The refashion circular design strategy — Changing the way we design and manufacture clothes

M. Cristina Dan, Solve Studio, Bucharest, Romania

Andrei Ciortea, Institute of Computer Science, University of St.Gallen, Switzerland, and WIMMICS, INRIA, Université Côte d'Azur, I3S, Sophia Antipolis, France

Simon Mayer, Institute of Computer Science, University of St.Gallen, Switzerland

Approximately 65% of a garment's climate impact stems from fabric production. With 53 M tons of fibre produced every year and 87% ending in landfills, the fashion industry is polluting and wasting precious resources. Therefore, waste prevention and recapturing value become essential. Our research explores the development of a new circular design strategy (CDS) - Refashion, for service innovation through a design thinking process. Grounded in sustainable design strategies and advanced manufacturing technology, the Refashion CDS aims to enable multiple reutilization of fabric before fibre recycling. This is showcased via a proof-of-concept collection launched on the market in 2022, where three pre-designed multifunctional fabric blocks create 11 different garments, accompanied by a diagram showcasing the product-service system's closed-loop material flow.

Keywords: circular design strategy, sustainability, system(s) design, design practice, design thinking

The fashion industry, in particular the manufacturing of apparel, represents one of the most resource-intensive sectors that is employing a linear *take-make-use-dispose* logic in its mainstream. At present, approximately 65% of a garment's climate impact stems solely from the production of fabric: fibre, yarn, fabric and wet treatment (Mistra Future Fashion, 2019). As such, addressing the reutilization of fabric through a novel CDS would be an effective way to reduce these negative impacts. Moreover, the value of reuse surpasses that of recycling as the accumulated "burden" in a textile material increases with each production step; the more production steps that are replaced, the higher the environmental gain (Roos et al.,

Corresponding author:
M. Cristina Dan
studio@cristinadan.com

www.elsevier.com/locate/destud
0142-694X *Design Studies* **88** (2023) 101205
https://doi.org/10.1016/j.destud.2023.101205

2019). This is based on the circular economy technical cycle which (in addition to reduce, reuse, and recycle) includes repair and remanufacture and implies that a specific item passes through multiple loops (Ellen MacArthur Foundation, 2017) where the environmental gain increases with decreasing loop size. In the case of the fashion industry, fabric reuse would permit bypassing the resource-intensive production steps of fibre, yarn, fabric production, and wet treatment, which is the most energy consuming. Hence, fabric reuse surpasses fabric recycling which also implies material recovery, but instead of making use again of the material "as is", this loses value (through downcycling) while at the same time burdening the environment (through additional production steps).

1 Introduction

The new Circular Economy Action Plan[1] (European Commission, 2020) issued by the European Commission in March 2020 prioritizes the top of the sustainability chain – product design – as up to 80% of the environmental impact of a product is determined at the design stage, outlining the set of resources and production processes needed for each product (European Commission, 2009, 2020). To succeed in the forthcoming 15 years, manufacturers will need to change operating models in new directions through technological advancements, and structural industry shifts, as "three industry-wide trends will transform the consumer-goods landscape by 2030: vertical integration, digitalization, and cost leadership" (Krings et al., 2016, p. 3). Furthermore, extended producer responsibility schemes have been set in place by governments, holding companies accountable after the post-consumer phase.

Due to its current linear system and large investment in long-lasting equipment along the supply chain, the fashion industry tends to edit out innovation by favouring convenient practices that are supported by the already established procedures. Efforts within the industry hence mainly focus on optimizing the current regime rather than transformative change (Buchel et al., 2018). However, to strive against an environmental collapse that is bound to occur at the current status, radical change in design, production and consumption models is inevitable (Ceschin & Gaziulusoy, 2016; Earley, 2017; European Commission, 2020; Fletcher & Tham, 2019; McQuillan, 2020; Niinimäki, 2017). As Victor Papanek (1972) suggests, we might need to consider new aesthetics that develop as a result of human awareness for the environment. This implies fundamental adjustments to the current business model of clothing companies (Gwilt, 2014; Muthu, 2019; Niinimäki, 2017), as a circular approach proposes narrow, slow, and closed-loop resource flows (Stahel, 2016; Bocken et al., 2016). Fashion designers can have a significant positive contribution, but they are not yet equipped with the necessary knowledge, skills, and standing to support or even drive this shift (Dan & Østergaard, 2021; Karell & Niinimäki, 2020): they would need to develop and connect circular design strategies (CDS) to a circular value chain, the involved supply chain and manufacturing technologies, and a circular business model – requiring competencies that range from sustainability assessment to business model design and to industrial engineering. Furthermore, the work of designers should also have an ethical perspective, holding among the goals the intent to generate outcomes that benefit society (Lloyd, 2019; Manzini, 2013). These concepts are interdependent and necessary to consider in the development of a CDS for product-service systems. While circular business models can provide economic sense (i.e. value is economically recovered from a product) if aligned to a systems' capabilities and resources, the designers' ethical perspective offers a responsible, holistic approach towards the created system that benefits altogether people, planet, and profit.

This paper focuses on the development of a CDS for product-service systems that could be technologically integrated within a circular value chain—and then, systematically integrated into organisations and the workflow of designers. Product design and other systemic factors such as enabling technologies are essential (Bocken et al., 2016) and, as this paper shows, play a determining factor for scaling circular economies in the industry. The research objective of this paper is to design a solution that recaptures value from textiles and prevents pre- and post-consumer textile waste. We propose a novel approach to garment design and manufacturing through the use of a design system based on multifunctional fabric blocks that are dis- and re-assembled to form new garments. To support designers in applying this CDS, we intend to automatize the dis- and re-assembly of garments with automated planning. In this article, after giving an overview of product-service systems and discussing related sustainability-oriented design strategies in Sections 2 and 3, we detail this "Refashion" circular design strategy in Sections 4 and 5.

1.1 Sustainable product-service systems in fashion

Sustainable Product-Service Systems (PSS) are business innovation strategy offerings that meet a need by selling utility instead of providing a product only. This is achieved through a mix of product and services, in this manner creating the potential of minimizing the environmental impact (Ceschin & Gaziulusoy, 2016; Manzini et al., 2001). They have the potential to enable closed-loop resource flows by reusing products and components (e.g. through garment trimming reduction, clothing refurbishment, clothing remanufacturing) or by recycling materials (Zeeuw van der Laan & Aurisicchio, 2020; Larsson et al., 2019). Sustainable PSS require a combination of circular design principles, Internet of Things and data analysis techniques, advanced manufacturing ("Industry 4.0", especially regarding flexible manufacturing), marketing and communication strategy, stakeholder management (Bressanelli et al., 2018; Han et al., 2020; Larsson et al., 2019; Zeeuw van der Laan & Aurisicchio, 2020) —and are often based on adding connectivity, sensing, and analytics on top of formerly "dumb" products (Wortmann & Flüchter, 2015). There are three types of PSS: *product-oriented*, where services are embedded to the sold product; *use-oriented*, where the product is still the main offering but it remains under the provider's ownership; and *result-oriented*, where the provider sells results instead of products or services (e.g., Rolls Royce offers power by the hour). In the fashion industry, there is a significant amount of scientific literature and some application on niche markets focusing on product servitization for finalised garments. More specifically, in recent years in the fashion industry, product-oriented PSS (e.g. swapping and second-hand) and use-oriented PSS (e.g. fashion rental) have gained some popularity (Khitous et al., 2022). However, there is still little focus on servitization applied in the value chain. In our research, we aim to use sustainable design and flexible manufacturing technology as vantage points to develop and implement a novel circular design strategy (CDS) at industry scale. In addition to these, in order for a PSS to function, the development of a circular value chain needs also to be addressed.

1.2 Circular economy value chain for fashion based on PSS

The development of circular economy value chains (CEVC) requires collaboration, negotiation and co-creation amongst stakeholders across the value chain (Ehn et al., 2014; Moreno et al., 2016; Ellen MacArthur Foundation, 2017; Pedersen & Clausen, 2019; Goldsworthy & Ellams, 2019; European Commission, 2020). Highly specialized roles of industrial system stakeholder ask for collaboration in order to enable the circulation and cascading of resources (Blomsma et al., 2019).

A CEVC model supports its stakeholders to recapture value of products in various ways by reducing, reusing, repairing, redesigning, remanufacturing and up-cycling/down-cycling products and their components (Paras et al., 2018). Moreover, it is through their resource reconfiguration and the synergistic deployment of their capabilities that participating companies in the fashion value chain can enable the cycling and/or cascading of circular material resources (Blomsma et al., 2019). Bringing together diverse stakeholders from different stages of clothing product flows by engaging them in collaborative networks (Hultberg & Pal, 2021) can generate innovative circular business model scaling through critical insights via co-creation and build more inclusive societies through democratic participation (Institute for Urban Research, 2022; Manzini, 2013). A relevant example for such initiatives is the Portuguese Textile Cluster, where 60 members spanning across the value chain are engaged in close collaboration to streamline processes and promote sustainable development

(Clustertextil, 2020).[2] A precondition for close relationships and collaboration is proximity manufacturing or "point of use production", where stakeholders can work together to solve problems, drive the development of customized and high value-added fashion products, and facilitate fast delivery of new materials close to the place where they are needed: the point of use (Sirilertsuwan et al., 2018; Manzini, 2013). This is very well portrayed by Manzini through his concept of Cosmopolitan Localism (2013), where local flexible manufacturing through micro-factories are combined with digital distribution systems. Relevant examples for micro-factories in the fashion industry were the Adidas Speedfactories[3] in Ansbach, Germany and Atlanta, USA. Clothing micro-factories can enable in-house and on-demand production, thus minimizing inventory and textile waste from unsold products.

2 Building blocks for the novel CDS

After this portrayed overview of the general context in which the novel CDS could function, the following sections make enquiries on the sustainable design strategies to build on (see Section 2.1), sustainable clothing construction techniques (see Section 2.2), circular product and customer journey (see Section 2.3), and automated manufacturing (see Section 2.4).

2.1 Selected sustainable design strategies to build on

Design largely dictates the set of resources, infrastructure, processes and activities that will be committed for each product (Bocken et al., 2016; European Commission, 2020): As today's infrastructure was determined by the way the first garments were designed and produced at industrial level, we claim that designing differently now holds the potential to change the infrastructure to a more sustainable setup. The inherent reluctance to change today's working infrastructure is also the reason why we propose Refashion as an add-on to today's practices — and why it is created in close alignment with current manufacturing technologies and design tools: Permitting to keep using processes and machines that are already deployed, but on top enabling processes that close the loops.

Using as a starting point the first author's past work, the current research draws inspiration and user insight from two past projects: The Omdanne project which promotes product life extension through design for attachment and trust (i.e. emotional durability) and multifunctionality, where three biodegradable pieces of clothing can each be transformed *by the user* into over 10 styles (Vezzoli et al., 2022). Then, the S-bags project exemplifies the same design strategy by inviting the user to co-create through downloading the product design and using a novel standardized construction system that allows for local and flexible manufacturing (via laser cutting at makerspaces and assembly by the user) to make the products (Blum, 2021). While the co-design approach of these two projects can work for niche markets, for the mass market (and the

Image 1 Omdanne - one garment transforming into 7 styles by Solve Studio[4]

Image 2 S-bags - downloadable bags by Solve Studio

entailing environmental savings) a system that is mass-compatible is required. Hence, drawing from these two projects, the design features of multifunctionality, dis- and reassembly, and standardization for flexible manufacturing were considered as starting points in the development of the novel CDS.[4]

When designing for a circular economy, there are three main types of resource cycling: slowing, closing, and narrowing resource loops (Stahel, 2016; Bocken et al., 2016; Ellen MacArthur Foundation, 2012; Moreno et al., 2016) for which different types of design strategies apply. For the purpose of this research, a combination of design strategies for narrowing, slowing, and closing resource loops was considered as they are mutually reinforcing (Bocken et al., 2016). Narrowing resource flows aims at using fewer resources per product. Slowing loops addresses reutilization and product life extension, while closing loops focuses on material reutilization through recycling. A collection of sustainable design strategies was created from the framework developed by Bocken et al. (2016) on product design strategies, and TED's TEN developed by Earley et al. (Centre for Circular Design, n.d.), which can be seen in the table below (see Table 1).

Upon analysing these strategies, correlations of mutual reinforcement were made between initial design strategies (design for dis- and reassembly, and design for standardization and compatibility) that addressed slowing resource flows, and strategies that addressed narrowing resource flows and closing resource flows. The selected strategies are.

- Design for standardisation and compatibility: products with parts or interfaces that fit other products as well (Bocken et al., 2016);
- Design for (re)manufacturing and dis- and reassembly: products and parts can be separated and reassembled easily, increasing material and component reuse and separating materials entering different cycles (biological or technological) (Bocken et al., 2016);
- Design to minimise waste: decrease pre- and post-consumer waste, that among other measures includes zero waste cutting and avoiding making things that people don't want (TED's TEN, n.d.);
- Design to reduce energy and water use: decrease the level of embodied energy within products by addressing all stages of the lifecycle of textiles - production, use, and end stage (either disposal and/or re use of the material) (TED's TEN, n.d.);
- Design that explores clean/better technologies: replace or redesign systems of production with novel technologies so that it reduces environmental impact (TED's TEN, n.d.);
- Design for a technological cycle (Bocken et al., 2016) or design to dematerialise and develop systems & services (TED's TEN n.d.): products work as a service, undergoing various service loops (eg. repair) and are leased or rented, ensuring that ownership is kept by the manufacturer so that materials can be continuously recycled into new products. This type of design lies at the heart of PSS.

In the Omdanne project, product life-extension was achieved via users transforming multifunctional garments into various styles, In contrast, our

Table 1 Sustainable design strategies in the fashion industry based on TED's TEN (n.d.) and Bocken et al. (2016)

Narrowing Resource Flows	*Slowing Resource Flows*	*Closing Resource Flows*	*Lifecycle stage*
Design to minimize pre- and post-consumer textile waste			Production
Design for cyclability/Design for product life-extension (design for: maintenance & repair,upgradability, standardization & compatibility, dis- and reassembly)	Design for cyclability/Design for product life-extension (design for: maintenance & repair, upgradability, standardization & compatibility, dis- and reassembly)		Production, use, end stage
Design to reduce chemical impacts			Production
Design to reduce energy & water use			Production, use, end stage
Design that explores clean/ better technologies			Production
Design that looks at models from nature & history (biomimicry, societal habits in times of scarcity)	Design that looks at models from nature & history (biomimicry, societal habits in times of scarcity)		Production, use
Design for ethical production			Production
	Design to reduce the need to consume/Designing long-life products (design for attachment and trust, design for reliability and durability)		Production, use
		Design to dematerialise and develop systems & services/ Design for a technological cycle; Design for a biological cycle	Production, use, end stage
Design activism	Design activism	Design activism	Production, use, end stage

proposed novel Refashion CDS *transfers the creative multifunctional feature to the designer and the manufacturing stage*. This could be achieved by designing *garment components* - instead of the whole garment - to be multifunctional, and then utilize flexible manufacturing and disassembly to extend the life of the product and its parts. The user then would only have to return unused garments to be reused/repaired/remanufactured. This would decrease user-interventions in the circular life cycle of the product, while increasing the level of adoption for circular products by a wider range of users and thereby make Circular Fashion - and the environmental benefits this would entail - ready for the mass market.

Furthermore, the novel Refashion CDS would bring together, for the first time, sustainable design strategies that address *all types of resource flows* (slowing, closing, and narrowing), increasing efficiency for material recirculation at each stage of the product's lifecycle.

The next section will look into various ways of garment construction.

2.2 Sustainable clothing construction techniques

Garments can be constructed in multiple ways so that they produce little to no waste. Five methods have been identified: full cloth wrap and drape, cut-and-sew, fully-fashioned, A-PoC (A Piece of Clothing), zero-waste pattern cutting, and modular textile systems. Each of them are described. While other creative sustainable construction techniques exist, these are the ones that can be widely replicated in design studios and possibly at industry level with currently available technology.

2.2.1 Full cloth wrap

Rectangular fabric cloth was utilised in ancient times, by wrapping it around the body and draping, without any cuts or stitches. The garments had to be assembled every time when dressing and pins and rope were used to hold some of the garments in place. In ancient Rome, the toga was constructed out of a single rectangle of woven wool fabric. In Hellenic clothing, the doric chiton, peplos, himation, and chlamys were also manufactured out of a single rectangle (in different sizes) of woollen or woven fabric that was draped and wrapped around the body (Bingham, 2005).

Multifunctional fabric cloths emerged together with the Indian sari, where an unstitched draped woven fabric would take various forms and styles on the body (Katiyar, 2009). Usually worn together with a fitted bodice called a choli and a petticoat called ghagra, the sari was tucked in or pinned close to the body for assembly. Knots were also used to secure the fabric in place.

The Japanese kimono and the Arabic djellaba, also manufactured out of woven rectangle fabric, manifested a new paradigm in clothing design and manufacturing: This introduced multiple rectangles, straight cuts, and stitching, with minimal fabric waste. The new method of construction was cut-and-sew. The sari, the kimono and the djellaba remain to this day highly popular garments with a high rate of utilisation, offering timeless sustainable design and construction technique.

2.2.2 Fully-fashioned

Fully-fashioned construction is commonly used in the manufacturing of knitted garments. The process consists of knitting the garment pieces individually and then sewing them together, with no fabric cuts involved. A more technologically advanced version of fully-fashioned became available in the mid 1990's called seamless knitting, where a machine knits a garment in its finished 3D shape, requiring no sewing actions (Rissanen, 2013). Fully-fashioned and cut-and-sew are to this day the most popular methods of manufacturing at industry level (Rissanen, 2013).

2.2.3 A-PoC

The late 1990's introduced **A-PoC** (A Piece of Cloth), an innovative outfitting system with knitted garments by Issey Miyake and Dai Fujiwara (MoMa, 2022). The manufacturing technique resembles seamless knitting, in that it knits a circular tube and joins its front and back in specific areas so that it creates a cavity within the tube (Rissanen, 2013). The distinctions between A-PoC and seamless knitting is that A-PoC uses warp knitting as opposed to weft knitting done in seamless knitting (Black, 2002), and the fact that A-PoC leaves the task of cutting off the extra fabric to the user, offering as well the opportunity to the user to customise the products this way.

2.2.4 Zero-waste pattern cutting

Zero-waste pattern cutting uses the same approach as cut-and-sew, but while avoiding any fabric waste (McQuillan, 2019). As Rissanen (2013: p 35) describes it, "the pattern pieces interlock on a length of fabric; no waste is therefore created". Two of the most prominent proponents of this technique are Timo Rissanen and Holly McQuillan.[5] McQuillan goes on to develop zero-waste system thinking (ZWST) which she defined as "a posthuman, transition design posture or lens that argues for a wider frame of reference beyond that of the design of the form and aesthetics of a product. Design enters into the realm of 'how things ought to be' which in ZWST centres the Earth." (McQuillan, 2020, p. 4). She proposes a new method for whole garment weaving, potentially viable in the context of Manzini's Cosmopolitan Localism (McQuillan, 2020). This new method is similar to A-POC but with a focus on weaving instead of knitting and it proposes 3D weaving via a digital jacquard loom, thus enabling micro-factories to manufacture whole garments on the loom, with no fabric waste.

2.2.5 Modular textile systems

Modular textile systems use small (approx. 2–6 cm wide) standardised units that can be combined by the user in various configurations to generate different shapes (Chen & Lapolla, 2020). The systems encourage user participation in the design process as they are part of the *maker* or *do it yourself* (DIY) movement where modular toolkits are made available to the end-user (Hur, 2015). Notable examples of such systems come from Eunsuk Hur[6] and Chanjuan Chen,[7] where they use interlocking units designed using principles of symmetry, tessellation and geometric shapes (Chen & Lapolla, 2020; Hur, 2015). Assembly takes place via laser-cutting the units and manually assembly and disassembly by the user without the need of sewing, similar to the S-bags project.

While these methods produce little to no waste, disassembly and re-use of fabric is limited as well as industrial scaling. The full cloth wrap relies on time-consuming manual fitting which makes it difficult to scale. Moreover, should the piece of fabric suffer stains or rips, it could not undergo disassembly and replacement of the affected part and hence the entire garment would be unusable. For fully-fashioned garments textile waste is prevented, however disassembly and re-use of fabric is not possible due to specific tailoring. The A-PoC technique produces textile waste when the garments are cut out from the main tube and the garments cannot be dis- and re-assembled. The zero-waste technique avoids fabric waste effectively during the design and manufacturing stage, as does the whole garment weaving, however it does not offer the possibility to reuse the fabric for other designs via dis- and re-assembly. Finally, the modular textile system allows for dis- and re-assembly of garments, however the process is highly time-consuming due to the size of the interlocking units. Moreover, this construction technique confers a niched aesthetic and allows for limited functionality of the garments thus making it suitable mostly for haute-couture clothing.

Drawing inspiration from these construction techniques, our novel Refashion CDS would come under the form of a circular zero-waste creative design system where a collection of reusable standardized compatible components can be assembled, disassembled, and reassembled together to build N-numbers of products. As these components are the building blocks of the system, we call them fabric blocks. In this way, the design system would enable a PSS and a circular value chain that is suitable for broad deployment.

2.3 *Refashion: user/garment journey*

In order to better comprehend the complexity of the Refashion system, an overview of a possible journey of one garment through its multiple life cycles will be briefly depicted below. Of course different scenarios can take place apart from the presented one.

A dress composed of two fabric blocks is assembled and sold as a first-life product. Alongside the purchased garment, the user is also offered the possibility of a buy-back service that will offer her store credit amounting up to e.g. 20% of the initial value of the product. This acts as an incentive to the user to consider returning the product to the company once she no longer wants to wear it. Once recovered after several months/years, the dress is evaluated via a thorough inspection, washed, and since it is in good condition, moves on to be sold as a second-life product at a reduced price. Once returned by the second user, the dress is evaluated again and, since one fabric block is slightly damaged, it is classified as a medium-grade product and will undergo repair. Then, it goes back to being resold as a third-life product at a reduced price. One more year has passed and the dress is returned. One of the fabric blocks is severely damaged while the other one is in good condition. So, the garment passes as a medium-grade product and moves on to be disassembled so that the damaged fabric block is replaced, as the dress is still in demand. It is then resold as a fourth-life product. Meanwhile, the damaged fabric block is sent to be recycled via fibre-to-fibre recycling. Another year passes and the dress is returned again to the company; this time being evaluated as a low-grade product, as one fabric block needs a small repair while the other is severely damaged. The dress is sent to be disassembled, the former fabric block is determined to be useable, and so it is added to the fabric block library as available and ready to be used, while the latter fabric block is sent for fibre-to-fibre recycling. The company checks to see if the dress is still on demand and if not, new combinations of fabric blocks are proposed to generate other garments that are on demand or create new designs.

2.4 *Industrialization of sustainable fashion*

Industry 4.0 technology is widely seen as one of the key enablers for a circular economy (Bressanelli et al., 2018). In what follows, we introduce from a technical perspective the key developments that can support the industrialization of sustainable fashion and the core novelty of our Refashion CDS: mass-market readiness of circular fashion through multifunctional garment components and the integration of all types of resource flow enhancements (slowing, closing, and narrowing). We identified digital technologies for creating and capturing value from product-service offerings across two main processes: (a) enabling the automatic assembly and disassembly of garments from fabric blocks through the dynamic configuration of manufacturing devices based on automated planning, and (b) monitoring the current state of resources and resource flows for informing *both*, the manufacturing systems and the creation of new garment components and designs already at the design stage.

The fourth industrial revolution, often referred to as "Industrie 4.0" or "Industry 4.0" (Kagermann et al., 2013), emerged in close relationship with developments in the Internet of Things (IoT). Industry 4.0 promotes the networking and interoperability of industrial devices, and the decentralisation of decision processes in manufacturing environments. Most relevant to our current investigation, these developments enable the dynamic reconfiguration of manufacturing systems: As we are witnessing an accelerating trend towards highly customised products across a broad range of industrial domains, higher interoperability among manufacturing devices (from logistics systems to handling robots to machines that process the goods directly) permits the replacement of devices by functionally similar ones, thereby creating the technical foundation for more flexible manufacturing; at the same time, the decentralisation of decision processes leads to individual sub-processes becoming more autonomous, permitting the flexible replacement of entire functional units: Industrial manufacturing systems thereby assume more and more properties that are traditionally ascribed to software rather than hardware, which permits patterns that were originally reserved for software processes (e.g., rearrangement, refactoring, library-based integration) to also be deployed in this domain. For industry, this (among others) enables the production of items in lot sizes of as little as a single item at the price of mass-produced goods, i.e. mass customization. This evolution challenges the current practice of designing, verifying, implementing, and commissioning manufacturing lines with long target lifespans (e.g., of more than thirty years). Such manufacturing systems are well optimised for mass-production, but they are also tightly coupled and can hardly be reused or reconfigured for new products: even small variations in the design of a product usually require a complete re-engineering of the manufacturing line. In contrast, mass customization calls for the rapid and dynamic reconfiguration of manufacturing lines. Over the past decade, we have seen the introduction of such higher flexibility in the clothing and apparel industries: 3D printing has enabled sports shoes manufacturing to simplify the manufacturing process while increasing its flexibility and reducing cost - the core of this transition is the move from expensive (hardware) moulds to less expensive but much more adaptable (software) models (Berman, 2012). Regarding clothing products, microfactories have emerged that integrate different manufacturing flows (print-on-demand, digital textile cutting, sewing) and deliver their products for diverse brands.

While we argue that both these developments support our proposed Refashion CDS, the programming of these processes and especially of their integration to create complete products are today still done manually and do not include sustainability as a core nun-functional property of the manufacturing design. To automate this process while integrating sustainability targets, we propose that Refashion (and similar systems) should be enabled with the ability to automatically synthesize manufacturing plans and execute them. Such dynamic reconfiguration of manufacturing lines poses many challenges and has been a major topic in academic research for several decades (Koren et al., 1999). In discrete manufacturing, and hence very relevant to clothing, one central challenge is plan synthesis for product *assembly*. To illustrate this problem with a concrete example, in previous research we investigated the automated assembly of furniture (Ciortea et al., 2018; Mayer et al., 2016): plans for assembling furniture items are synthesised automatically from a specification of the final product and are then executed by collaborative industrial robots. An assembly plan in this context is defined as a sequence of operations that is applied to a set of components to yield the final product. Such assembly plans can be synthesised using methods for automated planning (Ghallab et al., 2004), a branch of AI research with a long history and with applications ranging from industrial manufacturing (Bourne et al., 2011) to digital service composition (Sheng et al., 2014). To synthesise an assembly plan, a planning system requires as input formal specifications of (i) the product to be assembled, (ii) a set of candidate components for the final product, and (iii) a set of atomic operations that are provided by the manufacturing environment and can be used in the assembly process. The same approach could be applied to create a zero-waste system in the fashion industry, in which garments are assembled automatically from predefined fabric blocks and, when no longer needed, dis-assembled for fabric block reuse.

Flexible manufacturing and disassembly at industry scale is, however, only one of the important technical components of a sustainable fashion CDS. In addition, this requires systems that track the flow of fabric pieces, systems that automatically analyse the state of products that are returned by customers, and systems that feed back this information to designers. The latter could be enabled through plug-ins for fashion design program such as CLO3D[8] and would permit designers to evaluate the sustainability of a new design, as these plug-ins could simulate the environmental impact of this design in terms of new fabric blocks that are needed in addition to those already in circulation. To deliver this information, i.e. to gauge the number of fabric blocks that are currently on stock or deployed with customers (and their current configuration in garments), existing tracking technologies could be used, where we believe that a CDS does not require the physical tracking of goods (e.g., through RFID tags) but that it is enough to virtually track sales of garments at the point of sale. The final component that our approach builds on and where we have witnessed large advancements over the past decade is the automated analysis of (returned) garments and their fabric blocks. Given large enough sample sizes, we can today employ computer vision systems that are trained on analysing fabric condition (Rasheed et al., 2020) where, recently, region-based convolutional neural networks (R-CNNs) have been shown to clearly outperform human evaluators (Wu et al., 2021).

3 Approach and method

The methodology of this research follows a design thinking approach. It is based on an iterative practice, under the form of practice-based research. The novelty we introduce with this paper is a creative system constructed through an exploratory experiment that is undertaken to see what follows by probing to get a feel for things and discover something new (Schön, 1983). This experiential learning process entails concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kolb, 1984, 2015), stages that have been applied in the creative process of this research.

The design thinking methodology proposed by Stanford University's Hasso Plattner Institute of Design, frames design as solving complex problems that are ill-defined (Brown & Wyatt, 2010; Vaughan, 2017). It involves five stages that undergo a non-linear process: empathizing, defining, ideating, prototyping, and testing (dschool.stanford.edu, n.d.). These stages accommodate for a better understanding of human needs, the creation of multiple ideas in multi-disciplinary brainstorming sessions, and a hands-on approach in making and testing. As such, design thinking facilitates collaborations that ease tackling multi-dimensional problems (Lloyd, 2019). Furthermore, systems thinking was applied throughout the process, as the CEVC based on PSS needed to have a holistic approach. Systems thinking (Meadows & Wright, 2009) aided in exploring the interconnectedness and interdependencies of parts within the CEVC, and helped to model a system's dynamics focusing on material flows.

An overview of the approach towards conceptualising, ideating on, prototyping, and testing of Refashion is given in Figure 1: The empathic understanding of the issue at hand was done both through user feedback from the Omdanne and S-bags projects (see Section 2.1) and from reviewing existing literature. Discussions with users from the previously mentioned projects suggested that a lesser implication on the user side regarding design and construction could encourage considerably more users to adopt circular products. Building on previous design work and after reviewing existing literature on sustainable and circular design strategies, the information was synthesized and the core problem was defined after several iterations. The design researcher and practitioner framed a possible design solution by applying systems thinking. This approach helped make informed decisions on the right design strategies to consider for the PSS but also consider the context in which the PSS would function (e.g., taking advantage of existing processes in the linear value chain, and enhancing them with novel technologies). After framing a possible design solution by the designer, discussions were carried out among the multi-disciplinary team, practising systems thinking to generate holistic solutions from both a design and a technological perspective (especially with respect to technological feasibility). Having established technological possibilities and delimitations, concrete experiments of garment building were conducted by the designer by cutting and draping fabrics on a small-scale mannequin and subsequently on a 1/1 scale mannequin following an iterative sequence of experiment, reflection, and action. During these experiments, among others the process involved firstly creating 2D patterns that were afterwards used to generate designs. In other words, it was designing with patterns rather than the conventional process of designing and then creating the pattern. Aside from only one rule – no cutting into the established pattern, no other rules applied: there was no "up" or "down", "right" or "left". The patterns had movement, they could rotate in any direction, twist, fold, or get knotted. A one-year iterative process, sometimes with many weeks of reflection that do not directly yield insights, finally gave form to the final outcome presented in the next chapters: Refashion. The intention is that by making the designer's own understanding of this experience accessible to other designers and researchers, they might learn from it too and ultimately practice it.

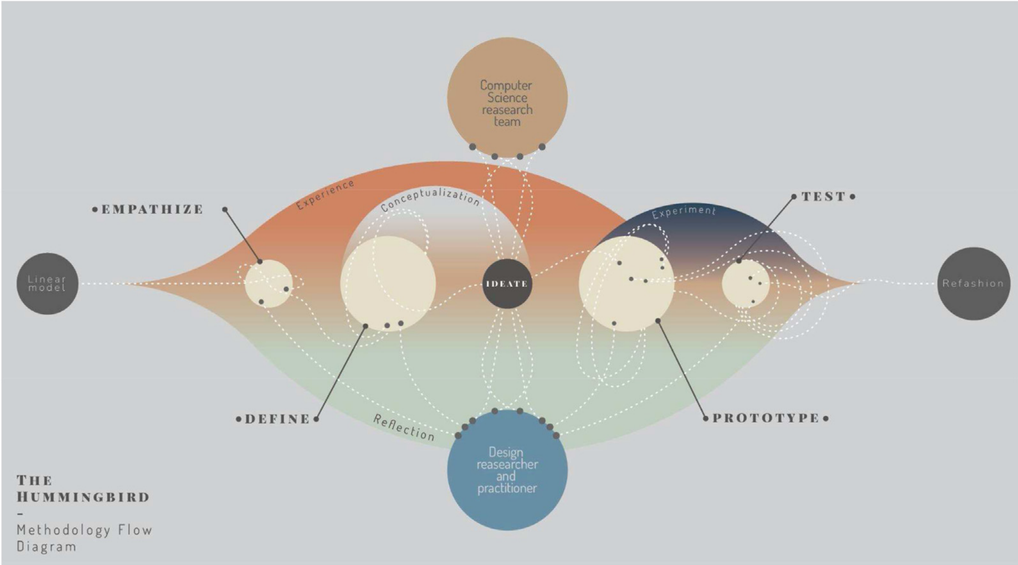

Figure 1 Phases and trajectory of the practice based research process. Diagram developed by the first author. Graphic design refined by Vlad Osiac

4 A new circular design strategy to Refashion garments

Based on the framework developed by Bocken et al. (2016) on product design strategies and TED's TEN developed by Earley et al. (Centre for Circular Design, n.d.), a hybrid CDS bridging six sustainable design strategies was generated. The designed strategies utilised were: *design to reduce energy and water use*, *design for standardisation and compatibility*, *design for (*re*) manufacturing and dis- and reassembly*, *design for a technological cycle* or design to dematerialize and develop systems & services, *design to minimise waste*, and *design that explores clean/better technologies* (see Section 2). In terms of manufacturing, four techniques were combined: *full cloth wrap* and drape, *cut-and-sew*, *zero-waste pattern cutting, and, to some extent, the modular textile system*. Following the development of the novel CDS, a proof of concept collection was created to showcase the textile servitization CDS's viability and commercial potential.

The Refashion circular design strategy is a design system based on standardised multifunctional textile modules that are compatible with each other, called *fabric blocks*. The proof-of-concept collection was created utilising three multifunctional fabric blocks, out of which eleven different styles were generated: a top, four dresses, two skirts, a bolero, two jumpsuits and a reversible jacket. This showcases how versatile the pre-designed fabric blocks are. Each garment can be easily disassembled, redesigned and remanufactured into another style (see Image 3).

Image 3 Selection of 6 styles from the Refashion proof-of-concept collection developed by the first author. Photography by Alexandra Petcu

This section is structured as follows: Section 4.1 presents the Refashion CDS in terms of manual assembly and small-scale manufacturing for refashioned garments. Here we focus our discussion on fabric block zero-waste pattern cutting, utilised fabric, and fabric block libraries. Section 4.2 presents the Refashion circular economy value chain for PSS to offer a holistic system's perspective. Section 4.3 presents the envisioned integration of the Refashion CDS at an industry level where the manufacturing techniques in Industry 4.0 systems are explained. To illustrate the complete life cycle of a refashioned garment, we present a user and garment story in Section 4.4.

4.1 Refashion CDS for manual assembly and small-scale manufacturing

4.1.1 Fabric blocks

The fabric blocks are the atomic building blocks of every collection. They are standardised multifunctional compatible textile modules. In the fabric block design, the fabric width was firstly considered. In order to achieve a zero-waste design, the fabric blocks have simple rectangular shapes that interlock on the length of the fabric, sharing the same cut edge. The three pre-designed blocks used to create the Refashion collection are shown in Figure 2.

For the piece of cloth to be reutilized multiple times, it had to be pre-designed with multifunctionality and compatibility in mind, executing all actions of

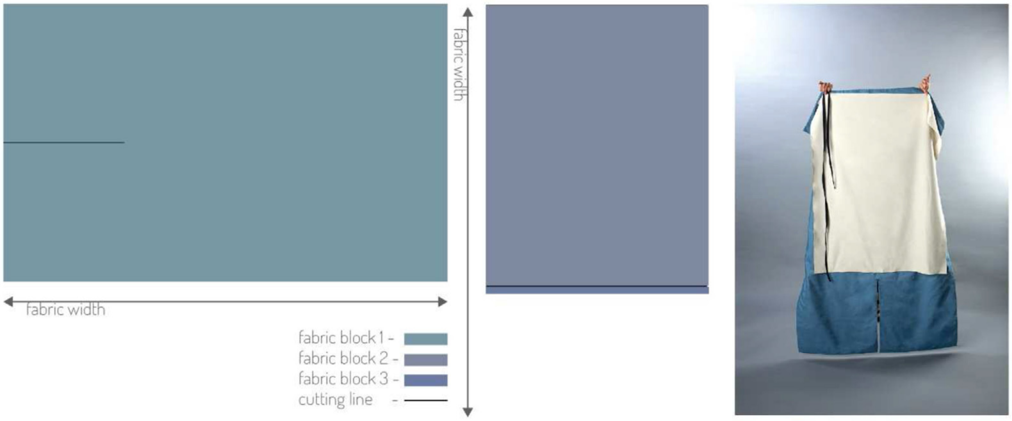

Figure 2 Pre-designed fabric blocks. Digital representation by the first author. Photography by Alexandra Petcu

cutting in the stage of manufacturing it, so as to prevent further cutting in the garment manufacturing stage and therefore keeping the fabric block intact for reuse. Various combinations of two fabric blocks are exemplified in Figure 3: utilising only fabric block 1, a jacket, a kimono and a jumpsuit were created. By adding fabric block 2 to the design and assembly process, two dresses and another jumpsuit were generated.

In the future, fabric blocks could be woven into the final shape. This would allow for further personalization (e.g. prints that can have both aesthetic function and help the assembly process via colour-coding), increase structure of the fabric block, and speed up manufacturing.

Woven fabric was utilised for the proof-of-concept collection. The aim was that all chosen fabrics had a mono-material composition, having in mind the fibre recycling stage. While two of them are made out of 100% Global Organic Textile Standard (GOTS) certified cotton, the third has a Tencel lyocell - GOTS cotton mix (due to the limitations of the 2021 market). All fabric blocks are designed for disassembly, utilising dissolvable thread technology (e.g. Resortecs[9]), to be easily separated for fibre recycling. Sewing tests were conducted in order to ensure that no needle marks remain when the fabric blocks are dis- and reassembled and the results were promising, allowing for multiple reutilizations.

To keep track of available fabric block designs and the styles they can create by themselves or in various combinations, a fabric library will be available for designers, utilising standardised identification solutions for traceability (see Section 4.3). To prevent manufacturing garments that users don't want, only styles that are on demand would be made-to-order with readily available

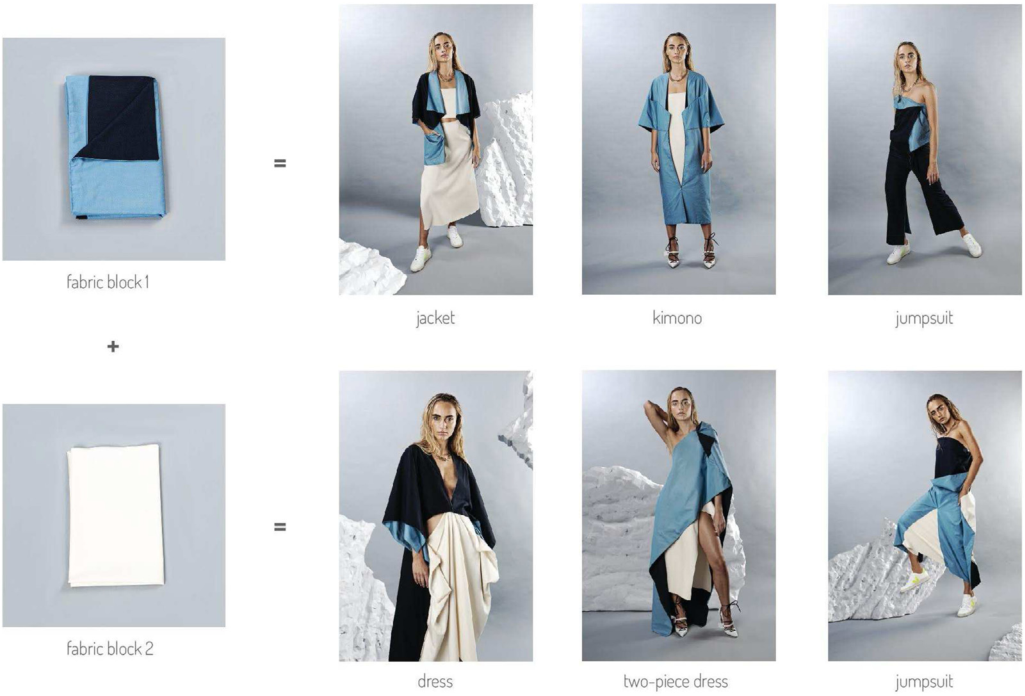

Figure 3 Various combinations of fabric blocks and the garments they create. Digital representation by the first author. Photography by Alexandra Petcu

fabric blocks (see Section 2.3). This would also allow designers to forgo a garment inventory.

4.1.2 Manufacturing for refashioned garments

The current manufacturing stages presented below are designated for manual assembly and small-scale manufacturing, with no textile waste generated. An easier way to understand the production process from fabric to garment can be seen in Figure 4 where a simplified formula composed of materials and actions is presented.

4.2 The Refashion circular economy value chain for PSS

This chapter zooms out for a holistic system's perspective. The CDS is designed to be implemented by automating recovery and manufacturing processes at industry level. For this purpose, a mapping of the material flow has been designed to showcase the resources, activities, processes, and infrastructure (see Figure 5). Essentially, it is a contouring of the circular economy value chain (CEVC) for the Refashion CDS, called from here onwards the *Refashion system*. Processes are distinguished between existing processes, future manual and automated processes, and future automated processes.

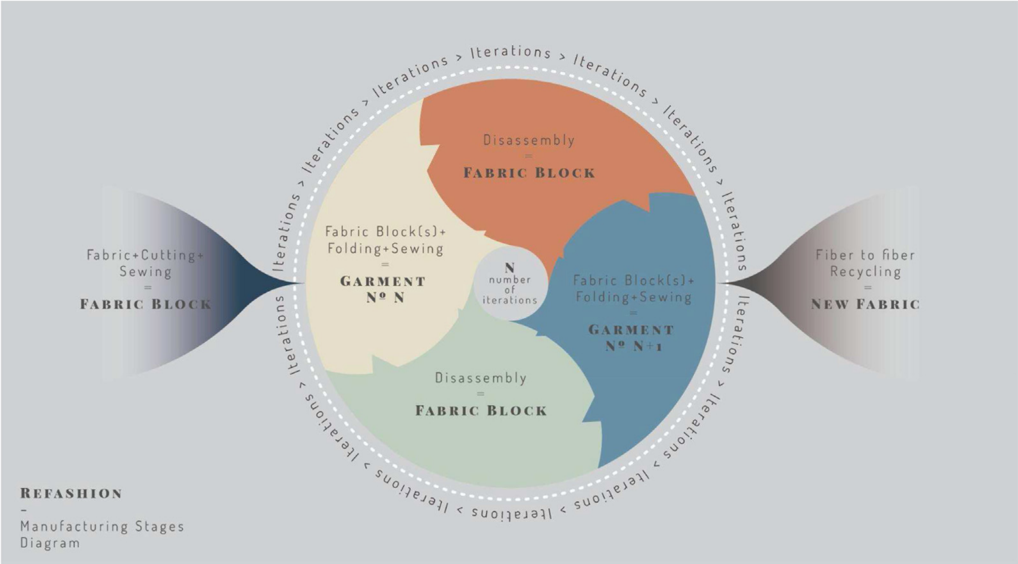

Figure 4 Refashion manufacturing steps for manual assembly and small-scale manufacturing. Diagram developed by the first author. Graphic design refined by Vlad Osiac

Consequently, these also determine the CEVC stakeholders and their roles. For example, for the stage of in-store collection partnerships can be formed with existing services such as I:CO[10] and similar take-back systems. Whereas for fibre-to-fibre recycling, partnerships with companies such as the Swedish Innovation Platform for Textile sorting (SIPTex[11]) and post-consumer textile recycling companies (e.g., Södra[12]) can expedite the process.

When determining what internal processes are automated and which are not, various considerations were also taken in regards to the social dimension. Technology can aid the human element, creating a synergistic collaboration, rather than an infringing or disadvantageous effect from a social perspective. For example, repetitive actions that require a large amount of data processing such as determining the number of available useable fabric blocks and their types, can be a completely automated process. Human contribution is reserved for creative processes or details that require human understanding and evaluation (e.g., creative repair of damaged blocks). These details were discussed during the multidisciplinary sessions and considerations based on explicit argumentation lied at the heart of each decision as technology ultimately must be used with the end-purpose of generating human wellbeing.

4.3 An envisioned integration of the Refashion CDS at an industry level

We argue, and aim to demonstrate in follow-up work, that the Refashion CDS can be realized at industry scale. This would not only permit corresponding

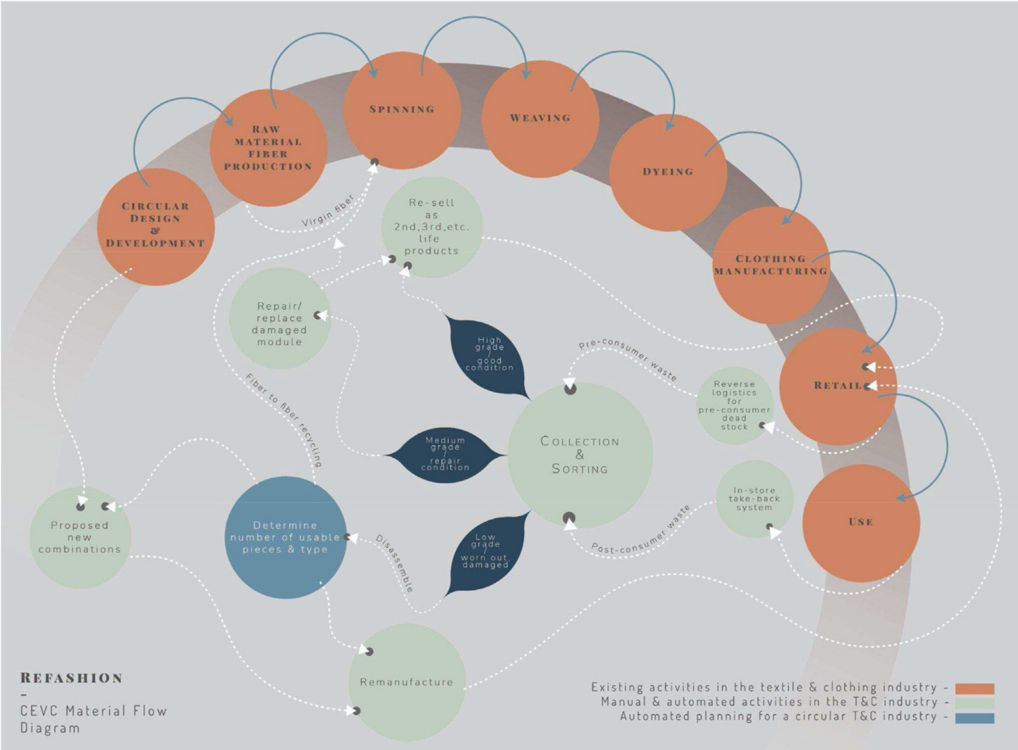

Figure 5 CEVC material flow diagram of the Refashion system developed by the authors. Graphic design refined by Vlad Osiac

cost savings through scaling up, but would specifically reduce the implication of users/buyers in the system — that is, we are proposing industrialization also to create an interface to users that they are already familiar with. Rather than involving users more in the design and logistics processes, this would merely require users to return unused clothes, which is already being implemented by large fashion chains (e.g., through refund schemes). Specifically, we propose to apply techniques similar to those that enable lot-size-one manufacturing in Industry 4.0 systems to the assembly and disassembly of garments. We argue that, in the same way as how such more flexible methods are applied to discrete manufacturing, assembly plans (e.g., seam paths) could be synthesised automatically using AI techniques such as automated planning (Rogalla et al., 2018; Ciortea et al., 2018) and then transferred to CNC sewing machines for execution.

Towards enabling this industrialization, we have already catalogued the steps required for manual assembly (see Section 4.1) and verified that it is possible to use these as components of *Bills of Processes* (BoP) that are applied to the Refashion blocks (which form *Bills of Materials*; BoM) to create specific pieces of the Refashion collection. Based on this possibility, we will in a next step—and with the support of industry partners, e.g., manufacturers of CNC sewing machines—implement and test the automated virtual and physical assembly of blocks to garments. After assembled garments have passed the point of sales, have been used/worn by customers, and have been returned to a collection point, we propose to disassemble the returned pieces and then analyse the resulting individual fabric blocks using already available technology (cf. Wu et al., 2021), where the disassembly can be enabled through the introduction of suitable techniques, such as dissolvable seams. By collecting this information from, ideally, all nodes of the circular chain (manufacturing, assembly, point of sale, point of collection, disassembly) based on well-established backend systems such as GS1 Electronic Product Code Information System (EPCIS),[13] we are furthermore able to *trace* assembled pieces as well as individual blocks through the circular value chain, which forms the basis of engaging designers in the Refashion CDS. This approach, and especially the involvement of globally standardized systems such as EPCIS, brings the potential to re-use recently widely deployed systems for increasing logistics transparency for advancing the fashion industry.

In addition to automating the manufacturing of garments, our technology-driven approach aims to lower the entry-barrier for adopting the Refashion CDS through specialised software, to support new creative designs, and to enhance sustainability by optimising the distribution and usage of fabric blocks across geographical areas. Designers today predominantly use standard tools such as Adobe Illustrator to make 2D technical sketches, and in recent years 3D visualisation and simulation softwares such as CLO, Browzwear[14]or Optitex.[15] The latter three are used to create true-to-life digital samples that bypass physical production of garment samples before they go into production (which is costly, time-consuming, and damaging for the environment). Realistic draping directly on the avatar may allow the designers to play with pre-designed fabric blocks and test new designs by combining them in various configurations.

However, no currently available design software aims to provide sustainability hints to designers. Our Refashion CDS, on the other hand, enables the creation of a user interface that will support designers in taking more sustainable design decisions based on the collected information about currently circulating fabric blocks: The system hence might nudge (or even regiment) the designer to (re)use a specific type of fabric block that it knows is in high supply at the moment, so as to avoid that many new fabric blocks need to be manufactured to realise the envisioned design. Furthermore, the system will aim to exploit the automated synthesis of assembly plans in order to lower the entry barrier for adopting the Refashion CDS: The user interface will allow designers to draft garments while leaving the system responsible for finding a viable assembly plan that yields the envisioned design—or an approximation of the envisioned design—from the set of available fabric blocks. Such tooling would allow fashion designers to adopt the Refashion CDS in a rather straightforward manner. In addition, the technologies used for synthesising assembly plans can also further enhance creative design: Once designers have an approximate design for their garment, the system can generate variations of the envisioned design to allow designers to explore the entire design space around the envisioned garment. We hence propose a tool that overall enhances the creative process and at the same time provides efficiency, transparency, and sustainability throughout the value chain. Opening up to new aesthetics may result in exciting creative pathways.

5 *Conclusions and future work*

This multidisciplinary practice-based research has made use of design thinking and systems thinking processes to develop a novel CDS that prevents pre- and post-consumer textile waste with the aim of recapturing value through textile servitization in the supply chain. The novel Refashion CDS is a creative design system that makes use of pre-designed multifunctional fabric blocks that are compatible with each other to create multiple styles using and reusing the same fabric through the dis- and re-assembly of garments.

The proof-of-concept fashion collection bearing the name of the CDS - Refashion, showcases how three fabric blocks have been used to develop a collection of 11 styles from jackets and tops to jumpsuits and dresses. Furthermore, a closed-loop PSS value chain was conceptualised depicting the *R. system* that includes the use of IoT and AI methods to create and capture value from product-service offerings, while also connecting manufacturers with customers and suppliers to co-create value. The innovative product design and manufacturing process that is based on the Refashion CDS is planned to be implemented through automated planning of manufacturing as well as recovery and AI-aided design processes and IoT-based monitoring, making it suitable for Manzini's concept of Cosmopolitan Localism. Currently, the CDS is however limited to the manual assembly and reassembly of styles. To the best of our knowledge, this is the first research project to deal with this topic through an integrated lens of circular design and automated manufacturing.

Future research will look into extending and integrating the CDS with AI techniques for automated manufacturing in order to semi-automatically synthesise machine-understandable recipes (i.e., bills of processes and bills of materials) for the automated assembly of garments from the given fabric blocks, thus scaling the CDS to industrial scale. This will furthermore support sustainable decisions already during the design phase by making up-to-date market information (e.g., on the current fabric blocks in circulation and their status) readily available to designers. The digitalization of these processes will make the value chain more efficient, transparent, and sustainable. Then the aim will be to support fashion companies who intend to close the loop.

In parallel, a bottom-up approach for sharing the knowledge behind the Refashion CDS with fashion students and designers will begin to take place through lectures and workshops delivered at various universities who express an interest. The aim is to continuously enable others to practice the new Refashion CDS, and build a community of practice around it. Furthermore, participants will be invited to contribute to further develop the Refashion fabric block library. The intent is to generate ownership among designers, and co-create a space that is inclusive and open to all.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

The authors would like to thank Vlad Osiac for his support for this project, and for refining the graphic design for the diagrams representing methodology, material flow, and manufacturing steps. We thank Alexandra Petcu for capturing the Refashion CDS so elegantly on her lens.

Notes

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