textile products. For a more detailed assessment and quantification of digitalization's contribution to sustainability in a DTMF, there should be a model-based evaluation method with all sustainability indicators considered (Weiß et al. 2023).

3.2. Economical Dimension of Sustainability

From an economic perspective, the DTMF process facilitates manufacturing costs evaluation and poses more efficient value creation, flexibility, and customization of products and services. This automation, digitalization, and increased connectivity throughout manufacturing value chains leads to reduced lead times and costs (through efficient use of capital, resources and space), and enhanced quality.

Additionally, new sustainability-driven business models based on novel value creating mechanisms can achieve increasing customer satisfaction. The DTMF can be applied to various business models within both Business-to-Business and Business-to-Customer contexts to address challenges and drive profitability (Winkler et al. 2022). The foremost application is in response to customer demands for personalized products of high quality. This can be effectively achieved through the implementation of fast local value chains and organizational structures that capitalize on end-to-end digitalization, opening up new opportunities. Apart from small lot sizes, which is particularly relevant for product individualization, there are other promising applications and business models related to sampling, reordering, event-driven production, and locally centered manufacturing. These applications also benefit from the utilization of digitally networked end-to-end design and production processes (Winkler et al. 2022).

The consistent use of CAD and simulation makes entirely new designs possible here that were previously reserved for haute couture. This also makes the rapid, resource-saving production of small series and one-off items a realistic possibility (Tilebein 2019b). Furthermore, by increasing data availability and transparency in intra- and inter-firm logistics, lead and storage times can be reduced. As a result, logistics costs can be reduced significantly due to the end-to-end digitalization.

Although promising, DTMF-based business models could as well face archetypical challenges with regard to upscaling and growth. Among these challenges, the limits to success archetype could apply. In particular, different capacity restrictions and growth dynamics of process steps involved in the respective DTMF can affect perceived customer value and related purchasing behaviour (Martinez Jaramillo/Tilebein 2023).

Yet the economic advantages of DTMFs have sparked a noticeable trend among several fashion retailers towards adopting in-house manufacturing, often through the implementation of the Factory-in-Factory setting. This strategic decision enables retailers to exert greater control over their supply chain, while also reaping the benefits of accelerated speed to market and enhanced sustainability practices (McKeegan 2021).

In summary, DTMFs can contribute to economic sustainability by reducing manufacturing and logistic costs, enhancing value creation, and adoption of new sustainable business models.

3.3. Social Dimension of Sustainability

DTMFs offer improvements in the social dimension of sustainability, in addition to their ecological and economic characteristics. Customization applications play a key role in enhancing the social aspects of DTMFs. By offering personalized designs, colors, labeling, and made-to-measure products, DTMFs can meet individual demands and increase customer satisfaction.

The proximity of DTMFs to the consumer market provides several social benefits such as shorter delivery times, resulting in customer convenience. Moreover, this proximity allows DTMFs to have better control over labor relations, promoting social justice in the production of ready-made clothing.

DTMFs actively involve customers, motivating them to contribute to improving social sustainability. This engagement fosters consumer empowerment and a sense of responsibility.

Data transparency is another significant advantage of DTMFs that contributes to social sustainability. It enables DTMFs to focus on innovation and socially responsible production activities. By having access to transparent data, DTMFs can develop new channels and approaches that strengthen customer relationships, ultimately leading to competitive advantages.

Furthermore, DTMFs have the potential to expand into educational and hobby fields. This expansion opens doors for new users and cultivates the creative potential of the younger generation, which often faces limited opportunities for self-expression. Additionally, DTMFs contribute to training individuals who will assume manufacturing responsibilities in the future, ensuring a skilled workforce for the next generation.

In general, DTMFs improve social sustainability through customer satisfaction and engagement, data transparency as well as expansion into educational/workforce-training fields.

3.4. Social Value

Social value can be created by changes driven through Social Innovations (SI), which have gained a great attention in recent times (Eichler/Schwarz 2019). SI can be described as changing social relations, involving new ways of doing, organising, framing and knowing (Haxeltine et al. 2016). On European level SIs are granted the same importance as traditional innovations (Sabato et al. 2017). Thus, SIs are regarded as a solution for most of the challenging problems facing today's society and for mitigating inequalities inherent to traditional solutions (Cruz et al. 2017, Angelini et al. 2016).

Especially in a technology-driven environment, like DTMF, there is a high potential for SI, by offering new possibilities in developing individualised products in small lots or for niches. This covers new methods of working, new business models, new spaces of knowledge generation using DTMFs as design labs (creating emotional intangible values), making labs (transforming skilled labour into material value to increase the common good) and place labs (creating spatial, community and social values) and may lead to some extent to a transformation of the industry which is realized through a community supported by a digital platform.

4. Two Case Studies of DTMFs

This section aims to concretize the concept of DTMF by focusing on two key technologies: digital textile printing and 3D flat knitting, and the related DTMF workflows as outlined in Figure 1. Exploring the sustainability and social value contributions of these core technologies, will shed light on the practical implementation of DTMF and its potential to revolutionize the textile industry towards a more sustainable and socially conscious future.

4.1. DTMF with Printing

4.1.1. Process Description and Technologies

Factors such as dynamic market trends, evolving consumer preferences, customization requirements, sustainability concerns, reshoring initiatives, and technology-driven business models have propelled the adoption of digital printing (Artschwager et al. 2022). Conventional printing methods consume significant energy, water, and valuable resources. In contrast, the DTMF presents a sustainable manufacturing solution that incorporates digital textile printing, minimizing resource consumption and environmental impact (Artschwager et al. 2022). Table 1 highlights the main characteristics of analogue and digital printing through a comparison (Artschwager et al. 2022).

Analogue Printing	Digital Printing
Less flexible	Flexible and versatile
Expensive	Low inventory and risks
High pollution	Sustainable, lower water consumption
Simple repeating patterns	3D effects (high creativity)
Limited colors, gradation and details	Unlimited colors and gradation
Hard to personalize	High potential of personalization

Table 1: Comparison between analogue and digital printing

The development and implementation of DTMFs has enormous potential to trigger a fundamental change in processes within the TCI. This is also supported by developments in digital printing. Textile printing is one of the DTMF's core value creation steps, as it is very environmentally friendly, adaptable and can be integrated into digital design software (Artschwager et al. 2022). For ensuring a continuous digitally integrated workflow, the processes of the DTMF should be completed by digitalized communication between all value creation steps during the manufacturing. For this purpose, in the following, a full workflow of a production line in a DTMF that takes the digital textile printing as a core process will be explained:

3D scanning:

Technology for 3D body scanning can be used to create digital twins and virtual try-ons in a 3D simulation program. This can be applied in made-to-measure production and used to obtain body data on demand, which can then be integrated into existing processes. The scanner can replace traditional tape measurements with digital measurements on a personalized avatar. This enables the reuse and comparison of measurement data in the long term (Shen 2020).

3D design and simulation:

The design process begins with creating designs in CAD software that involve mapping digital versions of garments with realistic materials such as colors and textures onto virtual models. These avatars can be created using body scanning technology as described above to adapt and grade cuts to individual measurements (Artschwager et al. 2022). This realistic representation allows for the visualization of the interaction between the material, cut, and body, which can help in virtual fit analyses (Lin/Wang 2014), thereby reducing the number of physical samples needed and saving costs. After finalizing the design, a 3D simulation is used to prepare it for cutting out followed by Raster Image Processing (RIP) which is used for creation of a "print and cut" file (Artschwager et al. 2022). This file consists of multiple layers displaying various elements, such as contours and textures, and includes QR codes and position markers for accurate positioning during production (Artschwager et al. 2022).

Digital textile printing:

In the subsequent step, the fabrics are printed with unique designs using the digital printing process, which is the core process (Moltenbrey/Fischer 2021). In this specific DTMF process the necessary production files are directly generated from the 3D simulation environment. The RIP program mentioned earlier makes it possible to prepare the design data with accurate colors.

Automated cutting:

The DTMF uses QR codes and position markers to accurately identify the position of each component and the material during the cutting-out process. This enables fully automatic cutting of the material with the help of a camera (Artschwager et al. 2022).

Confection:

The final step in the DTMF process is to join the individual components together to produce the final product, which can be done using various methods such as sewing or ultrasonic welding machines (Artschwager et al. 2022).

Figure 2 summarizes the workflow of a production line in a DTMF, with digital textile printing as a core process (Artschwager et al. 2022).

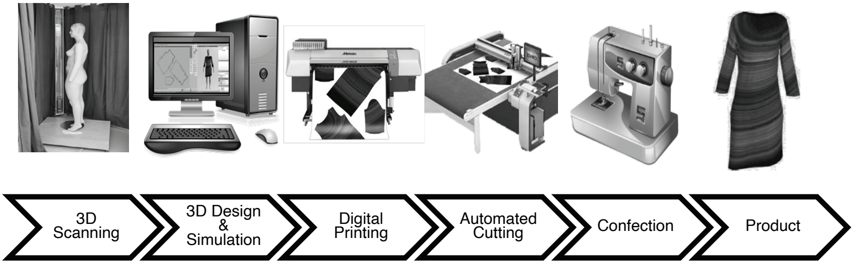

Figure 2: Workflow of a production line in DTMF, with digital textile printing as a core process

4.1.2. Contribution to Sustainability and Social Value

Digital textile printing makes significant contributions to ecological, economic, and social sustainability. In terms of ecological sustainability, digital printing reduces resource consumption by minimizing water, energy, and chemical usage compared to traditional printing methods (Tilebein 2019). It also minimizes waste generation through on-demand production, eliminating excess inventory and reducing fabric wastage. Additionally, digital printing enables design optimization and sampling through virtual design and simulation, reducing the need for physical sampling and minimizing material waste. The color accuracy of digital printing further enhances ecological sustainability by eliminating the product returns due to printing wrong colors on textile products resulting in less production of waste.

From an economic perspective, digital textile printing brings cost efficiency to the forefront. On-demand production eliminates the need for excessive inventory, resulting in cost savings and reduced material waste. The flexibility of digital printing allows for customization and personalization, meeting the changing demands of consumers and increasing market competitiveness. By enabling shorter lead times and local production, digital printing enhances supply chain control, leading to cost savings and improved speed to market.

In terms of social sustainability, digital textile printing contributes to enhanced customer satisfaction. The ability to customize and personalize products meets individual customer demands and preferences, fostering greater customer engagement. Microfactories that utilize digital printing, especially when located closer to consumer markets, can ensure shorter delivery times and maintain better control over labor relations, promoting social justice in production.

Integration of digital textile printing and modern online technologies while involving customers in the design process with the help of digital platforms and a digital intermediary of orders not only encourages consumer engagement but also empowers them to contribute to improving social value.

4.2. DTMF with Knitting

4.2.1. Process Description and Technologies

Another textile production workflow that has recently come in the focus of digitalization research is the workflow producing individual knitted textiles, such as knitted shoe uppers, knitted technical textiles, and knitted compression textiles suitable for sports and medical applications. This involves new digitalization concepts in product design and their direct coupling to manufacturing - in this case the knitting machine. In particular, this example of a DTMF can center around manufacturing individualized made-to-measure 2D garments (Šurc et al. 2020) as well as 3D flat knitting and utilizes new technologies that automatically convert scan data or CAD models into knitting patterns.

In other industries, additive manufacturing represents an important driver of innovation. With this manufacturing method, products can be developed and introduced to the market much faster. It already enables cost-effective and automated production of prototypes with minimal resource consumption (Rayna/Striukova 2015, Candia/Beltaguib 2019). 3D knitting as an additive manufacturing process also offers comparable potential due to its flexibility and the possibility of producing final contours directly.

On a flat knitting machine, 3D knitted fabrics with intricate, fully or partially closed, hollow-body-like structures can be produced in a resource-saving and efficient manner (Artschwager et al. 2017). Furthermore, with a 3D knitted surface, the fabrication of constitutive parts of a single product can be saved by knitting them once and all together, which significantly reduces the susceptibility to faults and the time required for post-processing. This has also gained acceptance on the market to the extent that many 3D knitted and, in some cases, individualized products are already being manufactured using this technology (Au 2011). However, conventional processes are characterized by a low level of automation, many trial productions and iterations between models and knitting programs without the possibility of direct interaction between the 3D model, material models and the digital twin of the product (McCann et al. 2016). Consequently, there is a lack of approaches that consider the complete manufacturing processes, starting with the creation of a 3D model, through the effects of material properties on the geometry of the knitted fabric, to global segmentation as the basis for robust algorithmic processing of the 3D model. This gap could be closed with the help of new 3D flat knitting process developed for DTMFs. Based on McCann et al. (2016), Narayanan et al. (2018), Wu et al. (2018), Popescu et al. (2018) and Liu et al. (2020), table 2 highlights the characteristics of both conventional and new 3D flat knitting technologies. In the following, we provide a comprehensive process description of the new 3D flat knitting process.

Conventional 3D flat knitting	New 3D flat knitting in DTMF
Limited to specific geometries and materials	Validity for a variety of 3D models and materials
No potential of individualization in production	Potential of individualization at the geometric and material level
Many trial productions and iterations between models and knitting programs	Rapid prototyping without the need for costly preliminary tests
Machine configuration dependant manufacturing system	Automated machine independent manufacturing system
Time consuming development	Low development time
Low degree of innovation	High degree of innovation
Low level of automation	Direct interaction between the 3D model, material models and the digital twin of the product

Table 2: Comparison between conventional and new 3D flat knitting

3D flat knitting is a resource-saving and efficient technology for textile production of 3D geometries. It is considered as a holistic approach across the entire production chain that would enable the application of 3D knitting as a universal tool for textile additive manufacturing and have the potential to revolutionize the knitting industry. This technology approach explores the necessary measures to prepare 3D geometries for the algorithmic generation of knitting programs, develop global segmentation approaches with validity for a variety of 3D models, and create a model to describe different materials. The aim of this technology in a DTMF is to develop a machine-independent production system that enables knitwear manufacturers to produce a wide range of products, starting from the 3D model, in small batches or individualized, in an automated and efficient way. In addition to knitwear manufacturers and manufacturers of technical textiles, mechanical engineering companies and software producers can also benefit from this technology.

3D scanning technology, CAD, material science as well as algorithmic processing of geometries represent the building blocks for this digitized manufacturing system for individualized textiles. The individual process components are partially available, their networking is possible in principle and can lead to an efficient overall process. The process model illustrated in Figure 3 links the aforementioned building blocks. The model first considers the creation of the triangulated surface of a 3D geometry. Depending on the material and the machine, the geometry is sampled algorithmically and transferred into a parameter set for the knitting machine. This parameter set is created in such a way that immediate production with the knitting machine is possible. Textile additive manufacturing technology is designed in such a way that the digital twin of the geometry (CAD model or 3D scan) and the material is created in the form of material parameters at the very beginning of the manufacturing process. The geometric digital twin of the product can be derived from the initial geometry by means of an algorithm. All subsequent process steps up to the creation of the knitting program must also be carried out digitally. Only in this way can the data transfer take place quickly and without errors.

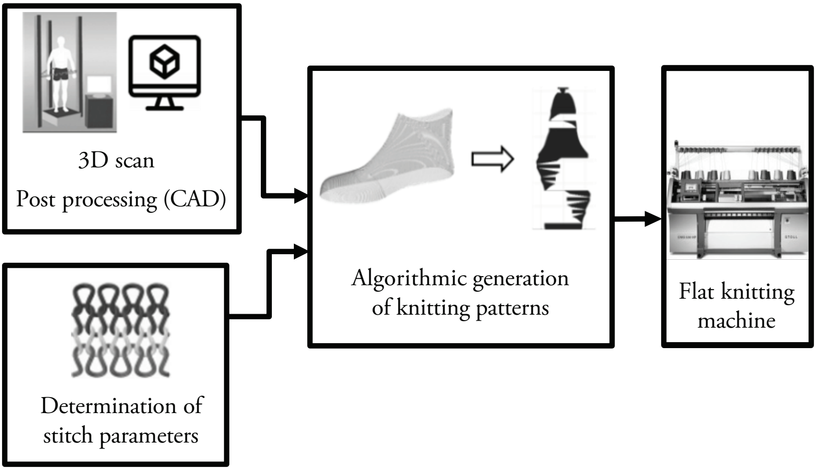

Figure 3: Overview of 3D flat knitting technology in a DTMF (example of knitted upper shoe)

The algorithmic generation of knitting patterns (jaquards) begins with an input mesh with user-specified knitting direction as well as stitch parameters (stitch height and width).

It remeshes the surface to create a row-column graph that represents the knit structure and finally translates it into stitch instructions that are scheduled for a flat knitting machine.

The innovation of this technology lies in the algorithmic interpretation of the 3D geometry as well as systematic holistic consideration of the knitted product, its properties and application, and the integration of these characteristics into the automation solutions. On this basis, production can be designed to be flexible and resource-saving for rapid prototyping and individualization.

4.2.2. Contribution to Sustainability and Social Value

Flat knitting machines are capable of producing near-net-shape finished products, eliminating waste and requiring little to no fabrication in subsequent steps. With the algorithmic processing of 3D geometry into knitting programs, the iterations between models and knitting programs as well as sample production can be largely eliminated. Additive knitting technology thus contributes to resource-efficient and environmentally sustainable production.

The automated creation of jacquards can then enable the development of new products as well as the production of individualized technical knits with significantly less trial-and-error leading to significant savings in production costs in the knitwear industry. The jacquard creation is done in a few minutes, time expenditure is only caused by the configuration of the machine and the production.

Not only can material, costs and time be saved, but at the same time the degree of innovation in product development can be increased by initiating new developments that are not directly based on experience from existing products. Investigating the influence of material properties on the shape of the knitted fabric also contributes to the development of production standards. Existing knowledge is thus systematically and continuously recorded and expanded.

Examples of technical 3D knitted fabrics with high individualization potential such as orthopedic knitted shoe uppers, seat covers for offices and wheelchairs, or therapeutic compression textiles show promising contributions to social sustainability. The potential user group of these knitted products including disabled or patient individuals in need of urgent medical assistance, can benefit directly from this technology when provided with individual service in a short amount of time.

3D flat knitting as a technical approach for individualization offers solutions for previously unaddressed or poorly addressed groups with very special needs which underlines its potential to add to social value.

5. Summary and Outlook

The textile and clothing industry is facing challenges such as increased customer individualization and the need for flexible value chains. Digitalization offers opportunities for innovation and addresses these challenges. The Digital Textile Microfactory is a flexible production system that enables decentralized manufacturing and on-demand products. It utilizes digital technologies such as digital textile printing or 3D knitting to create a digitally networked design and production process. Regarding its aim to explore the basic concepts and benefits of DTMFs, their impact on sustainability and social value, this paper's findings can be summarized as follows:

DTMFs, compared to conventional textile development and production, show a decent potential for improving sustainability in textile manufacturing. Besides of the economic dimension of sustainability leading to reduced costs and increased innovation in terms of different sustainable business models, there are ecological aspects related to e.g. reduction of waste and transportation needs. Also, the social dimension of sustainability can be improved by e.g. local or regional production being close to the customer. Plus, the DTMF technology itself can serve social value via serving customers with special needs, or use of a digital platform for plug-in micro-services, i.e. a platform whose aim is to include diverse stakeholders in the production process.

Besides having numerous benefits, implementing DTMFs include challenges such as technological aspects that need further development to broaden the range of possible products, difficulty for SMEs to catch up with the digital transformation, the need for new skills and organizational change, evaluation challenges in assessing sustainability potential in detail, and market challenges related to consumer behavior and the risk of rebound effects. Addressing these challenges will require collaboration among stakeholders and a joint industry approach to speed up the process of establishing digital models and case-specific parameters.

Future research could perform a quantitative analysis for each technology in DTMFs in order to provide specific evidence for ecological and economical sustainably of DTMFs and therefore encourage their adoption. Additionally, for supporting the social sustainability and also adding to social value, digital services and platforms could be developed and integrated within DTMFs to support the establishment of larger business ecosystems. Moreover, research is needed to further explore and specify sustainable business models, market trends, and consumer behavior.

More research is underway to address the remaining open questions, and to help these smart, sustainable and socially valuable new technologies thrive.

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