THE INDUSTRIAL REVOLUTION 4.0: MANUFACTURING APPAREL FOR CIRCULAR REUSE

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Abstract

The textile industry stands at the precipice of a revolutionary transformation, poised to embrace the principles of circular economy and zero waste. In this presentation, we - at the company Unspun - introduce a groundbreaking approach to textile manufacturing that reimagines the entire lifecycle of clothing, from production to reuse. While most textile and circularity projects focus on material innovation, we will reimagine how clothes are produced and designed from the outset, leveraging deep tech hardware innovation.

Traditional textile recycling methods often involve energy-intensive processes of mechanical or chemical disassembly, compromising the integrity of the original fibers. Our innovative solution proposes a paradigm shift: creating seamless garments that maintain yarn integrity throughout their lifecycle. This approach allows for direct unwinding and reuse of yarns, significantly reducing waste and energy consumption in the recycling process. This aligns better with the principles of design, where all components of something retain their value indefinitely.

At the heart of this revolution is Vega, our proprietary 3D weaving machine. Vega represents the culmination of years of research and development, designed to produce clothing that is not only stylish and functional but also inherently hyper-circular. By eliminating seams and preserving yarn structure, Vega-produced garments can be easily deconstructed, with yarns returned directly to spools for immediate reuse in new creations.

This paper will delve into the technical aspects of our 3D weaving technology, exploring how it facilitates easier design for disassembly and yarn recovery. We will discuss the potential impact of this technology on the textile industry, including reduced material waste, lower energy consumption in recycling processes, and the creation of a truly circular textile economy. We will examine a few case studies of this manufacturing being used for product that is sold in the market both through Unspun and partner brands.

Furthermore, we will examine the broader implications of this technology for sustainable manufacturing practices across industries. Our vision extends beyond textiles, imagining a world where all products are designed with circular reuse in mind, leading to a hyper-circular economy that minimizes waste and maximizes resource efficiency.

By revolutionizing how we produce and recycle textiles, we are not just addressing the symptoms of waste in the fashion industry; we are reimagining the entire system and taking a significant step towards a zero-waste, circular future.

Introduction and Motivation

Before humans, there was no such thing as trash. The cycles of nature, biology, and the universe as a whole have continued indefinitely, and all materials continue to be useful for these cycles. But once humans showed up, and especially once industrialization and globalization became the norm, humans started converting the world's resources into this thing called "trash" - products, objects, materials that are deemed worthless.[12]

The fashion industry, in particular, is one of the most environmentally detrimental sectors. It contributes to deforestation, water, air, and land pollution (not to mention the human rights violations it so often gets called out for). An industry that has historically operated with little legislative oversight and contributes up to 4-10% of global carbon emissions makes it one of the world's most carbon-intensive industries. Like many other industries, this one operates on a linear business model.[24]

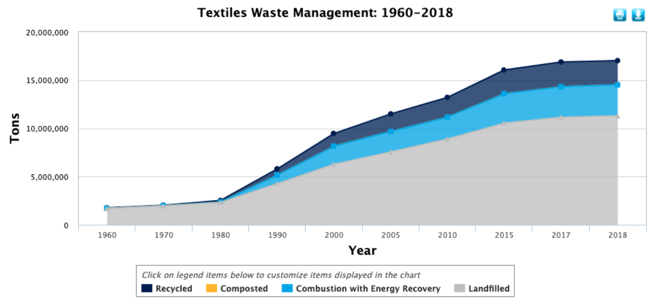

Figure 1: Textiles waste management, 1960-2018

According to the EPA, only 13% of textile waste is recycled.[28] Historically, the fashion industry has gone largely unchecked on production volumes and waste generation (Figure 1). Legislative efforts to curb the waste issues are relatively recent. For instance, the EU Strategy for Sustainable and Circular Textiles (2022) aims to ensure that, by 2030, all textile products in the EU market are durable, repairable, and primarily composed of recycled fibers.[11] However, such measures are still in their infancy, and their impact remains to be seen.

A lot of these emissions are driven by a mismatch between supply and demand. Global, opaque, and overly complex supply chains lead to rampant overproduction, with an estimated 30% of manufactured items never being sold.[23] This inefficiency is a major contributor to emissions and waste. Addressing overproduction is critical, as the current volumes of unsold goods far exceed the capacity of existing resale or textile recycling systems. Without systemic change, collectors and recyclers cannot manage the growing influx of waste.[27]

For instance, in 2023 alone, it is estimated that between 2.5 and 5 billion pieces of unsold goods were produced, illustrating the industry's severe lack of transparency.[2] This disparity highlights the pressing need for solutions to reduce overproduction and transition toward a sustainable, circular fashion model. Without such measures, the industry's environmental and social impacts will only continue to escalate.[19]

Nature does produce in abundance. But nature does not have the same problems that humans have created, especially the problem of product (whether excess product just produced or product at the end of its lifecycle) being worthless when not in use. In the natural, or biological, world things are happily converted into other products of value. If we could replicate nature's production processes — additive and circular — we could solve these problems.[13]

Current State of the Technology Industry Uses

The clothing industry still relies primarily on the sewing machine, making products via the "cut-and-sew" manufacturing method. This method takes fabrics, which are 2-dimensional or planar materials comprised of (in the case of clothing) yarn, lays those fabrics out along with pattern pieces, cuts the pattern pieces from the fabric, discards the material that isn't included in the pattern pieces, then assembles together the materials cut from the pattern pieces, and sews them together into 3-dimensional clothing products. This method of manufacturing has existed for millennia and was assisted with machine power with the advent of the sewing machine in the mid-1800s.[5]

Clothing is still made this way because it is inexpensive to exploit cheap labor overseas, and therefore the industry has felt little incentive to disrupt it. The industry is stuck in this method for mass production because the current way to make products for cheap is to hit large economies of scale - where a huge order of one specific product is placed and made in bulk.[29] This leads to overproduction because it is still impossible to predict the future, especially a year ahead of time.

Beyond incremental material and recycling innovations, there is an opportunity from ecological and financial impact standpoints to rethink the fashion industry value chain changing how and where textiles are produced and consumed. We at Unspun envision a world where every garment is made on-demand, eliminating waste and overproduction and reconnecting people with the clothing they wear. A customer would visit a website or store, choose the piece they want to buy, customize it to their style and fit using our fit technology, and it would get 3D woven on-demand on Vega in minutes. On-demand, made just for them. Once the garment reaches the end of its first life, the customer can bring it back to us and we would unweave it and recover the yarns to give them a new life.

Our 3D weaving technology is unique in the apparel industry, with no direct competitors currently. While 3D or circular weaving exists in sectors such as medical textiles and plastic tape bags, our specific approach and application set us apart.[22] 3D weaving, when used in industrial applications, typically denotes a fabric made with thickness, i.e. a flat fabric that has an additional thick dimension, almost like weaving a cube.[18] This is different than the Vega 3D weaving we have developed for apparel. Some academic projects have also explored weaving via flat jacquard looms to create double cloth, where a flat fabric is woven with a pocket or double layer so that when take off the loom it can be opened into a 3D shape like opening up a pop-up card, but none have taken a similar path in creating 3D structures directly.[14]

Tangential competitors exist in related industries, such as SoftWear Automation (robotic manufacturing), Bally Ribbon Mills (3D weaving for medical textiles), and various 3D knitting or circular weaving companies like Shima Seiki.[1] Our differentiation lies in building an entirely new supply chain focused on sustainability and made-to-measure, on-demand apparel.

Technology Approach

Vega 3D Weaving As A Solution

Over a decade of developing the concept of indefinite growth and decay in the physical things humans wear, we have developed and refined a revolutionary production and recovery process that is grounded in accepted materials. That is, the concept is novel in its approach but relatively conventional in its end result, making consumer adoption easier. We call this concept and process ‘3D weaving’ and we have branded the overall technology offering ‘Vega’. It begins with a conventional form of conventional material, using the same yarns that would typically be used in clothing. (The requirements for the yarn used in this process are equivalent to those used in flat fabric weaving; both processes require higher tensile strength than is needed for knitting.) The way that this yarn is assembled (woven, more specifically) together is what differs from the traditional process. The current manufacturing of woven products requires that yarn in one direction or axis (typically called warp) is then intertwined with yarn in the orthogonal direction or axis (called weft) to create a 2-dimensional material comprised of two axes, each the warp and the weft (Figure 2).

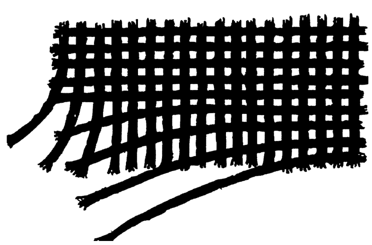

Figure 2: Woven fabric construction

This Vega 3D weaving process takes the liberty of yarn’s flexibility and ability to itself embody a 2D form, so that when warp and weft yarns are combined they can realize beyond just a 2D form - a 3D form (Figure 3). In the case of our Vega 3D weaving, warp yarns are configured around some sort of imagined core, themselves already loosely taking on a 3D form just as a flat warp would inherently loosely take on a 2D form in their initial, pre-weaving layout. Then weft yarns are woven into the warp in a 3D format, to lock the already 3D form in place. Weaving is intrinsically about locking yarns together and in a way that is dense enough that no knots or other affixing is required. Vega 3D weaving follows this notion, but the final form is 3-dimensional. The closest analogy would be basketmaking: reeds are woven together to form a 3-dimensional product *without* the need to first create flat 2-dimensional sheets of that material, then cut that material out, and then attach them back together to form a 3-dimensional form.

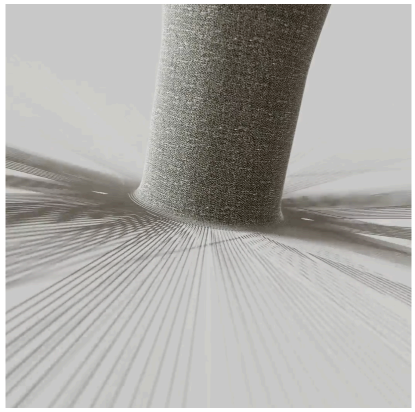

Figure 3: Vega 3D woven fabric construction

In this process, thousands of yarns are fed into the Vega machine where they are woven in a circular pattern to form a seamless, 3D tube. Each warp end is computer-controlled, allowing for the creation of jacquard patterns and various weave structures. The 3D tubes are suitable for making pants, tops, accessories, and more. After being removed from Vega, these tubes are transformed into garments with a few additional steps, such as attaching two pant leg tubes at the center seam, or adding a button and a pocket.

Whereas traditional supply chains go from yarns → fabric → fabric finishing → *then* to garment manufacturing, Vega goes directly from yarn → garment (Figure 4). Not only does it significantly shorten the supply chain and reduce the resources used, it also eliminates almost all cut-and-sew waste. Manufacturing using yarn as the input is much easier to automate than with fabrics because yarn has a simpler form and can be held taught when manipulating. Fabric is much more difficult to hold taught and predict its shape. A car chassis, if being moved around in manufacturing, holds its form because it is a solid form. Fabric is constantly changing form and is challenging, if not impossible, to predict. Automation makes the localization of this production process appealing - a major reason that most of the United States' apparel manufacturing was offshored at the turn of the 21st century is because of the high cost of labor in the United States. Automation would offset labor costs with efficiencies.

Figure 4: Step consolidation using Vega 3D weaving

Yarn Recovery To Bring Full Circle

One large issue with the way humans manufacture is that humans take materials out of their inherent or natural cycles and bring them down a streamline that often renders the materials unusable after one “product life”. If we are able to emulate nature’s modular and additive approach in designing we may be able to also achieve a cyclical process. Here we have taken that approach: we design with the idea of both adding up and just as easily taking apart. Our Vega 3D weaving method can effectively be reversed to go back to the material the process starts with: yarn. We call this yarn recovery (Figure 5).

Figure 5: On the left, current jeans made of many short lengths of horizontal weft yarn, as the fabric is stamped when cutting pattern pieces; on the right, our technology allows for jeans to be made from a continuous single weft yarn, skipping the stamping stage

Figure 6: Process of removing weft yarn from a Vega 3D woven pant, keeping the yarn intact

At the end of the product lifecycle, continuously woven garments are more recyclable than traditionally cut-and-sewn products. If the proposed manufacturing process is reversed, the singular weft thread garment could be unwound back into a spool of yarn, enabling it to be easily reused (Figure 6). This is not feasible with woven products made with current cut-and-sew techniques, as the stamped, or cut, panels are composed of hundreds of thousands of short, individual yarns, which are not economical to respin into yarn. In bypassing the stamping stage and weaving straight from yarn to final product, the proposed technology keeps the weft yarn intact throughout the entire process, from yarn spool to pants and back again.

Discussion

Our business model is to license Vega machinery and technology for an annual fee to our partners, often apparel manufacturers. This format of this business model helps reduce manufacturers’ up front investment required and also permits us to continue to support the machines and technology, offering frequent upgrades both to the software and hardware.

To simplify our go-to-market and testing process, four steps are outlined below. After we build our technologies we need to test both that they work and also that they are as positively impactful as anticipated. After building out our R&D, we:

1. Test the technology, products, and business model in our microfactory at our Headquarters near Oakland, California.
2. Test the technology, products, and business model via publicly-launched and publicly-accessible collaborations, where we sell 3D-woven products in the market.
3. Deploy our Vega to manufacturers that are able to produce for brands.
4. Scale up manufacturing for brands via these manufacturing partnerships.

Of the outlined process, our current focus is step 3: deploying Vega to manufacturers capable of producing for major brands. This step builds on significant milestones achieved in steps 1 and 2.

Step 1 involved the development and optimization of Vega's core technology, ensuring it met the demands of scalability, precision, and sustainability. This phase was marked by rigorous testing and refinement, enabling us to achieve a solution that aligns with the evolving needs of global brands. Step 2 was focused on piloting Vega with select brands. For example, we gained learnings and traction through high-profile launches, including a collection debut at New York Fashion Week in September 2023 and a capsule launch planned for Paris Fashion Week in March 2024 (Figure 7). These pilots provided critical insights into the integration process, confirming that Vega could seamlessly enhance existing production workflows while delivering measurable efficiencies.

Now in step 3, we are deploying Vega to manufacturers positioned to serve global brands at scale. This deployment phase is supported by strategic plans to enter step 4, which will involve scaling operations further to meet anticipated demand. We've secured significant commitments from global partners to drive this growth. We have established multiple offtake agreements totaling over $100M in commitments. Among these partners are Decathlon and Walmart, with products expanding from pants into other soft goods like bags and pillows (Figures 8, 9, 10). Although exciting, there are major hurdles to overcome in deploying our technology all over the world. We do not have a lot of example factories with our deployed technology, and so it is difficult to convince new manufacturers that they can trust our technology or at least trust that we will create a partnership that is beneficial to all parties. Fortunately, as the number of partner factories increases, we anticipate this will become less and less challenging.

Figure 7: Vega 3D woven product evolution

Figure 8: first Vega 3D-weaving product type, pants

Figure 9: other product type, bags

Figure 10: other product type, pillows

Yarn recovery as a method for recycling and/or reuse should be considered among other methods of the circular economy. Generally when a garment can be reused it should be reused or resold via resale methods. This is simply giving the product a new home. The circular economy alternative to resale at the moment is recycling, where the garment is collected and either shredded or somehow reduced down to the fiber or polymer level for the reuse of the material. There is no in-between method. We see yarn recovery as an in-between alternative, where the material - the yarn itself- does not need to change phase or be shredded in order to go through more steps for reuse. This could be described in the hierarchy: resale, recovery, recycling. Yarn recovery can be used with Vega 3D weaving and is not realistic with typical cut-and-sew methods because the yarn is more continuous. Still, there are limitations. Anywhere the yarn is broken, whether currently at the rise seam of the pant (plans exist to avoid this seam in the future) or where a hole occurs, will present a problem. The yarn could be spliced together but this may be tedious. Instead yarns should be at least 10m long for reuse. (Note that a typical weft might travel 150m around the leg, with 6 wefts simultaneously traveling around. This number was obtained with the assumptions that the specs of the pant are 35ppi, the circumference of the pant is around 25in or 0.6m, the length is 40in or about 1m, and there are 6 shuttles or weft yarn insertions.) With industrially-made (i.e. not handspun) yarn this will be less of an issue. For example, sweaters, which often feature yarn that has been handspun or at least more loosely spun, frequently get holes in high-wear areas like elbows because of the weak nature of the yarn. For yarns that have lost strength in wear, we can add sizing to strengthen the material.

Conclusions & Recommendations

This technology has proven its effectiveness through successful collaborations with fashion brands, where we have launched small collections selling in the low thousands of units, and developed products approved for mass production by some of the world's largest retailers. These achievements demonstrate that we can create improved products while paving the way for transformative changes in the industry. The implications of this shift in process are not only significant for the apparel industry but also highly beneficial for the planet.

As we move into the scaling phase, the technology will be tested further from both an impact and financial perspective. Alongside the growth of the Vega 3D weaving technology, we plan to expand testing of the yarn recovery process on a larger scale. Brand partners who are already implementing Vega 3D weaving are also eager to adopt yarn recovery technology, completing a fully circular approach. Collaboration with a wide range of industry players will be critical to the success of these technologies and their positive impact on people and the environment. In addition to adopting Vega 3D weaving and yarn recovery, we recommend exploring other circular concepts, as addressing the industry's massive challenges will require diverse and multifaceted solutions.

Acknowledgements

So much appreciation over the past 8+ years to:

- Annika Visser, Unspun's Brand Lead, for calling this opportunity to Beth's attention and for her ever-present guidance and support, including with this paper
- the entire Unspun team for seeing and realizing the dream, and continuing to chase with open arms
- all of Unspun's investors and mentors for their support
- the National Science Foundation for providing Unspun with its first grant through the SBIR program
- other granting agencies and institutes like Advanced Functional Fabrics of America and the Defense Logistics Agency for their support in previous and ongoing projects
- customers + partners for continued collaboration

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