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COMMUNICATIONS IN DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Disassembly of Garments: A Review of Separation Technologies for Sewn, Welded and Bonded Joints

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Annette Kölling[1,2,*]

1 Hochschule Hannover – University of Applied Sciences and Arts, Hanover, Germany
2 Annette Kölling, Fashion Design & Research, Berlin, Germany
* Address for correspondence: hello@annette-koelling.com

Abstract

Textile waste continues to be a growing environmental problem that must be addressed by the textile industry. New products and production solutions are required according to the European Commission's Ecodesign Working Plan. Durability, reparability, and digital product passports are now regulated under the Ecodesign for Sustainable Products Regulation (ESPR), to support the transition toward a circular economy. Furthermore, the ability to disassemble a product at its end-of-life is expected to become an important requirement under the revised Waste Framework Directive in the coming years. To enhance the circularity of textile products, we must understand how these products are assembled, and based on that understanding, evaluate their disassembly. This review examines sewing, welding, and adhesive bonding of textiles, the three principal methods for assembling clothing, and evaluates their potential for controlled disassembly at end-of-life. Four thread-based assembly methods are discussed in this review, and the various triggers for disassembly are compared and analysed. Due to the material bond through polymer fusion during welding, the process is generally incompatible with reversible disassembly. Adhesive bonding is also considered a permanent process, which is being investigated in some initial material studies. The review shows that sewing has the highest potential for disassembly, however reversible thread systems remain limited. It identifies the lack of standardized testing procedures for seam strength and disassembly time as the most critical gap, which limits industrial scalability.

Keywords

garment disassembly, circular fashion, design for disassembly, water-soluble thread, sewing technology

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1 Introduction

The earliest finds of clothing date back to 3000 BC. Ancient Egypt and early Germanic times provide impressive evidence that constructed clothing already existed. At that time, clothing was often knotted or fastened with clasps [1]. The exact time and origin of the use of needle and thread cannot be precisely determined in history. However, the time of the Industrial Revolution also spurred the development of sewing machines [2]. The assembly of clothing is based on joining two-dimensional fabric pattern pieces with seams, thereby creating a three-dimensional form that dresses the body. These seams can be constructed in various ways [3]. In textile processing, sewing, welding, and gluing are commonly used to manufacture clothing [1]. However, given the environmental impact of discarded garments, whether used, damaged, or even unworn, it is important to also consider disassembly already during the manufacturing process [4]. This review provides a brief overview of the three assembly methods: sewing, welding, and gluing, and evaluates their current potential for disassembly (Figure 1).

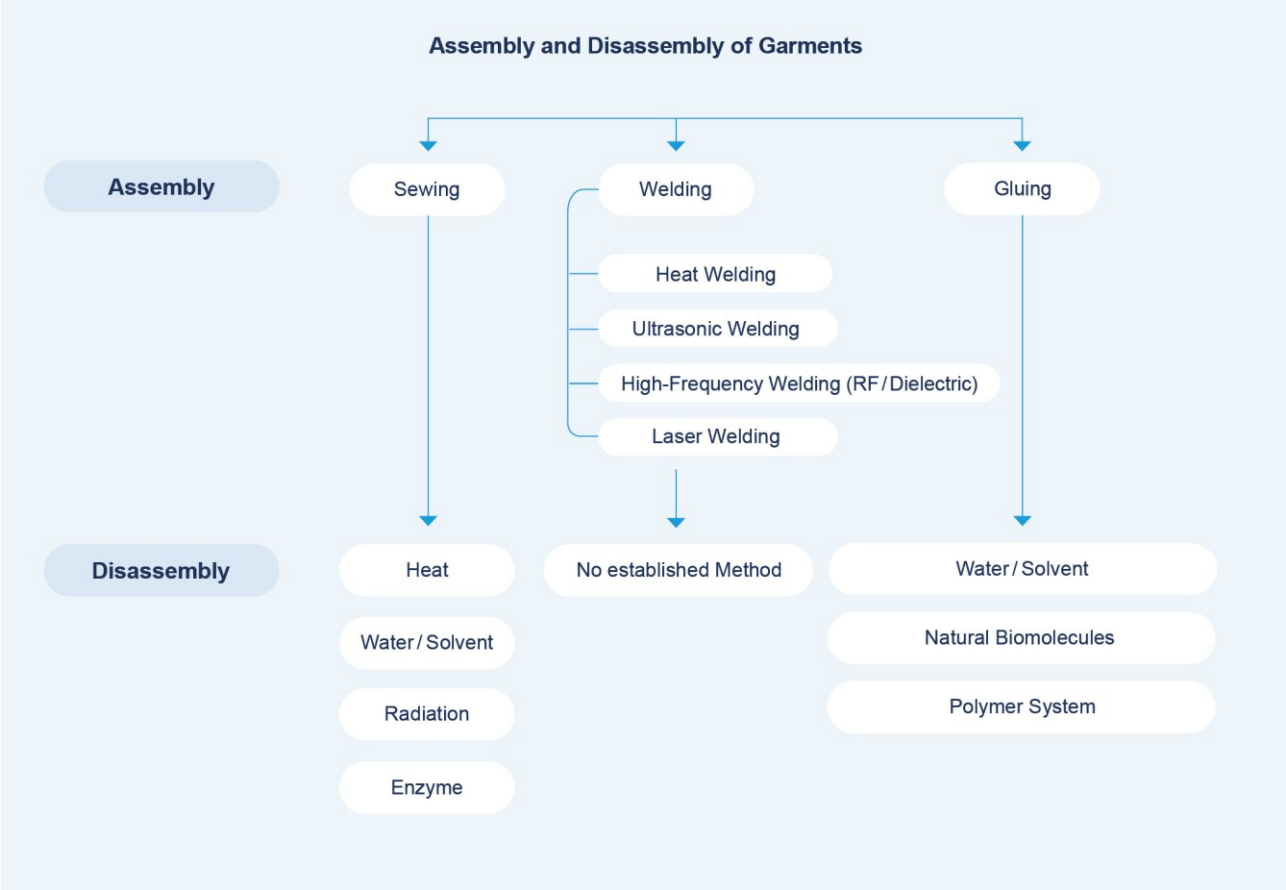


Figure 1. *Assembly and Disassembly of Garments, an overview of the three main methods. Own illustration.*

The urgency to develop textile disassembly solutions has increased due to the Ecodesign for Sustainable Products Regulation (ESPR), which has been in force since July 2024. Products placed on the EU market will have to meet requirements including durability, reparability, recycled content and recyclability once product-specific delegated acts are adopted. The pressure on textile producers increases, imposing responsibility for unsold textiles and footwear which may no longer be destroyed by large companies as of July 2026. A Digital Product Passport (DPP) is legally anchored in the ESPR and expected to include disassembly instructions among its required data fields. It further supports Extended Producer

Responsibility (EPR): the revised Waste Framework Directive (Directive (EU) 2025/1892), in force since October 2025, requires all member states to establish EPR schemes for textiles within 30 months [5,6,35], requiring producers to take responsibility for the collection, recycling, and safe disposal of products at the end of their life.

2 Main methods for assembling clothes

2.1 Sewing

Sewing is the procedure of joining two or more materials with one or more threads together in a structured process, by hand or machine. Stitch formations hold pattern pieces together to create the garment [2,3]. The performance of a seam depends on parameters such as stitch density (SPI – stitch per inch), stitch width, seam allowance, stitch length, seam thickness, seam extensibility, seam strength and seam efficiency [2,7]. The comfort of a garment is influenced by seam elasticity, therefore, stitch type, seam type and thread material are among the most important elements in garment construction and in joining two pattern pieces together [8]. The choice of seam type is also a key factor in determining the longevity of a garment and the use of a variation of stitching types is indispensable in the clothing industry [9]. Stitch and Seam types are designated according to the classification of ISO 4915:1991 and ISO 4916:1991, as adopted in the German editions DIN 61400:2002-04 (stitch types; nationally modified) [10] and DIN ISO 4916:2002-04 (seam types; identical adoption of ISO 4916) [14]. Both ISO standards remain current; ISO 4915 was last confirmed in 2021 and ISO 4916 in 2022 [13,14].

Table 1 summarises the ISO 4915 stitch classes and their relevance for DfD; reference images are provided in Appendix A (Table 5, Figure 4).

Table 1

ISO 4915 Stitch Classes and their relevance for Design for Disassembly (DfD). Adapted from Eberle et al. (2022) [1]; Colovic (2015) [3]; Gurarda (2019) [8]. Reference images: see Appendix A (Table 5, Figure 4).

Stitch Class (ISO 4915)	*Stitch types*	*Disassembly Relevance*
100 Chain Stitch (single-thread)	101–108	Easily unpicked from last stitch, extensible, best suited for DfD-intended seams
200 – Hand stitch (single-thread)	201–220	Moderate ease of opening, mainly edge finishing; limited DfD relevance.
300 – Lockstitch	301–351	Most common in industry, very difficult to unpick mechanically. Least suited for automated disassembly
400 – Multi-thread chain stitch	401–417	Easily unpicked, extensible seam. Preferred stitch type for seams DfD.
500 – Overedge chain stitch	501–522	Edge finishing /neat; secondary seam role, moderate disassembly potential.
600 – Cover-seam chain stitch	601–609	Three thread systems; flat seams in knitwear; complex to remove. Less DfD-friendly.

From a Design for Disassembly (DfD) perspective, stitch classes 100 and 400 offer the greatest potential for controlled seam separation. Both stitches can be unpicked from the last stitch and produce extensible seams [3]. In comparison, the Class 300 stitch is very difficult to open mechanically, thereby

generating more waste. However, if seams are sewn using water-soluble thread or heat-dissolvable thread, the parameters change fundamentally, and the stitch class used for DfD must be re-evaluated [9].

In the context of a circular economy and a sustainable fashion industry, sewing thread is considered a key element for change. During recycling, sewing thread often poses a major problem, since 75% of clothes is made from a different material than the fibre that it holds together. The Design for Disassembly (DfD) approach addresses this issue by considering and enabling recycling or even redesign from the very beginning of the design stage [12].

Table 2

ISO 4916 Seam Classes and their relevance for Design for Disassembly (DfD). Adapted from Gurarda (2019) [8]; ISO 4916:1991 [14]. Reference images: see Appendix B

Seam Class (ISO 4916)	*Seam types*	*Disassembly Relevance*
1 – Super-imposed seams (SS)	SS a–z	Most common structural seam; two or more layers joined on the same side. High DfD potential when combined with Class 100 or 400 stitches; fabric layers remain intact after thread removal.
2 – Lapped seams (LS)	LS a–r	Overlapping layers increase fabric contact area and seam complexity. Moderate DfD potential; fabric distortion likely during separation. Disassembly requires careful unpicking to avoid damage.
3 – Bound seams (BS)	BS a–f	A binding strip wraps around the edge of another component, introducing a third element. Planned disassembly requires sequential removal of binding first. Lower DfD potential without targeted design intent.
4 – Flat seams (FS)	FS a–c	Butted edges joined by cover stitch (Class 600); multi-thread construction with no seam allowance. Least suited for DfD; complex thread interlocking makes controlled separation very difficult.
5 – Ornamental seams (OS)	OS a–d	Decorative function only; no structural edge inclusion. Since this seam bears minimal load, removal is simple and the risk of fabric damage is low. Strong DfD potential for non-structural applications.
6 – Edge finishing seams (EF)	EF a–h	Single-component seam enclosing one edge; purely functional finishing role. Low structural complexity and limited thread interlocking. Moderate to high DfD potential; secondary priority in disassembly sequence.
7 – Attaching of separate items (AS)	AS a–j	Joins structurally distinct components (e.g. waistbands, trims, labels). Priority DfD target as attached items frequently differ in material composition, hindering mono-material recycling. Moderate DfD potential with planned seam access.
8 – Single ply construction (SP)	SP a–d	Both edges of a single component are enclosed; typical for belt loops and narrow trims. Because this element is constructed separately, it can be removed on its own. Moderate DfD potential; relevant where mixed-material trims are attached to a main garment body.

When examining the standardized seam types (ISO 4916, Table 2; reference images in Appendix B, Table 6 and Figure 5), superimposed seams of Class 1 offer the simplest approach for automated disassembly. This seam also represents the standard stitched seam; in comparison, the remaining seven seam classes are of greater complexity and will require more precise testing methods for the disassembly process in the future [1,8].

2.1.1 Heat-dissolvable thread

A heat-dissolving sewing thread, with different melting points at 150 °C, 170 °C and 190 °C, offers a potential solution for the future circular economy through automatic thermal disassembly. Developed by the Belgian company Resortecs (**RE**cycling, **SOR**ting, **TEC**hnologie**S**), Smart Stitch™ enables a controlled thermal process in a low-oxygen chamber without material damage (Figure 2). Smart Stitch™ comes in 16 different sewing threads, and is already used for projects with BERSHKA, DECATHLON and other clothing brands. According to the manufacturer's own analysis, Smart Disassembly™ supports closed-loop production with up to 90% material recovery and makes it easy to remove accessories such as buttons and trims [12,15,16].

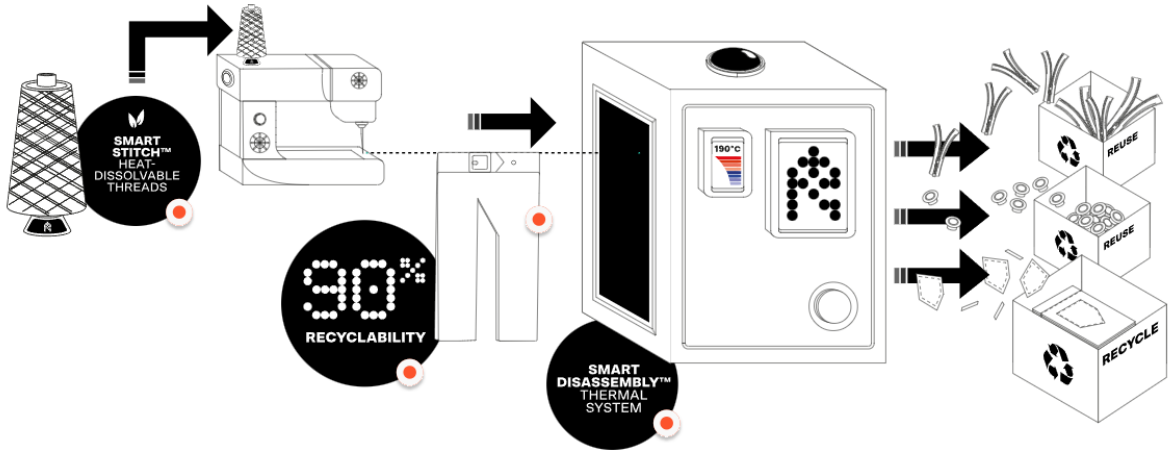


Figure 2. Smart Stitch™ and Smart Disassembly™ process. Image: © Resortecs, reproduced with kind permission.

The thermoplastic yarn keeps its full structure below 100 °C and is therefore suitable for all domestic and industrial washing processes. In the Smart Disassembly™ process, garments are placed in an oxygen-depleted thermal chamber and heated to the fibre-specific melting point of 150–190 °C. The reduced-oxygen atmosphere prevents fabric oxidation and combustion. At the melting point, the forces which holding the polymer chains together weaken. The thread melts and moves away from the seam, so the fabric pieces can easily come apart. Life cycle assessment data show that recycled jeans can reduce CO_2 emissions by up to 50% and water use by up to 98% per pair compared to conventional recycling methods. Because the thread material dissolves, even Class 300 lockstitch seams can be separated. This makes Smart Stitch™ compatible with standard garment construction methods [12,15,17].

2.1.2 Water-soluble thread

To support the transition to a circular economy in the textile industry, the British Company Coats offers a sewing thread made from water-soluble thermoplastic PVA (polyvinyl alcohol). According to its 2024 report, the thread certified with OEKO-TEX STANDARD 100, Product Class 1, is washable at 40 °C without any loss of quality in the garment. The company identifies the main purpose of this product in circular fashion, particularly in basics for women's and men's wear. EcoCycle™ can be used extensively, as it is available in four different variants and 15 different colours. While it shows good resistance to alkalis and does not react to organic solvents, it must not be treated with bleach or ethanol, and it dissolves during a 30-minute wash cycle at 95 °C [18,19].

The disassembly process of EcoCycle™ is based on the material properties of polyvinyl alcohol (PVA). PVA is a synthetic polymer produced by the hydrolysis of polyvinyl acetate. In sewing threads, PVA is typically processed as a staple-spun vinylon fibre, in which short fibres are twisted together to form the yarn structure.

Garments sewn with PVA-based threads can generally withstand standard washing conditions up to 40 °C without significant changes in seam stability during use. At temperatures around 95 °C, thermal energy weakens the hydrogen bonds between the polymer chains, allowing water to penetrate the material. As a result, the polymer structure swells and gradually dissolves in water. Chemical agents such as bleach or ethanol may influence the solubility behaviour of PVA and should therefore be avoided.

Table 3

Comparison of thread-based disassembly methods. Adapted from D'Itria and Trejo Machin (2024) [12]; Resortecs [17]; Coats [18,19]; Wear2Go [20,21]; Egan et al. (2023) [23]; Lehmann and Herrmann (2025) [24].

Technology / Company	*Trigger*	*Mechanism*	*Stability (normal use)*	*Status*
Smart Stitch™ Resortecs	Heat 150–190 °C	Thermoplastic thread polymer melts in low-O_2 chamber; chains lose cohesion; seam opens cleanly; up to 90% material recovery.	Stable below 100 °C; safe for all normal laundry.	First Commercial Cooperations with Bershka, Decathlon…
EcoCycle™ COATS	Hot water 95 °C / 30 min	At 95 °C, water disrupts PVA's internal bonds, penetrates the material, and dissolves it. Higher temperatures speed up this process.	Full integrity at ≤40 °C. Resistant to alkalis; incompatible with bleach/ethanol.	Commercial OEKO-TEX Class 1.
Wear2® Wear2Go	Microwave <10 sec	The thread heats up when exposed to electromagnetic energy. This weakens the seam by over 80% without damaging the fabric around it.	No response under domestic conditions.	Commercial (early stage)
Enzymatic Disassembly	Enzyme solution	Cellulase/protease enzymes break down either cellulose or protein fibres — but only one fibre type per cycle, not both at once.	Stable to standard washing.	Research stage only

Chain stitch seams (Classes 100 and 400) appear more suitable for disassembly than lockstitch seams (Class 300), since dissolved thread residues are less likely to remain trapped within the seam structure. In certain applications, such as overlock seams used in T-shirts, the replacement of only one thread component with EcoCycle yarn may already reduce seam stability after dissolution and thereby make

the disassembly easier. In this context, systematic sewing, washing, and mechanical stress tests are required to evaluate the practical performance and disassembly behaviour of the seams [18,19]. Table 3 compares the four thread-based disassembly methods discussed in Sections 2.1.1 to 2.1.4 by trigger, mechanism, stability during use and market status.

2.1.3 Microwave-activated thread

To advance automation in clothing disassembly, the Belgian company Wear2Go is offering Ecostitching Technology, a microwave-based process. Wear2® thread is sensitive to electromagnetic radiation. A sewing thread composed of a polyester filament on the outside and a core which has a conductive sheath. When exposed to irradiation for less than 10 seconds at a frequency suitable for industrial use, the seam's tensile strength is reduced by more than 80%. This makes it easy to separate pattern pieces and accessories for disassembling [20,21].

The disassembly process of Wear2® is based on microwave-activated conductive sewing threads. The conductive core of the thread absorbs microwave energy and converts it into local heat through electrical resistance, when exposed to industrial microwave frequencies for less than 10 seconds. Since conventional textile fibres absorb only limited amounts of microwave energy, the heat is primarily generated within the thread rather than in the surrounding fabric. As a result, the structural integrity of the thread decreases, and the seam tensile strength is reduced by more than 80%. The textile components can subsequently be separated using only low mechanical force. Processing times below 10 seconds per seam indicate potential compatibility with high-throughput automated sorting and disassembly systems [20,21].

2.1.4 Enzymatic disassembly

Research has discovered enzymatic fibre treatment as a method for breaking down textiles, enabling their transformation into separable and useful components [23]. Since blended textiles are more difficult to recycle, studies pay particular attention to materials containing at least two different polymers, such as polyester (polyethylene terephthalate, PET) and cotton (cellulose). Currently, only one of the textile fibres can be extracted at a time because the processing conditions required for the cellulose or PET differ significantly [24]. Other studies on wool/polyester blended fabrics report complete degradation of the wool fibres, leaving pure polyester behind [25]. To date, no literature specifically addresses the enzymatic decomposition of yarn or thread while preserving the undamaged state of pattern pieces.

Experiments exploring enzymatic removal or decomposition of only the sewing thread under controlled conditions would therefore be of great interest.

The mechanism of enzymatic approaches to textile recycling operates through two complementary strategies. Cellulase enzymes selectively hydrolyze cotton fibres in polyester/cotton blends under mechanical agitation, leaving polyester fibres structurally intact for recovery by simple filtration. However, reactive dyes and durable press finish significantly inhibit enzymatic efficiency [23]. To recycle a PET polyester chemically, enzymes must break it down into its basic monomers, which is challenging because PET in its natural textile form is highly crystalline and the polymer chains are tightly packed. To recycle it efficiently the structure of the polyester textile needs to be physically and thermally destroyed first.

Enzymatic accessibility depends primarily on substrate morphology, particularly crystallinity and chemical finishing. The effective circular textile processing requires substrate-specific pretreatment strategies tailored to fibre type and finish chemistry [26].

2.2 Welding

Welding is a non-stitch, permanent method of joining two fabrics using heat, pressure and speed. It is among others, particularly used for waterproof materials, non-wovens, disposable medical products, and protective clothing, where needle and thread would damage the textile surface [1,11,27].

The most used technique in the clothing industry is **ultrasonic welding**. It uses high-frequency vibrations in the range of 20 kHz to 70 kHz, to generate localized frictional heat that melts thermoplastic fibres at the seam without any external heat source. Pressure, time, and cooling lead to the fusion of the molecules in the material and it produces strong, neat and often waterproof seams. Ultrasonic welding can be used for fabrics up to 0.5 mm thickness. Heavier fabrics burn on the outside before the inner material is melted and bonded. The welding parameters are roller pressure, speed and the energy of the amplitude, generated by the sonotrode [1,28].

Heat welding, or thermal welding uses direct heat and pressure to melt thermoplastic fibres like polyester, nylon or PVC-coated fabrics at the joint and the materials fuse when cooled. Thermal welding is melting the thermoplastic fabric and therefor bonds it without an extra adhesive layer. Pressure is an important parameter in thermal bonding and therefore it works better with thinner material that has a high thermal conductivity. Heat welding methods include hot wedge welding, hot air welding, hot air tape welding [27].

Hot wedge welding uses a thin, heated metal blade which is pressed between the layers of thermoplastic fabric that are to be permanently bonded. The pressure from the moving rollers and subsequent cooling fuse the fabric layers together permanently. The welding parameters are roller pressure, speed and temperature of the heated metal blade [1,29].

Hot air welding can be performed with the same machine used for hot-wedge welding after simple modifications. A nozzle for the hot air flow with a width of 10–50 mm is attached, depending on the textile product. The system has a heating capacity of about 3300 W and enables sealing speeds of up to 10 m/min under standard conditions. The welding parameters are roller pressure, speed and temperature of hot air that flows through the nozzle [29].

Hot air tape welding is used to seal a conventional seam with taping and is suitable for water-resistant, waterproof and breathable materials. It is an adhesive process, often referred to as seam sealing by hot-air tape welding. The tape is heated with a hot air stream through a nozzle, the size of which varies depending on the seam. The adhesive on the tape melts and bonds the tape to the seams. It is then pressed onto the shell material at a maximum speed of 7 m/min and a sealing temperature from 300 °C up to 700 °C. The welding parameters are roller pressure, speed and temperature of the hot air [1,29].

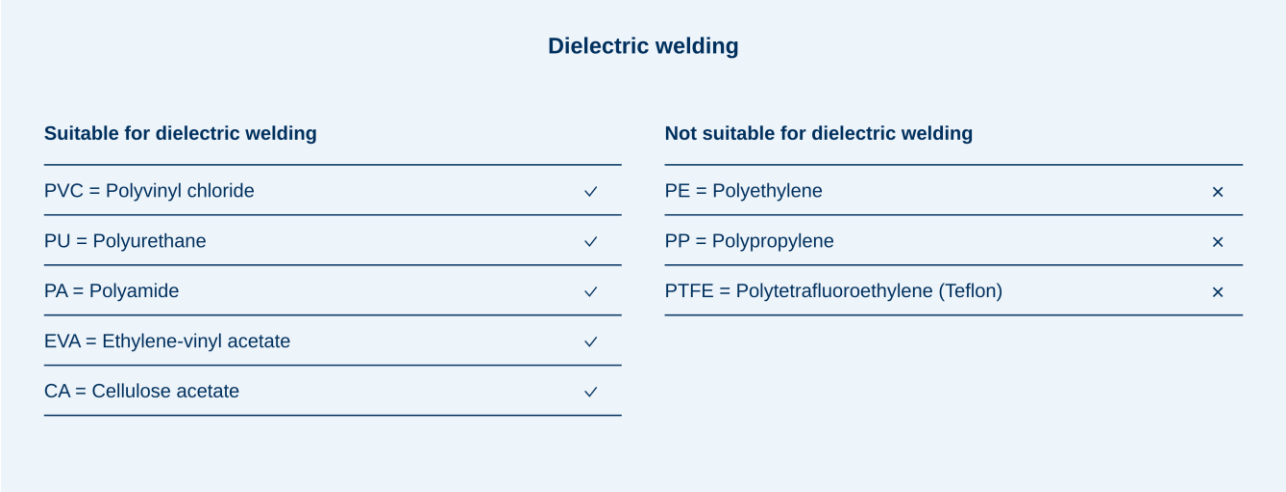


Figure 3. *Polymers suitable and unsuitable for dielectric welding. Own illustration based on data from Jones, I. Ultrasonic and Dielectric Welding of Textiles. In Joining Textiles: Principles and Applications [28]*

Dielectric Welding also known as Radio Frequency or High-Frequency welding, uses a rapidly switching electromagnetic field to heat and fuse fabrics containing polar polymers like Polyvinyl chloride (PVC) or polyurethane (PU). Often used for tarpaulins, inflatable products and protective clothing and provides airtight and watertight bonds. Dielectric welding only works with polymers that contain molecules capable of responding to an electric field, have short flexible chains, and can create temporary charge separations under the electromagnetic field, like PVC, PU, PA, EVA, or cellulose derivatives, but not with nonpolar ones like PE, PP, or PTFE (Figure 3). In dielectric welding, pressure, heat, movement and material are crucial parameters for the result [27,28,30].

2.2.1 Welding methods: overview and DfD potential

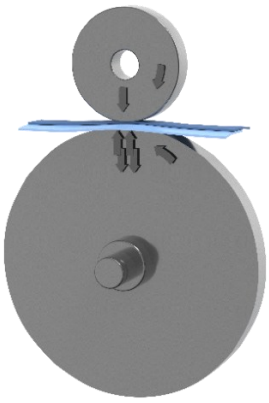
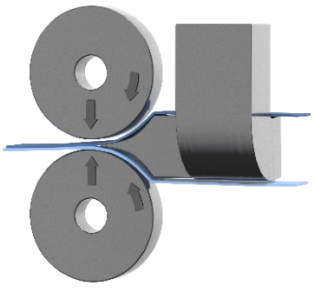
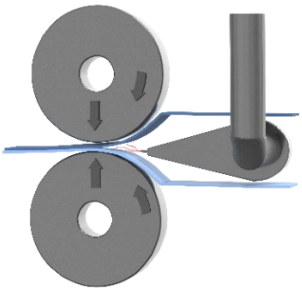
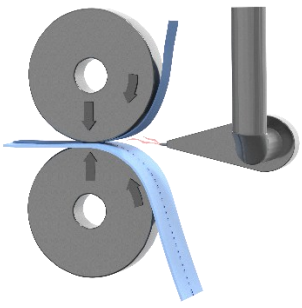
Table 4 summarises the welding methods described above together with their key parameters and DfD potential.

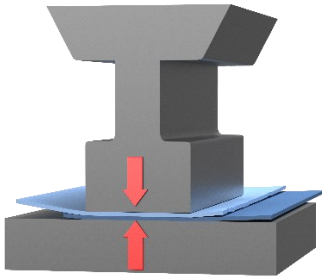
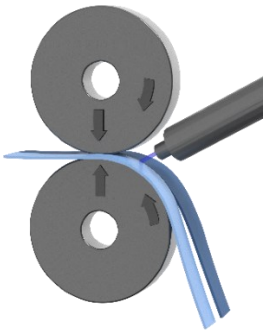
Laser Welding uses light energy which melts a narrow line of thermoplastic fibres, the applied pressure on the melted layers creates a strong weld without additional adhesives. It can create precise seams with minimal material deformation and a higher seam strength than ultrasonic welding. It is more commonly used in technical textiles for applications as airbags or aerospace textiles. To use laser on natural fibres, an adhesive layer for bonding is required [27].

Currently, no welding method offers a controlled end-of-life disassembly possibility. All welding techniques produce permanent molecular bonds between the fabric layers themselves. There is no separate component like thread or adhesive, that can be selectively dissolved or degraded. Therefore, welding is structurally incompatible with Design for Disassembly in its current form.

Table 4

Overview of welding methods and their DfD potential. Adapted from Eberle et al. (2022) [1]; Serdar (2023) [27]; Jones (2013) [28]; PFAFF [29]; TWI [30]. Illustrations: own drawings by the author (CLO3D) after PFAFF [29].

Category/ Variant	*Description*	*Key Parameters*	*DfD Potential*
Category: Ultrasonic Welding Ultrasonic Welding	Ultrasonic Welding uses high-frequency vibrations (20–70 kHz) to generate localised frictional heat that melts thermoplastic fibres at the seam without any external heat source. Pressure, time, and cooling lead to molecular fusion, producing strong, neat, often waterproof seams. Limited to fabrics up to 0.5 mm thickness – heavier fabrics burn on the outside before the inner material bonds.		Fabric layers are molecularly fused. No separate thread component; seam cannot be selectively dissolved or degraded. No DfD Potential.
Category Thermal Welding: Hot Wedge Welding	Hot Wedge Welding uses a thin, heated metal blade pressed between thermo-plastic fabric layers. Pressure from moving rollers and subsequent cooling fuse the layers permanently.		Permanent molecular bond. No pathway for controlled disassembly. No DfD Potential.
Category Thermal Welding: Hot Air Welding	Hot Air Welding uses the same machine as hot-wedge welding with a modified nozzle (10–50 mm width). A 3300 W heating system enables sealing speeds up to 10 m/min.		Permanent thermal bond. No DfD Potential.
Category Thermal Welding: Hot Air Tape Welding (Seam Sealing)	Hot Air Tape Welding seals a conventional seam with adhesive tape heated by a hot air nozzle. The adhesive melts and bonds the tape to the seam surface. Suitable for water-resistant, waterproof and breathable materials.		Adhesive tape forms a permanent barrier layer over the seam. No DfD Potential.

Category: Dielectric Welding Dielectric Welding	Dielectric Welding (Radio Frequency / High-Frequency) uses a rapidly switching electromagnetic field to heat and fuse fabrics containing polar polymers such as PVC or PU. Works only with polymers capable of creating temporary charge separations (PVC, PU, PA, EVA, CA) – not with non-polar polymers (PE, PP, PTFE).		Airtight/watertight permanent bond. No disassembly pathway identified in literature. No DfD Potential.
Category: Laser Welding Laser Welding	Laser Welding uses focused light energy to melt a narrow line of thermoplastic fibres. Applied pressure on the melted layers creates a precise, strong weld without additional adhesives, with minimal material deformation. More common in technical textiles (airbags, aerospace). Natural fibres require an adhesive layer for bonding.		Highest seam strength of all welding types. No disassembly pathway identified. No DfD Potential.

2.3 Gluing

Gluing is a method of permanently bonding two layers of material by applying a synthetic adhesive. The adhesive sets and forms a durable hold through both surface contact and molecular interaction. To be suitable for garments, the adhesive must retain flexibility and softness so that the bonded joints behave like the surrounding fabric. Seam sealing by bonding is widely used and can be applied across a broad range of fabrics. In the textile industry, bonding is mainly applied to fabrics designed to resist water, wind, and moisture [1]. Recent research and industry initiatives have shifted focus toward adhesives that not only provide strong bonds but also enable recyclability and disassembly. This is a key step toward achieving circular-economy goals in fashion.

2.3.1 Switchable Water-Based Adhesives

In June 2025, the Centre of Expertise in Advanced Materials and Sustainability (CEAMS) partnered with Burgessy Rise Ltd. to develop a water-based adhesive capable of switching between strong bonding and easy release. This innovation enables durable yet recyclable garments, offering a practical pathway to circularity in apparel design [22].

2.3.2 Reversible FMDA Polymer Systems

Researchers from University of Warwick have studied adhesives based on a furan–maleimide Diels–Alder (FMDA) polymer system. This reversible adhesive bonds effectively but can be separated when exposed to heat. The system combines plant-based furan with petroleum-derived maleimide, forming a strong yet recyclable glue that holds particular promise for advancing circular apparel design [31]. Aligned with developments in adhesive technology, automation technologies are being developed to enhance textile disassembly. The University of Warwick, in partnership with CreateMe Technologies, has presented an automated disassembly solution that employs robotics to process cotton and low-spandex polyester blends. Such systems, when integrated with reversible adhesives, could enable large-scale garment recycling by combining material science with advanced manufacturing [32].

2.3.3 Bio-Based Hot-Melt Adhesives

Conagen, a US biotechnology company, introduced in July 2023 a sustainable, removable textile hot-melt adhesive made from natural biomolecules. Based on precision fermentation technology, this adhesive forms strong bonds with nylon plastic, knit fabric, and polycarbonate plastic. Importantly, it can be debonded on demand with heat, eliminating reliance on fossil fuel–based solvents [33].

Because of the permanent bond that conventional adhesives create, they are not suitable for DfD. However, unlike welding, the adhesive is a separate material layer, which means it can potentially be removed. Emerging reversible adhesives with different triggers like water, heat, or enzymatic action, demonstrate that glueing can be compatible with DfD.

3 Challenges in Multi-material Textiles and Combined Joining Methods

The effective disassembly of garments is complicated by multi-material constructions, such as fibre blends consisting of, e.g. 65% polyester and 35% cotton. The presence of several different material types, like shell fabrics, linings, interlinings, trims, and elastic bands, further complicates the disassembly process [34]. In blended fabrics, fibres composed of different polymers are physically intertwined at a microscopic level. Even after the sewing thread has been removed, the piece of fabric remains a substrate of mixed materials, requiring further steps for fibre separation. Current enzymatic processes can process only a single fibre type per cycle [23]. Effective garment recycling requires a comprehensive sequence of subsequent material separation steps [24]. Many modern garments combine sewing with welding, by pairing sewn seams with welded-on waterproof sealing tapes or adhesive bonds. In such constructions, the disassembly process must address the bonded or welded seam as well, rather than only the sewing thread. Otherwise, the welded or bonded joint persists even after the sewing thread has been dissolved [27]. Reversible adhesive systems (FMDA) could complement yarn-based disassembly in hybrid constructions; however, no integrated system combining several of these methods has yet been realized on an industrial scale [22,31].

In summary, the entire material complexity of a given garment determines the feasibility of its disassembly. Future research should approach disassembly design holistically: sewing thread, fabric composition, the combination of joining methods, and the attachment of accessories must be considered simultaneously.

4 Discussion

This detailed listing of clothing assembly methods is intended to illustrate different seam connections by sewing, welding and gluing and their potential for disassembly. However, it remains unclear how seams can be designed to remain intact during use but still enable controlled disassembly at end-of-life. In particular, no established method exists to determine appropriate disassembly timing or to evaluate seam durability under different conditions. A larger study is needed to clarify these open questions. The need for functional disassembly is increasingly urgent due to current EU regulations like the Ecodesign for Sustainable Products Regulation (ESPR, 2024) [5,6] and the revised Waste Framework Directive (2025) [35] introduced binding guidelines regarding recyclability and circularity.

This review has provided insights into the assembling and disassembly of clothing and summarized the current state of technical scope. The work clarifies that sewing with needle and thread is established in clothing production and currently offers the most realistic potential for developing practical disassembly solutions. Welding, however, is primarily designed for permanent joining two materials and

has not yet shown viable options for disassembly. Adhesives have produced some promising results in both research and production but remain experimental and not widely scalable. The unresolved issues around seam durability and dismantling time highlight the need for further, focused research. Because sewing is the only method with proven scalability, future work should concentrate on optimizing sewing-based seams for durability during use and controlled disassembly afterward. Additionally, future research must address the challenge of multi-material garment construction and combined joining methods: seam-level disassembly alone is insufficient for recycling when fabric blends or hybrid joints are present [17,18,24].

5 Summary

This paper reviewed the three main methods of clothing assembly (sewing, welding, and gluing) and their potential for controlled disassembly at end-of-life. Sewing with needle and thread stands out as the most promising option for scalable disassembly, while welding is primarily suited for permanent joining and adhesives are still experimental and not scalable. A critical challenge lies in the lack of methods to protect seams, ensure durability during use, and enable controlled disassembly at end-of-life. In addition, dismantling time is still not clearly defined.

The study provides valuable insights into the technical possibilities of disassembly but also has limitations. Several of the referenced publications originate from company websites where processes and findings are not presented transparently, constraining the generalizability of the results. Moreover, the analysis is limited in scope, with meaningful conclusions possible only for sewing-based seams, as welding and gluing have not produced satisfactory outcomes. Although examples such as CEAMS [22], CreateMe [32] and Conagen [33] are already on the market, these disassembly products are not yet widely marketable or fully usable. These critical points should be taken into consideration when interpreting the findings.

Conflict of Interest

The author declares no conflict of interest.

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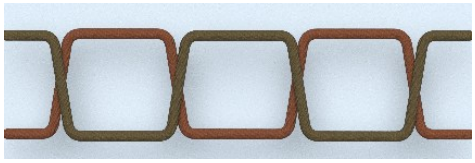
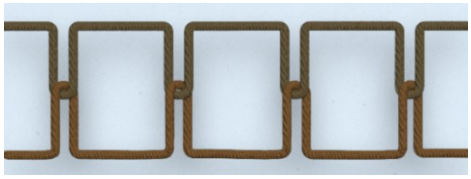
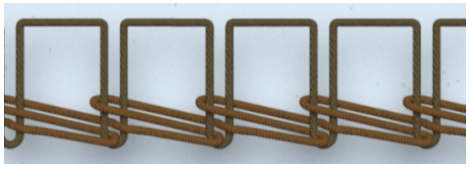
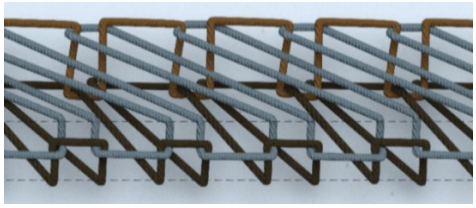
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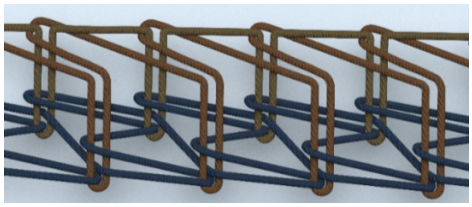
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Appendix A

Table 5

ISO 4915 stitch classes with reference images. Descriptions adapted from Gurarda (2019) [8], ISO 4915 [13] and Colovic (2015) [3]. Stitch illustrations: own 3D renderings by the author (CLO3D), based on ISO 4915 [13] and Eberle et al. (2022) [1], adapted with kind permission of Verlag Europa-Lehrmittel.

Class	*Stitch type*	*Description*
100	Stitch type 101 	"Chain stitch. Each loop is interconnected with the following loop of the same thread. Opposite sides of the seam look different. This stitch type can be very easily unpicked by running back from the last stitch to the first. The seam is generally quite extensible. Often used for temporary stitching e.g. basting."
200	Stitch type 201 	"Hand stitch. Needle and thread are both passed completely from one side of the material to the other. The thread is held through the material. Originally made only by hand, some of them can now be formed also by machine. Especially suitable for sewing edges."
300	Stitch type 301 	"Lockstitch. Formed by two different thread systems. A needle thread introduced from one side of the material is interlaced with an underneath supplied from a spool on the other side. This is the most popular type of stitch e.g. for closing, lapped seams, and decorative stitching. It is difficult to unpick, and both sides have the same appearance. Capable of making a firm closing of the layer."
400	Stitch type 401 	"Multi-thread chain stitch. Also formed from two thread systems. The loops of the needle thread are drawn all the way through the material and are interconnected on the underside by thread supplied from a looper. Top and bottom sides have a different appearance. The seam can easily be unpicked and is quite extensible. The fabric layers are less firmly closed compared to lockstitch. Special applications are elastic cross-over seams, seat seams and side seams."
500	Stitch type 504 	"Overedge chain stitch. Formed from one or more needle and looper threads. Needle threads interconnected with themselves or with another thread. At least one thread system passes around the edge of the material. Overedge stitches of various types are used to neaten and to bind the cut edges of woven and knitted materials."Klicken oder tippen Sie hier, um Text einzugeben.

600	Stitch type 601 	"Covering chain stitch. This stitch type is generally formed from three thread systems. The covering threads lie on the top surface and are held in place by the needle threads which in turn are interlaced on the back of the seam by the looper threads. They are used especially for making flat, extensible seams in knitted fabrics."[1]

Stitch class	Stitch type	Number of stitch types
100 Chain stitches (Single-thread)	101, 102, 103, 104, 105, 107, 108	7
200 Hand stitches (Single-thread)	201, 202, 204, 205, 206, 209, 211, 213, 214, 215, 217, 219, 220	13
300 Lock stitches	301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 351	30
400 Chain stitches (Multi-thread, Double-thread)	401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417	17
500 Overlock stitches (Over-edge chain stitches)	501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 521, 522	16
600 Chain stitches (Cover-seam stitches)	601, 602, 603, 604, 605, 606, 607, 608, 609	9

Figure 4.

ISO 4915 stitch classes and stitch types. Own compilation based on Eberle et al. (2022) [1], Gurarda (2019) [8], ISO 4915 [13] and Colovic (2015) [3], adapted with kind permission of Verlag Europa-Lehrmittel.

Appendix B

Table 6.

ISO 4916 seam classes with reference images. Descriptions adapted from Gurarda (2019) [8] and ISO 4916:1991 [14]. Seam illustrations: own 3D renderings by the author (CLO3D), based on ISO 4916 [14] and Eberle et al. (2022) [1], adapted with kind permission of Verlag Europa-Lehrmittel.

Class	*Seam type*	*Description*
1	Superimposed seams 	"Superimposed seams are made with at least two sewing components, both of which are bounded on the same side. Additional sewing components are similar to these two or bounded on both sides. (e.g. Single seam)"
2	Lapped seams 	"Lapped seams are made from at least two components one of which is bounded on one side and the other on the other. Their bounded sides are against each other, they are at different heights, and they overlap. (e.g. Overlap seam)"
3	Bound seams 	"Bound seams are made from at least two components, with one of them wrapped around the edge of the other. (e.g. Binding seam)."
4	Flat seams 	"Flat seams are made from at least two components, with one edge from each butted up against the other and on the same level. (e.g. Cover chain stitch)"
5	Ornamental seams 	"Ornamental seams - They are made with at least one component, with no edges included in the seam (only folding). Additional pieces of fabric can be limited on one or both sides. (e.g. box pleat)."
6	Edge finishing seams 	"Edge finishing seams are made from only one component, with one edge included. (e.g. Blind single chain stitch)."

7	Attaching of separate items 	"Attaching of separate items are made with at least two components, one of them has one edge included, the other has both edges. (e.g. Waistband seam with simple fold and insert)."
8	Single ply construction 	"Single ply construction are made with at least one component that is bounded on both sides. (e.g. Belt loop seam)."

Seam class	Seam type	Subgroup numbers of seam types
Class 1 SS	Superimposed seam	55
Class 2 LS	Lapped seam	101
Class 3 BS	Bound seam	18
Class 4 FS	Flat seam	6
Class 5 OS	Ornamental seam	8
Class 6 EF	Edge finishing seam	32
Class 7	Attaching of separate items	
Class 8	Single ply construction	

Figure 5. ISO 4916 seam classes. Own illustration based on Gurarda (2019) [8] and ISO 4916:1991 [14].

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