Stepping out of line: A systems-thinking, materials-centric approach to designing for sneaker circularity

by

Leslie Yan

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ABSTRACT

Designing for sneaker circularity presents an opportunity to recover material value within an industry that produces 20+ billion pairs of shoes each year. However, the barriers to a circular sneaker economy are reflected in the complexity of sneaker design, as well as the broader system elements dictating the linear model through which shoes have traditionally been produced and consumed. Sneaker circularity can only be realized by addressing the industrial, financial, and social contexts in which a product economy operates.

In light of this complexity, the goals of this thesis are twofold. The first is to construct a systematic understanding of the broad, product-oriented challenges facing the development of a circular sneaker economy. Direct insights from those within the footwear industry The second is to build upon this understanding in order to to inform a new ethos for designing sneakers for materials circularity. This holistic approach will be demonstrated through concept and practice through the material lens of a mono-polyethylene sneaker. Novel textile-based techniques oriented towards circular material design and recovery will be explored.

This thesis argues that advancing towards a circular sneaker economy will first require taking one step back: to recognize the larger systems picture surrounding the vision of sneaker circularity, as well as to ground their efforts in materials, the foundational currency of any circular product economy.

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CONTENTS

INTRODUCTION

Few objects embody the intersection between fashion and engineering as perfectly as the modern sneaker. The sneaker of today stands as a cultural icon that spans the realms of high-level athletics and daily essential wear. Yet, every pair of sneakers is a study of biomechanics, materials science, and advanced manufacturing processes.

However, the design complexity of a product produced at fast fashion volumes results in significant environmental implications. In 2020, over 20 billion pairs of shoes[1] were produced by a global industry independently responsible for a staggering 1.4% of global greenhouse gas emissions[2]. The sneaker, in particular, presents a lens through which to understand the basis of these disconcerting figures: for a standard running shoe, materials and manufacturing are responsible for 98% of its lifetime carbon footprint[3]. In other words, the manner in which sneakers are designed and produced today is inherently unsustainable. Furthermore, these numbers say little about the waste engendered in this design tradition: while few wide-scale efforts have been made to track the end-of-life pathways of shoes, available data suggests that the vast majority of shoes produced each year are destined for the landfill or incineration[4].

The footwear industry is not oblivious to the outsized role played by materials and design in their environmental burden. In light of such extreme levels of waste, the sneaker industry has begun to embrace the concept of sneaker circularity: an ideal that would divert the wastestream back into production and recapture material otherwise lost to disposal processes. However, the numerous challenges to achieving this ideal are already evident from the design stage. A standard running sneaker might consist of over 65 individual parts manufactured from more than a dozen different materials[5]. Furthermore, this jumble of multi-material components are glued and stitched together in a manner that, by design, prevents disassembly for material separation and recovery through means that would preserve the quality of the recyclate.

When I began my investigation into design for sneaker circularity, I naively adopted the same approach being practiced by well-meaning footwear brands: playing the replacement game with materials offering sustainability and recycling advantages. Before long, the short-sighted nature of this strategy became painfully evident. As I attempted to align material

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[1] Portuguese Shoes, "The World Footwear 2021 Yearbook."
[2] Quantis, "Measuring Fashion."
[3] Cheah et al., "Manufacturing-Focused Emissions Reductions in Footwear Production."
[4] US EPA, "Nondurable Goods."
[5] Cheah et al., "Manufacturing-Focused Emissions Reductions in Footwear Production."

circularity principles to the design requirements of the sneaker, I found myself needing to ask questions that expanded beyond the physical shoe itself. Early conversations with industry experts followed a similar direction. At the center of this questioning stood a fundamental frustration: how can circular design make sense for a system as complex as that of the sneaker?

Therefore, the goals of this thesis are twofold. The first, is to construct a systematic understanding of the broad, product-oriented challenges facing the development of a circular sneaker economy. The second is to build upon this understanding to inform a new ethos for designing sneakers for materials circularity, as well as to demonstrate this ethos through concept and practice. Part 1 and Part 2 of this thesis reflect the research efforts towards these two goals, respectively.

While appreciative of the intricacy of sneaker design, this work does not claim expertise in the nuances of footwear development, nor propose a solution for a "circular sneaker." Rather, this thesis argues that making progress towards a circular sneaker economy will first require taking one step back: to recognize the larger systems picture surrounding the vision of sneaker circularity, as well as to ground their efforts in the foundational currency of any circular product economy--the materials that make up every shoe.

Certainly, to even begin a transition to a circular sneaker economy is a challenge that will require formidable effort on the part of a multitude of stakeholders in and beyond the footwear industry. However, this thesis seeks to contribute to the conversation by cutting through the complexity with a pragmatic approach to designing for a more sustainable system.

BACKGROUND

The circular economy

Over the past several decades, the idea of the circular economy has evolved[6] and broadened to encompass a vast range of conceptualizations[7] proposed in both literature and practice. Given the focus of this thesis on the material nature of sneakers, this thesis pulls from literature contextualized for tangible and durable consumer products[8] to describe the circular economy as follows: a framework that seeks to maximize the value and utility of materials circulating within a system for as long as possible. In this scope, the circular economy model closely follows the physical flow of materials through an ecosystem[9].

The circular economy is commonly segmented into a "technical" cycle for finite (often synthetic) materials to be kept in use and a "biological" cycle for renewable materials from which nutrients are to be returned to nature[10]. While both pathways are viewed with equal importance in this school of thought, this thesis will focus on circularity within the technical cycle given the overwhelming use of synthetic materials in sneakers, especially those of the athletic variety.

A key assumption of the circular economy is that products are currently designed for a "take-make-waste" business model that imparts significant environmental harm and is ultimately unsustainable from economic, ecological, and social outlooks[11]. Decoupling economic growth from the consumption of materials and production of waste is argued to be a key tenet of the circular economy[12]. Furthermore, language surrounding the circular economy highlights the financial advantages of circularity for business actors in light of increasing global resource scarcity and volatility[13]. The Ellen MacArthur Foundation, an organization regarded for its work in promoting the circular economy, claims that the circular economy "provides multiple value creation mechanisms," referring to both the environmental and financial value of materials[14]. The link between natural and economic capital emphasized by the circular

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[6] Bocken et al., "Product Design and Business Model Strategies for a Circular Economy."

[7] Geissdoerfer et al., "The Circular Economy – A New Sustainability Paradigm?"

[8] den Hollander, Bakker, and Hultink, "Product Design in a Circular Economy."

[9] Korhonen, Honkasalo, and Seppälä, "Circular Economy."

[10] Ellen MacArthur Foundation, Ellen MacArthur Foundation, "Circular Economy Principles."

[11] Ritzén and Sandström, "Barriers to the Circular Economy – Integration of Perspectives and Domains."

[12] Kjaer et al., "Product/Service-Systems for a Circular Economy"; US EPA, "What Is a Circular Economy?"

[13] Lieder and Rashid, "Towards Circular Economy Implementation."

[14] Ellen MacArthur Foundation, "Delivering the Circular Economy."

economy makes the framework particularly salient to industries driven by sales of consumer products, such as footwear.

There is a strong argument to be made for framing the shift to a circular product economy through the lens of design, a practice known by the shorthand of "circular design."[15] Decisions made at the design stage will determine the journey of a product, and thus its materials, through human systems. Therefore, it is key that circular design methods engage a holistic systems-based perspective that considers factors such as business needs and governmental regulations[16]. Iacovidou et. al underlined the importance of systems-based thinking in achieving a circular product economy by proposing a "system of systems" approach for resource recovery that can be utilized to identify central challenges. This holistic approach, visualized in Fig. 1a, presents a high-level understanding of the five subsystems key to supporting a transition to a circular economy. Crucially, interactions and flows between these subsystems are defined by spatial (geographic) and temporal boundaries[17].

The five subsystems can also be categorized into the "five levels of information" hierarchy, described in Fig. 1b, that lends insight into the mechanisms of resource recovery. At the top of this hierarchy lies natural resources and provisioning services, which encompasses materials, material flows, and material properties as it pertains to recovery. This is followed by technology, infrastructure, and innovation, which contends with aspects such as manufacturing and waste management. Subsequent levels include regulatory frameworks, business activities, and human behavior.

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[15] Ellen MacArthur FoundationEllen MacArthur Foundation, "Design and the Circular Economy."

[16] Webster, "A Circular Economy Is About the Economy."

[17] Iacovidou, Hahladakis, and Purnell, "A Systems Thinking Approach to Understanding the Challenges of Achieving the Circular Economy."

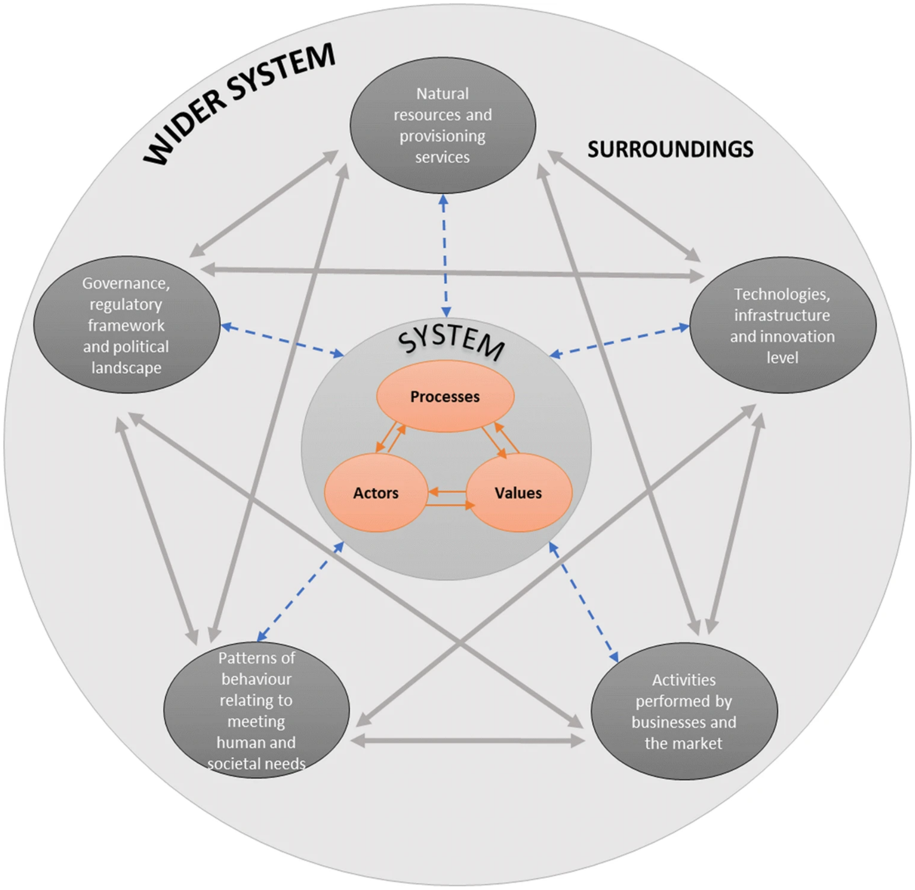

Figure 1a:

System of systems framework for resource recovery proposed by Iacovidou et. al

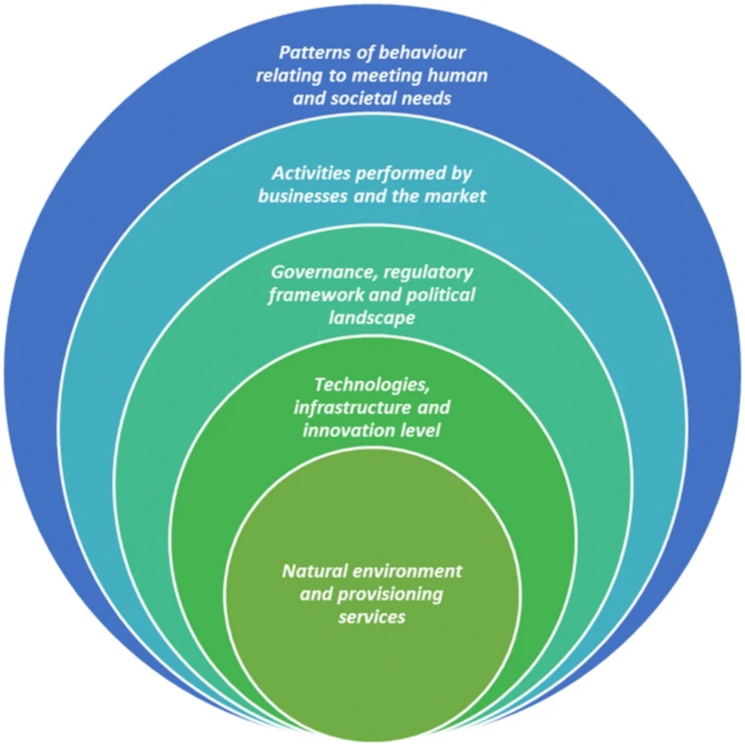

Figure 1b:

The five levels of information hierarchy as proposed by Iacovidou et. al. The hierarchy describing the relevance of the five subsystems to a resource recovery framework.

Another circular economy framework relevant to this work comes from Bocken et. al, who identified the following fundamental strategies to building a circular product economy: (1) slowing resource (material) loops by maximizing the life of products, and (2) closing resource loops by recovering material from products for continuous reuse[18]. A third strategy, (3) narrowing resource loops by increasing the material efficiency of products, is not exclusively "circular" but can also contribute to the development of a circular product economy.

The first two strategies, slowing and closing, were identified to be the most crucial to the transition to a circular economy. They can be used to situate specific circular design techniques; an adapted list is presented in Table 1.

Table 1: An overview of select design techniques categorized under the fundamental strategies of slowing resource loops and closing resource loops, described by their design intent and the corresponding product property. Adapted from Bocken et. al.

	Design intent	Product Property
Design for slowing loops	Design for long (useful) product lifetime	durability
	Design for product life extension	Maintainability, repairability, product upgradability
Design for closing loops	Design for biological circularity	Biodegradability, compostability
	Design for remanufacturing	Modularity and disassemablability of components
	Design for material recovery	Monomateriality, Modularity and disassemablability of separate materials

It should be noted that, closing material loops is distinct from closed product loops, defined here as the continuous recycling of a product into the same product type (in other words, "pure" circularity). In theory, a closed product loop presents the clearest means of upcycling, a key term in the circular economy that can be understood as the retention of material value or the addition of value to discarded material[19]. However, to achieve an entirely

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[18] Bocken et al., "Product Design and Business Model Strategies for a Circular Economy."

[19] Lindeberg, *Disclosing the Definition on the Upcycling Concept*.

closed single-product loop would require operating a strictly-controlled value chain under severe limitations with little room for error. Certainly, operating at the broader material level rather than the product level creates the risk of downcycling, also referred to as cascading. Cascading is attributed to the cycling of materials in a manner that degrades their quality and thus their value[20], such as the recycling of textile garments into rags or insulation[21]. Nevertheless, a materials-level perspective on circularity offers greater flexibility and opportunity for creative material flow pathways that may be more feasible than those mandated by a closed product loop.

In a discussion oriented around physical goods, it is also important to distinguish the circular economy from a system centered around recycling. As a technique aligned with the strategy of "closing resource loops," recycling serves an important role in the circular economy as a means to recover value from materials that can no longer be used in their existing state[22]. However, in the present day, recycling is applied only at product end-of-life, while the circular economy argues for preserving and enhancing material value from the very beginning of the product lifecycle. Use of recycling as a circularity solution in isolation merely prolongs the timeframe of the linear model, as use practices and infrastructural challenges in the recycling space means that recycled material is often of lesser quality and thus lower value. These challenges include limitations to the capability and scale of current recycling technologies; see Table 2 for an overview of these technologies adapted from Schyns and Shaver. For instance, the most common and cost-effective recycling solution for plastic waste is mechanical recycling, which involves the mechanical reprocessing (washing, sorting, grinding, etc.) of the plastic material for reuse. However, the frequent use of plastic additives and separability challenges presented by multi-material designs can make it challenging for present sorting technologies to remove impurities that degrade the mechanical properties of the recycled plastic. Correlating material value to the functional quality of the material relative to its virgin form, this means that recycling as currently practiced often results in some irreversible loss of material value.

Critical discourse in academia has raised the argument that, in light of technical barriers[23] and systems complexity, a fully-closed materials loop may not be achievable[24] in any

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[20] Campbell-Johnston et al., "The Circular Economy and Cascading."
[21] Ellen MacArthur Foundation, "A New Textiles Economy."
[22] Kjaer et al., "Product/Service-Systems for a Circular Economy."
[23] Korhonen, Honkasalo, and Seppälä, "Circular Economy."
[24] Allwood et al., "Material Efficiency"

product economy. Indeed, it is more productive to frame the narrative surrounding the circular economy as a transition effort[25] made with respect to temporal boundaries.

Table 2: Standard definitions of the four hierarchical tiers of recycling, as reproduced from Schyns and Shaver.

ASTM D7209 definitions (withdrawn 2015)	ISO 15270:2008 standard definitions	Example
Primary recycling	Mechanical recycling	Bottle to bottle closed loop recycling
Secondary recycling	Mechanical recycling	Recycling into lower value plastic
Tertiary recycling	Chemical recycling	Depolymerization of polyesters
Quaternary recycling	Energy recovery	Pyrolysis

The sneaker

Sneaker design and construction

Modern sneakers are found in an enormous array of styles geared for a variety of applications, whether athletic, lifestyle, or a combination of both. With such diversity, it is difficult to define a prototypical sneaker design; however, many sneakers do share similarities in fundamental construction. A sneaker is composed of two main functional units[26]: the upper is the top portion of the shoe that covers the foot, while the sole is the lower portion of the shoe that is underneath the foot. This section will provide a broad summary of the elements that make up both the upper and lower. Figure 2 visualizes this summary with an anatomical overview of a generic running shoe, and Table 3 describes the functional qualities by which a selected list of these elements can be assessed, as discussed by Werd et. al[27].

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[25] Ellen MacArthur Foundation, SUN Foundation, and McKinsey Center for Business and Environment, "Growth within: A Circular Economy Vision for a Competitive Europe | McKinsey."
[26] Cheah et al., "Manufacturing-Focused Emissions Reductions in Footwear Production."
[27] Werd, Knight, and Langer, *Athletic Footwear and Orthoses in Sports Medicine*.

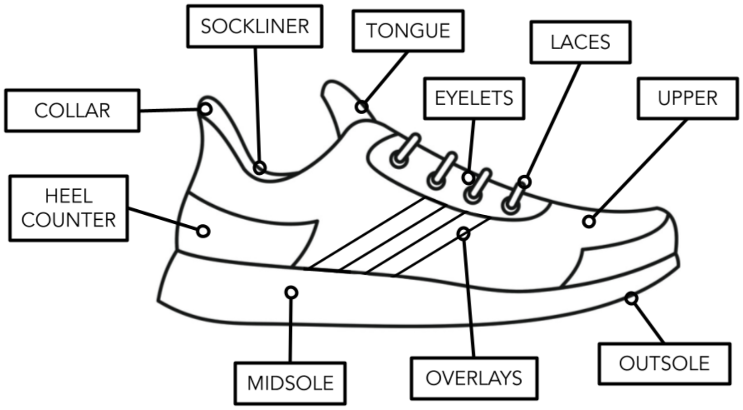

Figure 2: Diagram of a running sneaker denoting key parts of the shoe.

Table 3: Desired performance qualities of various sneaker components.

Shoe Component	Performance Quality
Upper	Water/Sweat-Wicking
	Water Resistance
	Drying Rate
	Breathability
	Abrasion Resistance
	Tensile Strength
Sockliner/Insole	Water/Sweat-Wicking
	Friction
Midsole	Shock Absorption
	Resilience
	Hardness
Outsole	Traction
	Torsion Rigidity
	Cracking Resistance

From a design standpoint, the upper tends to be significantly more intricate than the sole, serving as the central canvas for aesthetic contributions while also fulfilling multiple functional requirements[28]. Typically, these requirements differ between regions of the upper, depending on needs for distinct areas of the foot, manifesting in an upper with property gradients. A standard upper might be formed from a large piece (or multiple pattern pieces) of a single flexible material to which a myriad of separate internal and external components are joined together to form the final upper unit. The heel counter and toe box are key internal components that create select areas of stiffness for protection and foot support. Additional forms of reinforcements are often added in other parts of the upper, such as saddle overlays over the sides of the foot and eyelets to hold laces. Certain sections like the collar and the tongue tend to be padded for comfort, and lining plays an important role for moisture-wicking. An instructional resource from Nike describes eighteen (18) unique parts that are typical of a sneaker upper.

The sole of a sneaker consists of two main parts: the outsole is in physical contact with the ground and provides key traction and torsional rigidity, while the midsole is crucial for cushioning and shock absorption, especially for running shoes. The sockliner, or insole, is a padded layer that contacts the underside of the foot. Stitching and/or various adhesives are used extensively throughout the sneaker to join the parts of the shoe.

A huge variety of different materials are used for sneakers. Oftentimes, a combination of these materials are used to construct a shoe; a single sneaker might include a dozen different types of materials, such as leather, ethylene vinyl acetate (EVA), and nylon.

Sneaker supply chain

The amalgamous nature of the typical sneaker design is also reflected in the shoe supply chain, especially at the manufacturing stage. A 2012 study found that a standard sports sneaker required 360 processing steps for assembly of 65 discrete components. Figure 3 provides a visual diagramming of the numerous steps in the traditional footwear supply chain per supplier tiers and assembly stages as described by Goni et. al and Shirin[29]. It should be further noted that the geographical boundaries of shoe production is not reflected in this diagram; specifically, the role of Asia as a major hub of shoe production. In 2020, Asia produced over 87.6% of global footwear products, with China at the lead by a significant

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[28] Nike, "Anatomy of a Shoe."

[29] Goni and Kadarusman, "Local Company Contribution within Global Value Chain"; Shirin, *Traditional Supply Chain vs. Adidas Speedfactory Diagram*.

margin[30]. The vast majority of these shoes are exported to the U.S., home of the world's largest footwear market[31]. The widespread geography of the sneaker value chain adds another layer of complexity into the system.

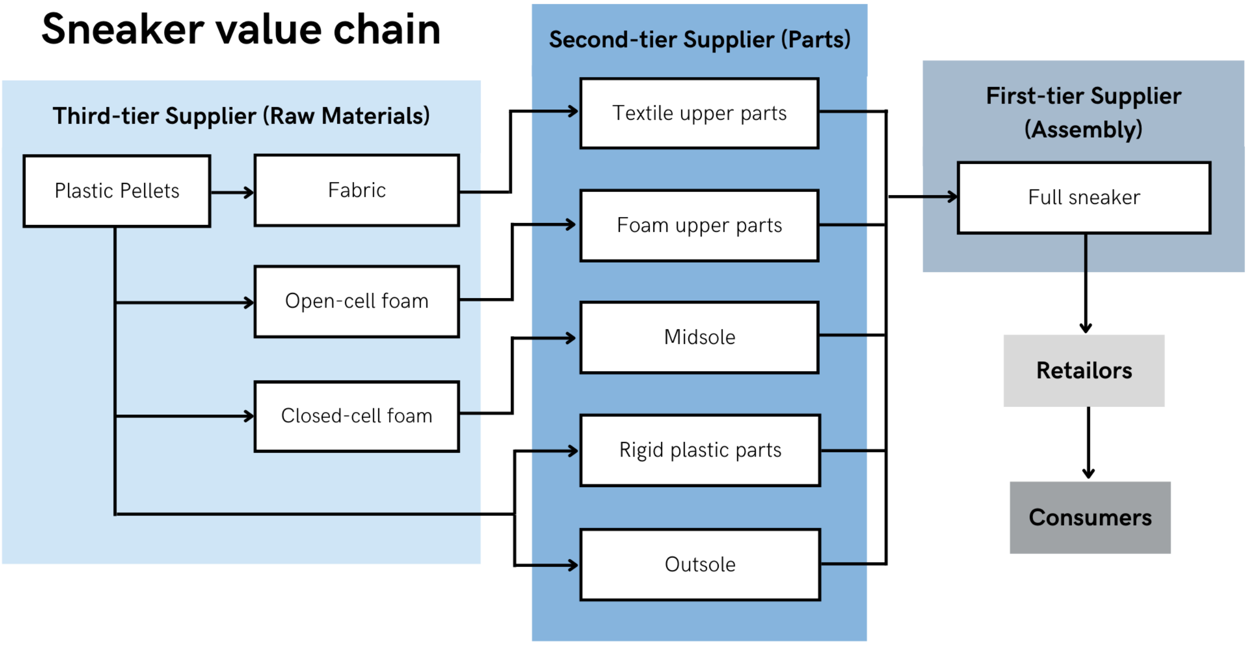

Figure 3: Simplified sneaker value chain organized by tier and stage of manufacture/distribution, adapted from Goni et. al and Shirin.

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[30] Portuguese Shoes, "The World Footwear 2021 Yearbook."
[31] Smith, "Footwear Market."

I. UNDERSTANDING THE PRODUCT-ORIENTED SYSTEM CHALLENGES TO SNEAKER CIRCULARITY

While shoe circularity is not a new concept to the sneaker industry, as will be later discussed, there has been little in the way of formal investigation into the barriers to the development of a circular sneaker economy. Hence, this first phase of research seeks to address this knowledge gap and construct an understanding of the product-oriented challenges aligned with a systems thinking framework. To achieve this goal, a streamlined version of Iacovidou's "system of systems" framework has been adapted to emphasize the five external subsystems key to a material recovery system and improve specificity to a circular economy for durable goods. Figure 4 visualizes this adapted system framework.

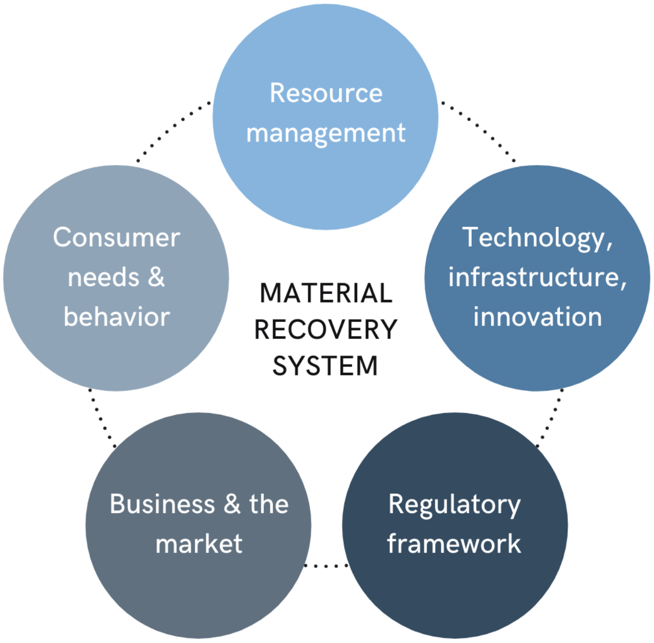


Figure 4: Adapted material recovery subsystem framework for durable goods, based on Iacovidou et. al

To begin building familiarity with ongoing discussions in this space, a broad review of topical articles and publications related to sneaker circularity was undertaken; in absence of relevant academic literature, the majority of these writings came from sneaker brands and media outlets. Nevertheless, it became evident that a complete understanding of the obstacles to a circular sneaker economy would require consultation with those closest to the industry. Thus, with the goal of developing a full awareness of these challenges, two modes of primary research were undertaken: a questionnaire and in-depth interviews.

Questionnaire

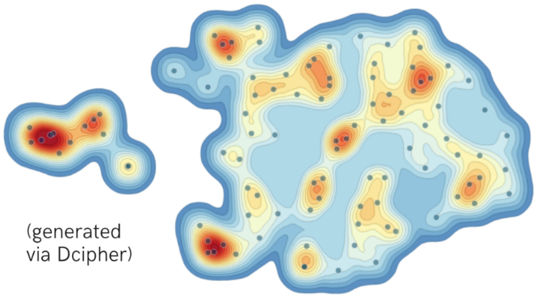
To construct a broader picture of the current state of circularity in the footwear space using insights aggregated directly from those in and adjacent to the industry, a questionnaire was developed and distributed to a wider network of professionals working in the footwear and/or sustainability space. 104 complete and unique responses were recorded after a three-week period, with footwear brand designers and developers making up the largest portion of respondents. A breakdown of the respondent demographics can be seen in Fig. 4.

Figure 4: Demographic breakdown of survey respondents by role and affiliation to footwear brand.

In the questionnaire, the following free-form response question was posed: "What do you believe to be the major barriers to developing a circular shoe system? Feel free to be as brief or detailed as you'd like." The recorded responses to this question were then entered into the Dcipher Analytics platform using a survey-optimized toolbox, a natural language processing software for analysis of unstructured text. From the dataset, Dcipher identified key topics extracted through sentiment analysis and grouped these topics by theme.

Question: What do you believe to be the major barriers to developing a circular shoe system?

Semantic Landscape of Responses



(generated via Dcipher)

Grouped Topics from Sentiment Analysis

- Circularity, recycle, design, current
- Life, shoe, end, way, time, material
- Technology, need, recycling, component, scale
- Infrastructure want, value
- Collection, process
- Brand, money
- Industry, company, cost
- Lack, education, end of life
- Consumer, sustainable product

Figure 5: (Left) Semantic text landscape of free responses showing a relational map of topics identified by the Dcipher AI-model; the color-coded clusters indicate a concentration of a recurring theme. (Right) Key topics extracted and grouped from the free responses via sentiment analysis performed by Dcipher.

Interviews

While the survey provided a useful overview of sentiments dominant among those in and adjacent to the footwear industry, it was clear that tapping further into expert perspectives on topics relevant to shoe circularity would aid in a more nuanced assessment of challenge areas. Thus, in-depth interviews were conducted with 13 professionals with senior roles from a wide range of backgrounds within footwear and sustainability. The identities and organizations of these senior professionals have been anonymized; however, a segmented overview of their backgrounds are described below in Fig. 6.

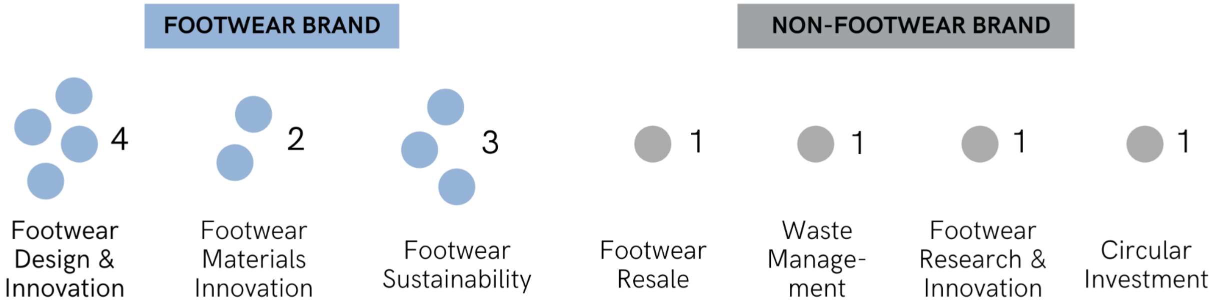


Figure 6: Demographic breakdown of interviewees by role and affiliation to footwear brand.

These interviews were organized in a semi-structured format in order to extract the greatest value from the conversation. A set of questions including topics general to shoe circularity and specific to the background of the interviewee, as informed by topics raised in the questionnaire responses, was prepared beforehand. However, conversations were allowed to expand beyond this list in order to probe deeper into topics that arose.

A thematic analysis was performed with the interview data to identify common themes that arose throughout all thirteen conversations. Given the product-oriented scope of this thesis and its material-based definition of circular economy, only themes tied to the circularity of sneakers or sneaker materials are presented below. However, guided by the topics highlighted in the questionnaire data and a systems-thinking perspective, the goal of the thematic analysis was to expand beyond the purview of sneaker design. The results from the thematic analysis are described in Table 4.

Table 4: Themes pulled from thematic analysis of 14 expert interviews, as well as corresponding frequency (frequency = 1 indicates mention of theme in one interview) and examples from the interviews.

Theme	Frequency	Examples
Material and construction complexity of sneakers	12	"I think part of the reason why shoes are further behind [with regards to circularity] than the general fashion or textiles space, it's just because of the complexity of the issue, especially talking about an athletic shoe or a hiking boot or something, like that's way more complex than a T-shirt." "We need to recognize that 95% of the shoes are made pretty much the same way, where we use adhesives and we cement on these pieces." "For an upper, you want it to be soft enough to stretch, breathable for the bottom, you want to have recovery, abrasion resistance, maybe stain resistance…it's the challenge of pulling out all these different properties."
Mechanical degradation of recycled sneaker materials	11	"With recycled polyester and other things, they all have a heat history. So there's only so many times you can recycle this material before it completely loses its integrity, and then what do you do with it?" "These circular post-consumer products, they're grinding it down and making it into stiffer components…you can't make your insole or foam because [the material] properties are so severely degraded in that second life."

Infrastructural limitations to waste collection & management for sneakers	11	"It's not going to be cost efficient to disassemble a shoe if it takes someone an hour to take it apart and separate out all the pieces…Taking apart or repairing a product is so expensive compared to how much you can then sell that product for that, economically, it just doesn't make sense." "On the post-consumer side there's a lot more complexity, not only in terms of the technical elements…let's say everybody in the states is going to turn in their product. We don't currently have the infrastructure here to collect it."
Immaturity of promising circular innovations	9	"It's just the lack of maturity of chemical recycling. I'm hopeful that it will take over and be able to get us more to like a shoe-to-shoe type of recycling capability, but it's just not there yet." "[There is a] whole new big pool of materials that we don't have access to today." "I'm a big fan of chemical recycling [but it] hasn't scaled yet, and it's very expensive. But I hope that we will have something like this in the future."
Wide geographical spread of sneaker supply chain and lack of localization	8	"As we start to think about a more global view of how things are made and recycled there needs to be a chain of custody or something that allows for that fluidity between us products and manufacturing in China." "The full shoe supply chain should be decentralized…Shoes for the U.S. should be produced in the U.S.. collected in the U.S., recycled in the U.S., and produced again in the U.S. The same for Europe, same for Asia. But initiatives that have tried it haven't succeeded.
Consumer behavior, expectations, and motivations with respect to sneaker circularity	10	"Even in terms of getting that product back, if you're relying on that as feedstock and consumers…hold onto it [or there is] inconsistency in terms of [when] consumers sent it back…you can't rely on it as steady feedstock in the supply chain." "At the end of the day, this is all going to be driven by what the consumer thinks, whether the

		consumer thinks that this product is good.” “The values and behaviors just don’t match…[and] the retail industry and the things around it don’t make it easy…like where do I take it if I want it recycled, is there a place I can take it for repair?”
Economics of shoe circularity	9	“At the end of the day, like we're all here to make circularity makes sense. And it's going to require upfront investment, it's going to require brands probably putting more time and resources and money into things than you know, then they're getting out of it at first.” “I couldn't necessarily design a circular shoe without some vision of how that take-back system would come into play, and obviously that would require tremendous investment from the brand. So that’s one of the big challenges, I think, is that business model.”

Summary of Challenges

By synthesizing the themes uncovered from the questionnaire responses and the interviews, and contextualizing these themes with knowledge shared during the primary research phase, an integrated overview of the identified product-oriented barriers to transitioning to a circular sneaker economy are described below in Table 5. Moreover, to emphasize alignment with a systems-thinking approach, these challenges are situated according to the five subsystems key to a circular economy transition. While a number of the barriers are closely interlinked to multiple subsystems, for the purpose of clarity, each barrier has been categorized to their best-fit sub-system.

Certainly, for a system as complex as the sneaker industry, capturing every obstacle to a circular sneaker economy is an impractical goal. However, the identified challenges may reflect many of the most prominent topics that have begun to arise in growing conversation and efforts on sneaker circularity in the industry.

Table 5: Overview of product-oriented challenges to a circular sneaker economy as mapped to material recovery sub-system; synthesized from questionnaire free responses and interviews.

Sub-system	Challenge	Description
Resource management	Design Complexity	Current design methods and materials choices used for sneakers are not aligned with circularity. Specifically, to meet performance requirements, sneaker constructions are very complex on both a material and component level, and disassembly for material recovery is not feasible.
Technology, infrastructure, and innovation	Technical Recycling Limitations	Current at-scale recycling technologies are not capable of recovering material from sneakers at their highest value. However, alternative technologies with this capability are far from maturity.
	Takeback Logistics	An effective take back system for post-consumer sneakers does not exist, nor has been successfully demonstrated in practice.
Regulatory framework	Geography	The vast majority of sneakers are manufactured in Asia, and particularly in China. However, policies surrounding the import of waste material (known as the "Prohibition of Foreign Garbage Imports: the Reform Plan on Solid Waste Import Management") may pose a regulatory barrier to re-manufacturing of material from post-consumer shoes.
Business and the market	Cost	Building systems and developing new technologies to support a circular sneaker economy requires very high upfront investment without immediate or obvious economic returns for sneaker brands.
Consumer needs and behavior	Consumer Literacy	Consumers play a key role at the use and disposal stages, but there are significant gaps in consumer understanding of circularity. This presents a particular challenge to enabling product take-back, a process in which consumer participation is crucial.
	Product Expectations	Even sustainability-minded consumers hold certain expectations with regards to product performance and aesthetics. These expectations can be difficult to meet in practice when employing circular materials and design strategies.

Case study: System challenges to circularity through the lens of the Adidas Loop sneaker

In recent years, an increasing number of brands have made attempts to practice circular design techniques through their products; however, few of these efforts can be described as a truly holistic approach that engages a breadth of the systemic challenges described above. A pioneering example of such effort, as well as its shortfalls, can be seen with the Adidas Futurecraft.Loop (Fig. 7).

The Loop sneaker, a beta-released performance running shoe made entirely from thermoplastic polyurethane (TPU), is perhaps the most prominent example of a circular sneaker product in recent years. The Futurecraft.Loop capitalizes on a mono-material design approach, engineering TPU into various foam, textile, and rigid components to create a sneaker that feels and performs similarly to a traditional running shoe but is fully recyclable as a single unit[32]. Ambitiously targeting a "pure" practice of a circular economy, the brand furthermore pursued a closed-loop product strategy by aiming to mechanically recycle the TPU from the Futurecraft.Loop into material for the next generation of mono-TPU Loop sneakers[33] (later called the Ultraboost DNA Loop).

Figure 7: (Left) First-generation Adidas Futurecraft.Loop sneaker. (Right) New "Ultra Boost Made to be Remade Shoe" with QR code on tongue.

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[32] Adidas, "Adidas Unlocks a Circular Future for Sports with Futurecraft.Loop."

[33] Fairs, "Adopting Circular Design Is 'Good for Business' Says Adidas Innovation Leader."

However, even with just 200 pairs distributed to select users[34], Adidas discovered that a significant challenge would lie with collecting the Loop shoes and building a sufficient volume of recycled feedstock into new sneakers[35]. In the end, only 10% of the material in the new Ultraboost DNA Loop sneaker was composed of material recycled from the original batch of sneakers[36]. Furthermore, this material was used only for the rigid components of the sneaker, a decision said to be made to shorten the manufacturing time frame[37]. Nonetheless, this raises questions regarding the mechanical performance of the recycled plastic.

It appears that Adidas has since expanded beyond the beta phase of the Loop sneaker and now sells a variation branded "Ultra Boost Made to be Remade Shoes." An update to the design includes a QR code on the tongue that can be scanned for details on how the shoe can be returned for recycling; perhaps intended to serve a visual reminder to the consumer[38]. However, multiple customer reviews complain of a lack of rebates or reward incentives for trading in their shoes.

By selecting a material and design strategy aligned with circularity, Adidas made a commendable effort towards creating a "circular" sneaker. However, the circularity shortfalls demonstrated by the product serve as testament to the importance of designing with both a materials and a systems-thinking perspective.

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[34] Burgess, "Futurecraft.Loop: New Adidas Shoe Uses Just One Material – and Is Fully Recyclable."
[35] Bain, "Adidas Is Learning It's Not Easy to Make 100% Recyclable Sneakers."
[36] Wilson, "Exclusive: Adidas's radical new shoe could change how the world buys sneakers."
[37] Bain, "Adidas Is Learning It's Not Easy to Make 100% Recyclable Sneakers."
[38] "Adidas Ultraboost Made to Be Remade Shoes."

II. DEMONSTRATING A SYSTEM-BASED, MATERIALS-CENTRIC DESIGN APPROACH

From above research, it is clear that progressing towards a circular sneaker economy through design will require a systems approach grounded in a holistic, materials-level perspective. With a framework to understand and situate the key challenges to sneaker circularity, the next part of this research will explore how a systems thinking approach to designing for sneaker circularity could be realized through a materials-centric lens in a present-day context. The goal of this demonstration is not to prescribe a particular design solution for the elusive circular sneaker; but rather, to illustrate how conscious material selection can drive unique circular design opportunities achievable with today's technologies and directly aligned with the systemic challenges to a circular sneaker economy. Thus, the discussed design possibilities will be mapped to their system barriers presented in the previous selection. Several highlighted materials-based design opportunities outlined in this design proposal will be validated in practice by prototyped material samples fabricated using scalable techniques.

Conceptual design of a recyclable mono-polyethylene sneaker

The case for polyethylene

While circular material innovations may conjure notions of novel organic matter or lab-synthesized inventions, a re-engineering of common polyethylene may be uniquely suited to address circularity challenges in the footwear space. Found in applications ranging from food packaging to shopping bags to toys, polyethylene (PE) is the most widely-used family of plastics in the world today[39]. Despite being among the cheapest commodity plastics available[40], polyethylene possesses many advantageous engineering characteristics such as good corrosion and durability[41].

The versatility of PE can be attributed in part to its thermoplastic nature, which means that it softens and/or melts when heated for easy processing. This also means that thermoplastics can be remelted for reuse, and are therefore mechanically recyclable. In fact, PE is one of the most commonly recycled plastics; unlike TPU, HDPE is one of the few numbered plastics broadly accepted in curbside recycling programs in the U.S.[42]

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[39] "A Plastic Fabric Could Keep People Cool — and Help to Fight Global Warming."

[40] Polymer Database, "Commodity Plastics."

[41] Boriskina, "An Ode to Polyethylene."

[42] US EPA, "Plastics: Material-Specific Data | US EPA."

Polyethylene further stands out from other thermoplastics due to the vast range of PE densities that can be synthesized. While all densities of PE share the same ethylene monomer (C2H4), they are differentiated by their molecular structure. The side-branching of the polymer chains in low-density polyethylene (LDPE) produces a plastic that is softer and more flexible than high-density polyethylene (HDPE), which is more rigid and durable due to its regular structure of densely-packed linear polymer chains (Fig. 8)[43]. Ultra-high weight molecular polyethylene (UHMWPE) has particularly long polymer chains, resulting in poor processability but superior performance when it comes to properties such as impact strength and abrasion resistance[44].

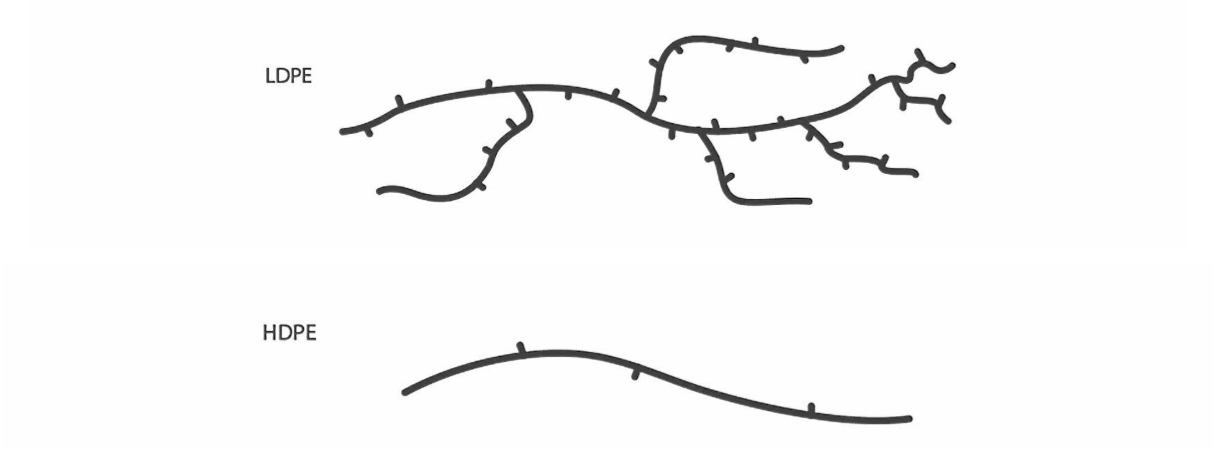

Figure 8: Comparison of the polymer chain for LDPE (top) and HDPE (bottom) (Polymer Properties Database). Note the extensive branching found on the LDPE chain, which decreases its packing density compared to the HDPE chain. Image adapted from Brown Ink Design.

Unlike many other types of plastics, different types of PE can be compatible when mixed, allowing for the creation of blends that optimize the advantages of both their constituent PE types[45]. The tailorable performance of PE blends presents an opportunity for the design of mono-PE products that avoid the need for separation and disassembly processes without compromising on performance.

As with other plastics, the current model of use for polyethylene is overwhelmingly linear. PE is generally synthesized from petroleum that is extracted from the earth via processes that harm the environment, while its low cost means that PE products tend to be seen as disposable. Furthermore, as previously discussed, thermoplastics that are mechanically

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[43] Omnexus, "Polyethylene (PE) Plastic."

[44] Omnexus.

[45] Sarkhel, Banerjee, and Bhattacharya, "Rheological and Mechanical Properties of LDPE/HDPE Blends."

recycled are susceptible to degradation of their mechanical properties due to current design and recycling practices. As a result, even HDPE and LDPE products that are recycled through common pathways may eventually suffer losses in quality and thus material value.

However, this does not mean that polyethylene is incompatible with a circular economy. The rise of bio-based plastics[46] that are synthesized from renewable resources, such as the bio-based I'm Green (™) PE from Braskem[47], demonstrates that use of PE can be decoupled from petroleum extraction. While chemical recycling technologies are far from being as wide-scale as mechanical recycling, they present a means of recovering the full value of recycled polyethylene by working at the polymer-scale, producing virgin-quality material[48]. It is also important to not discount mechanical recycling as a pathway for retaining material value, especially when designing for the process. HDPE can undergo several cycles of mechanical recycling without notable detriment to performance[49]; moreover, there continues to be considerable research being done on precluding the degradation of mechanically-recycled thermoplastics. One of the PE-specific design opportunities that will be covered later in this work will delve more deeply into a potential mitigation technique.

Sneaker circularity through mono-polyethylene design

As adroitly recognized by Adidas and other notable industry players, mono-materiality is a compelling circular design strategy for sneakers given the lack of existing infrastructure and technology for shoe disassembly at scale. However, with a mono-material approach, selection of an appropriate material that can meet the numerous functional requirements of the various parts of a sneaker is crucial.

While polyethylene is not among the plastics more commonly found in sneakers, recent innovation for a wearable application of PE and other unique advantages of the thermoplastic create a strong circularity argument for a mono-PE sneaker. A broad overview of this argument as aligned with the circular economy strategy framework from Bocken et. al is presented below.

> NARROWING LOOPS: The versatility offered by the many types of polyethylene, each presenting unique advantages that can be leveraged to meet different functional needs, enables mono-materiality underlined by a high level of material

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[46] Sherman, "Growth Rate of Bioplastics Higher than Overall Plastics Market Growth."
[47] Brasken, "Braskem I'm Green Bio-Based."
[48] Tullo, "Plastic Has a Problem; Is Chemical Recycling the Solution?"
[49] Schyns and Shaver, "Mechanical Recycling of Packaging Plastics."

efficiency. The manufacturability of polyethylene also enables production and collection practices that reduce input of resources like energy.

SLOWING LOOPS: Polyethylene offers excellent mechanical properties and wear durability. Performance can be further enhanced in form factors suitable for sneaker construction.

CLOSING LOOPS: Polyethylene stands out even among other thermoplastics as one of the few numbered recycling plastics typically accepted by curbside programs and recovered at a relatively high percentage rate. Moreover, scalable methods of maintaining and even upgrading the quality of recycled PE can be demonstrated. Finally, the growth potential for bio-based PE presents a model through which PE can be obtained from renewable sources.

It should be noted that the curbside recyclability of polyethylene raises the intriguing possibility of utilizing municipal recycling programs as a resource recovery pathway for a mono-PE sneaker. Such a pathway could be readily implemented without the need to build new infrastructure; brands would merely need to design for the existing system. Moreover, many consumers already practice curbside recycling, making the prospect of recycling a sneaker intuitive. Certainly, municipal recycling does not capture all material value and is likely to be channeled to downcycled applications; nevertheless, a sneaker that is curbside recyclable presents a compelling intermediate step in the sneaker industry's journey to building scaled product take-back systems for a circular economy.

The following sections will delve into the detailed PE design opportunities that contribute to all three circularity strategies, with a specific focus to textiles. The outcome will be a clear alignment between the conceptual design of a mono-PE sneaker to the proposed systems-thinking, material-centric ethos to sneaker circularity as grounded in key circular economy principles.

Again, this exploration doesn't aim to provide a fully-realized, comprehensive solution. In order to define a clear scope, focus will be placed on re-imagining the sneaker upper as a mono-PE form. From the perspective of mono-materiality, the upper arguably presents a greater challenge than the bottom unit. As previously discussed, the sneaker upper is traditionally composed of far more individual components and different materials, requiring different properties in different regions.

Certainly, this is not to say accomplishing a mono-material and recyclable sole is a simple task, especially given their high functionality requirements. A notable complication arises with the prominent use of cross-linked foams to achieve high levels of cushioning in performance athletic sneakers. While the cross-linking process yields desirable properties in an ultra-lightweight form factor[50], it also precludes re-meltability[51], thus rendering the foam non-recyclable via mechanical means into similar applications. In this sense, the challenge lies less with the specific material choice and more so with the way the material is engineered. Therefore, scaling novel recycling solutions will be an important tool to address this challenge; already, academic research and industry innovation in the space of recycling cross-linked polyethylene and other polymers is ongoing[52].

In the meantime, there is significant opportunity to advance sneaker soles towards circularity by designing for recycling capabilities available today. As brands continue to churn out new technologies in the sneaker cushioning space,[53] it is evident that midsole cushioning can be achieved with thermoplastics materials that can be mechanically-recycled, whether with non-cross-linked foaming technology as seen with Adidas Boost, or without the use of foam at all, as demonstrated with Nike Air.

This suggests the promise of a "bottom-up" approach to developing mono-material sneakers for recyclability: beginning the design process with a more traditional thermoplastic bottom-unit, then innovating the sneaker upper to achieve mono-materiality. Both the Adidas Futurecraft.Loop and the soon-to-be-released Cyclon Cloudneo shoe from ON Running appear to have taken this route with TPU and polyamide[54], respectively, emphasizing the relevance of understanding the potential for polyethylene as an upper material.

Performance and sustainability with polyethylene fabric

Despite its affordability and ubiquity in consumer products, polyethylene is not conventionally used for clothing and footwear, even as other synthetics like polyester and nylon have become dominant. While the value of PE as a rigid material or film is clear, its

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[50] Hsu et al., Crosslinked foam of ethylene vinyl acetate copolymer and acid copolymer.

[51] Fortman et al., "Approaches to Sustainable and Continually Recyclable Cross-Linked Polymers."

[52] Qudaih, Janajreh, and Vukusic, "Recycling of Cross-Linked Polyethylene Cable Waste via Particulate Infusion"; Borealis AG, "Unlocking the Value of Recycled XLPE."

[53] Newcomb, "The Technologies That Define Sneaker Cushioning."

[54] Adidas, "Adidas Unlocks a Circular Future for Sports with Futurecraft.Loop"; ON Running, "Tech Profile - The Cyclon Cloudneo."

hydrophobicity may have contributed to an impression that use of the polymer for fabrics would result in articles that would lock in sweat and moisture[55].

However, a high-performance polyethylene fabric engineered by the Multifunctional Metamaterials Group at MIT shows the significant potential of PE for wearable applications[56]. The PE fiber used for the textile is manufactured with industry-standard equipment through the fiber-melting spinning process, a common, affordable, and solvent-free method for producing synthetic fibers[57]. Yet, the researchers also demonstrated this standard process induces novel and efficient moisture-wicking and evaporative cooling abilities to the PE yarn. Once woven, the result is a textile that retains the traditional advantages of PE while unlocking new comfort and functionality without any chemical coatings. Notably, the PE fabric in woven form also has a lower environmental footprint than standard wearable textiles like cotton, polyester, and nylon when measured per the industry-standard Higgs Index.

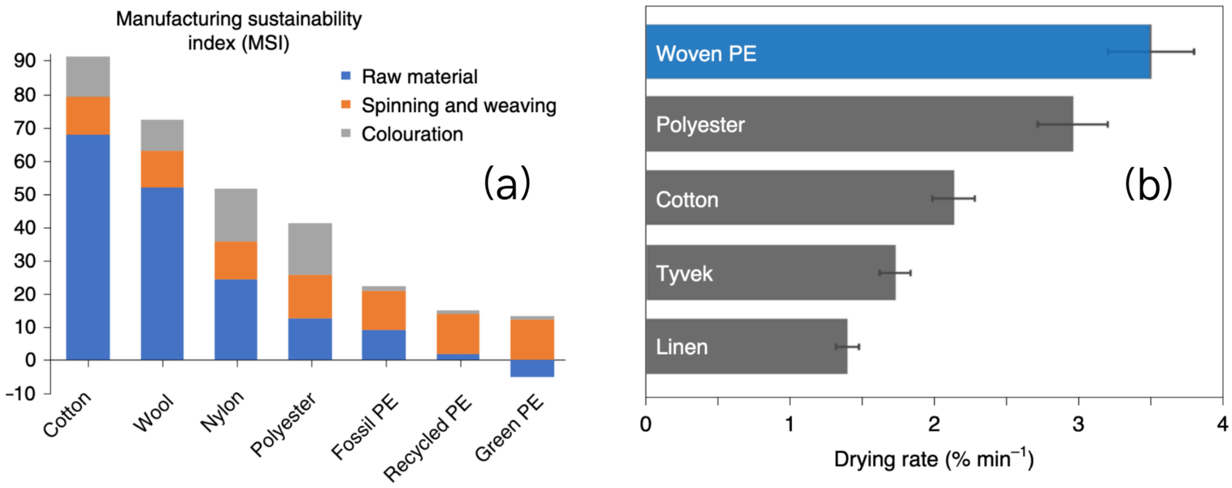

Figure 8: Comparison of drying rates (a) and the MSI Higg indices per 1 kg (b) of PE woven fabric and various standard woven textiles; figures from Alberghini et. al.

Lightweight, sweat-wicking, fast-drying, thermally cooling, the PE fabric is optimal for use in a sports sneaker upper even from a pure functionality perspective that does not consider circularity. In a product market defined by a competition to push the limits of athletic performance, this presents a clear business and marketing opportunity for a PE shoe. The lack of compromise in performance may also make a PE sneaker an appealing product to a wide

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[55] Chu, “Could We Recycle Plastic Bags into Fabrics of the Future?”
[56] Alberghini et al., “Sustainable Polyethylene Fabrics with Engineered Moisture Transport for Passive Cooling.”
[57] Cherif et al., “Environmentally Friendly and Highly Productive Bi-Component Melt Spinning of Thermoregulated Smart Polymer Fibres with High Latent Heat Capacity.”

sector of consumers[58], regardless of their awareness or concern for product circularity. The additional stain resistance and washability properties of the PE textile would enhance the durability of a sneaker upper, especially if used in conjunction with design techniques discussed later in this work, and even enable a higher resale value compared to sneakers that are not as easily maintained in good condition[59]. Yet, unlike many novel textile materials being promoted for circularity, the affordability of PE resin and its compatibility with standard manufacturing processes eliminates significant cost and logistics barriers that might otherwise preclude or delay adoption of the PE textile for production at scale.

Traditional textile techniques aligned with circular design practices can also be leveraged to further enhance the functionality of the PE fabric for a sneaker application. For instance, using different woven and knit structures can produce variation in fabric property and behavior even within the same material swatch. Already, this practice is widely used to produce sneaker uppers with regions optimized for support, flexibility, and breathability where needed[60], including by brands like Nike and Adidas. Often, this form of textile engineering can be used to replicate the cushioning that is needed in upper areas like the collar, eliminating a step in production. An alternative circular strategy is to use excess yarn or fabric scraps as padding material an inevitable by-product of the weaving process), as seen with The Lace Up sneaker from Rothy's[61]. Fig. 9 shows a sample demonstration of this technique with PE. In the case of a mono-PE design, the cushioned structure can be melted down as a single unit for material recovery, unlike the case with cotton or non-thermoplastic fabrics.

As a thermoplastic, the PE fabric is also well-suited to various heat-based operations that can produce rigid plastic regions in precise areas of a sneaker upper. A rigid sample of PE fabric produced through a heat-press operation can also be seen in Fig. 9. Ultrasonic welding, commonly practiced in the sneaker industry, could further be used for joining various parts of the shoe without adhesives (or reducing the amount of glue needed), reducing a potential contaminant to the PE material upon recycling. The manufacture of the Adidas Loop sneaker employs both of these techniques.

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[58] McDonald and Oates, "Sustainability."
[59] Atasu, Dumas, and Wassenhove, "The Circular Business Model."
[60] Peters, "The Race To Create Knitted Shoes That Cut The Wastefulness Of Our Foot."
[61] Rothy's, "The Lace Up."

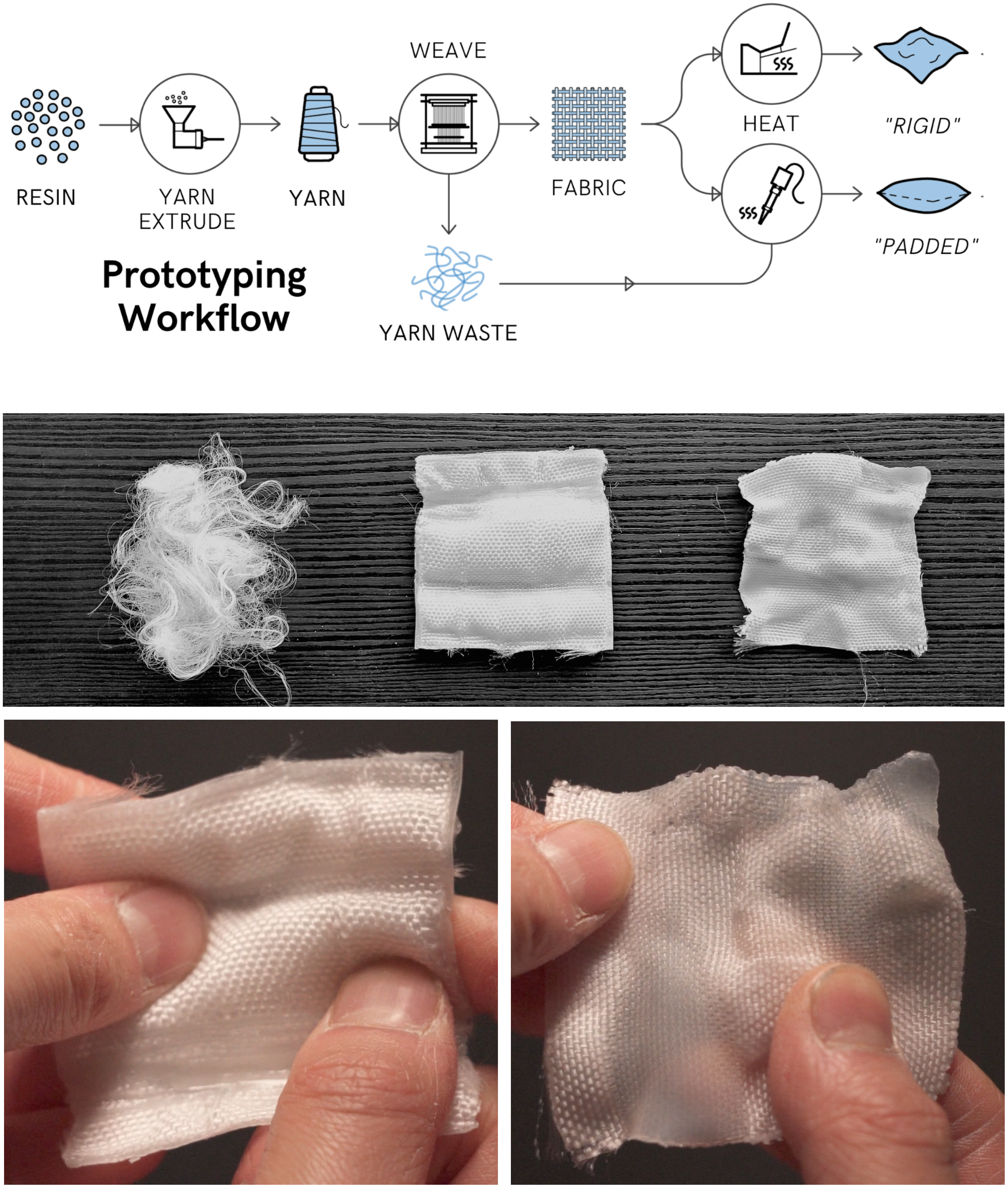

Figure 9: Visualized fabrication workflow (top) for prototyping of padded/cushioned PE fabric swatch (center, bottom left) using waste yarn (center left) and melt-rigid PE fabric swatch (center right, lower right)

Expanding beyond these established textile methods is furthermore possible through a mono-polyethylene design lens. The following sections will explore two innovative design opportunities that can be adapted to maximize the advantages of PE in a mono-material sneaker application. These explorations will be supported by physical prototyping.

Opportunity #1: Rethinking upper assembly and architecture with a mono-PE approach to 3D printing on fabric

Background

3D printing and the circular economy

3D printing has been widely recognized in both literature and industry as a technology with significant potential to support a shift to a circular product economy[62]. As an additive manufacturing process for digital design processes, 3D printing reduces waste generated during production. Moreover, the design flexibilities and freedoms afforded by the manufacturing technology can help condense assembly lines and reduce material usage[63]. In this sense, 3D printing is a powerful tool for narrowing resource loops, especially for the labor-intensive sneaker manufacturing process.

With the elimination of specific toolings in favor of digital design files, 3D printing also opens possibilities for distributed manufacturing, in which production is performed across a network of flexible, small-scale units that serve their local region[64]. A value chain that incorporates a distributed additive manufacturing network could be a promising solution to concerns voiced by the sneaker industry regarding the impact of China's plastic waste import ban on a potential circular sneaker economy. Part production, whether for a new generation of sneakers or other 3D-printed products, could occur in the same locality as sneaker recycling, side-stepping any regulatory uncertainties about directing recycled sneaker waste back to China-based manufacturing facilities.

It is evident that additive manufacturing still needs to overcome speed and cost barriers when it comes to use for full-run part production[65]. However, significant efforts and investment are being invested into scaling additive manufacturing for industrial use, and the space is projected to experience a double-digit growth rate over the next several years[66].

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[62] Unruh, "The Killer App for 3D Printing?"
[63] Sauerwein et al., "Exploring the Potential of Additive Manufacturing for Product Design in a Circular Economy."
[64] Johansson, Kisch, and Mirata, "Distributed Economies – A New Engine for Innovation."
[65] AMFG, "10 of the Biggest Challenges in Scaling Additive Manufacturing for Production in 2020."
[66] Statista Research, "Global Additive Manufacturing Market Growth 2026."

3D printing on fabric (3D-PPOT)

In recent years, 3D printing of polymers on textiles (3D-PPOT) has been increasingly explored by academic researchers, designers, and DIY makers. 3D-PPOT can present new design opportunities by allowing for the selective deposition of harder or stiffer polymeric structures onto a fabric surface without needing to compromise drape and free movement, depending on the structures printed. Work from designers such as Ganit Goldstein show the intricate textile craftwork that can be accomplished by leveraging the customizability of 3D printing[67]. Yet, 3D-PPOT can be easily done on inexpensive and widely available FDM printers without any modification to the machine by simply laying the textile over the printer bed[68].

Adhesion of the extruded filament to the surface of the textile has presented a challenge in the space, especially for certain material pairings[69]. However, past work has shown that the strength of the joint interface can be improved by 3D printing parameters[70] in addition to the selection of compatible filament and textile types[71].

It is important to note that 3D-PPOT is not entirely novel in the application of sneaker design and manufacture. Liquid Printed Textile Shoes from the The Self Assembly Lab at MIT was a 2016 project that extruded lines of liquid rubber onto a sock fitted over a shoe last, allowing the sock to act as a fully supported shoe[72]. Similarly, but realized to the scale of a limited-run commercial product, Reebok partnered with BASF to release sneakers with a printed outsole and lacing system manufactured through a novel process called Liquid Factory[73]. However, these few instances utilize a form of liquid additive manufacturing over a three-dimensional "drawing" bed, processes that are considerably more expensive and less accessible than FDM printing. Neither example is also oriented specifically towards sustainability. Smaller-scale explorations in 3D printing on textiles for sneaker uppers using technology that more closely resembles FDM can be seen in the work from Voxel8; still, the process utilizes proprietary technology and does not focus on recyclability[74].

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[67] Kaempfer, "Direct-to-Textile 3D Printing."
[68] Sabantina et al., "Combining 3D Printed Forms with Textile Structures - Mechanical and Geometrical Properties of Multi-Material Systems."
[69] Pei, Shen, and Watling, "Direct 3D Printing of Polymers onto Textiles."
[70] Spahiu et al., "Effect of 3D Printing on Textile Fabric."
[71] Eutionnat-Diffo et al., "Stress, Strain and Deformation of Poly-Lactic Acid Filament Deposited onto Polyethylene Terephthalate Woven Fabric through 3D Printing Process"; Pei, Shen, and Watling, "Direct 3D Printing of Polymers onto Textiles."
[72] Tibbits et al., "Liquid Printed Textile Shoes."
[73] Reebok, "Reebok Introduces New Liquid Factory."
[74] Molitch-Hou, "Voxel8 Returns to 3D Print Shoe Uppers."

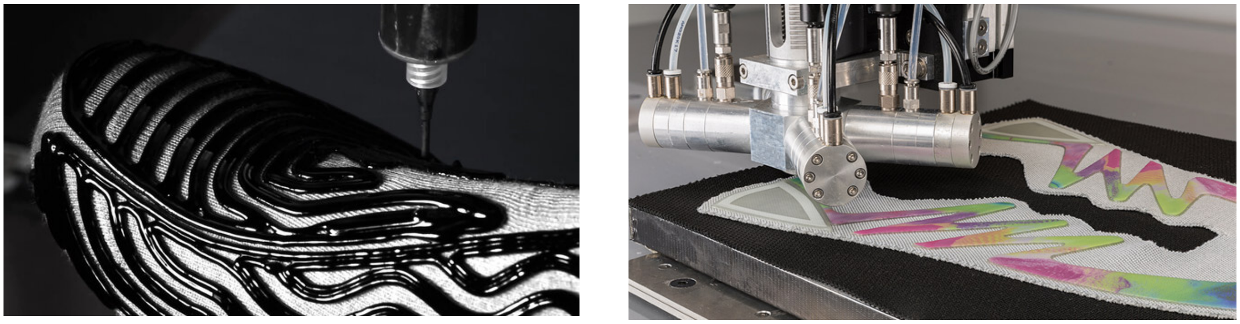

Figure 10: (Left) Self-Assembly Lab Liquid Printed Textile Shoes; (Right) Voxel8 sneaker upper printing

3D-PPOT for mono-PE sneaker construction

Many traditional sneaker designs include rigid components that are integrated or attached to a textile upper, oftentimes with adhesive: heel counter, toe box, eyelets, etc. are a few such components. Rigid components might also be used in more novel sneaker constructions, such as a shoe with rigid side panels for adjustable support. Assembling these multi-material components is oftentimes a labor-intensive, manual process.

Directly 3D printing these components onto the upper textile would condense part production and attachment into a single step that, if proper interfacial bonding is achieved between the fabric and printed layers, eliminates the need for adhesives that could pose a contamination risk to the recyclate. The direct deposition of the filament onto the fabric also prevents issues that could arise when heat-bonding two plastic materials with a similar melting temperature range. Yet, unlike 3D-PPOT practiced with dissimilar materials, printing polyethylene filament on polyethylene fabric requires no disassembly of the rigid structures from the textile upper for material recovery from the sneaker.

As previously discussed, mono-PE 3D-PPOT presents the opportunity to explore innovative design possibilities for functionality and aesthetics otherwise not feasible with traditional manufacturing methods, and without compromising recyclability. This includes easier customizability of the design of a sneaker upper, which may promote greater performance and thus utilization of the resulting shoe. With ownership of 3D printers growing increasingly common among home users and hobbyists, as well as the commercial availability of HDPE printing filament, a mono-PE sneaker could even be designed for customizability by its owner, allowing for a stronger user-product relationship that could prevent premature disposal[75]. From a functionality standpoint, DIY-repair of the sneaker upper could also be performed with at-home 3D printing, extending the useful life of the shoe.

While HDPE filament can be easily purchased online, PE is not traditionally used for 3D printing. This is because HDPE adheres poorly to conventional 3D printing build surfaces, and experiences considerable shrinkage when cooling[76]. However, as seen through the fabricated samples presented below, these issues can be avoided when printing on PE fabric.

Demonstrating mono-PE 3D-PPOT in practice

A workflow for developing mono-PE 3D-PPOT swatch prototypes was developed and is described in Fig. 11.

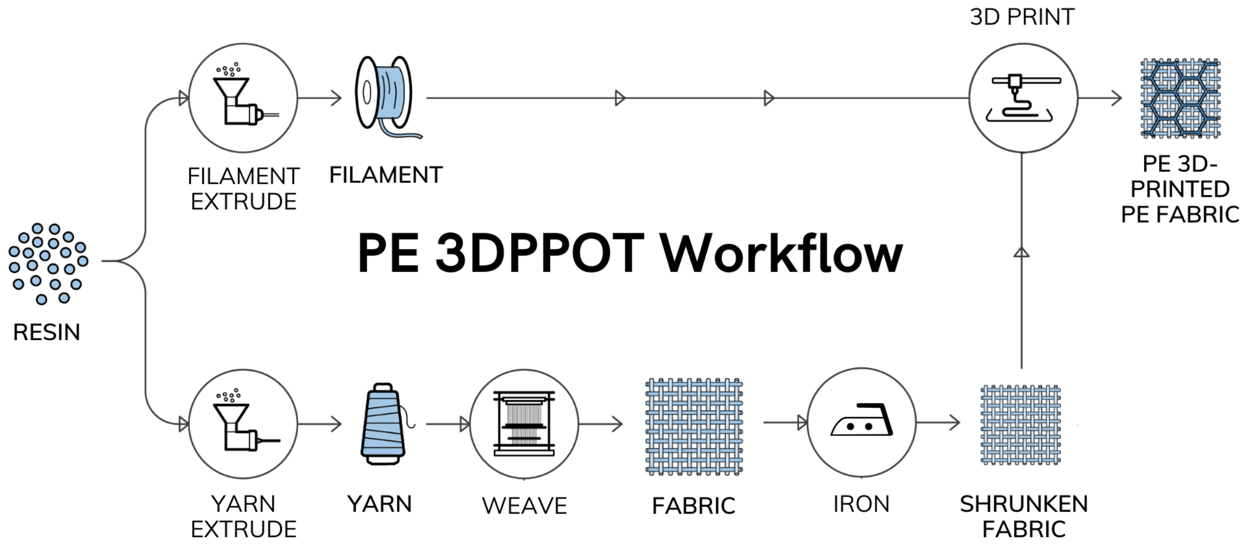

Figure 11: Visualized workflow for fabrication process of 3D printing of PE on PE fabric.

The plain weave fabric for these swatches was hand-woven on an Ashford 16” rigid heddle loom (Fig. 12) with untwisted, multifilament HDPE yarn manufactured at on an industrial Hills filament machine through the melt-spinning process performed at 230 degrees Celsius. The linear density of the HDPE yarn is 858 denier. Fig. 13a shows an SEM (Zeiss Sigma 300 VP microscope) image of the HDPE yarn, and Fig. 13b shows a representative load force-strain curve for the yarn, as obtained from uniaxial tensile testing (Zwick Universal Testing Machine) performed at a strain rate of 15mm/min and a gauge length of 25 mm.

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[75] Sauerwein et al., “Exploring the Potential of Additive Manufacturing for Product Design in a Circular Economy.”
[76] Koffi et al., “Extrusion-Based 3D Printing with High-Density Polyethylene Birch-Fiber Composites.”

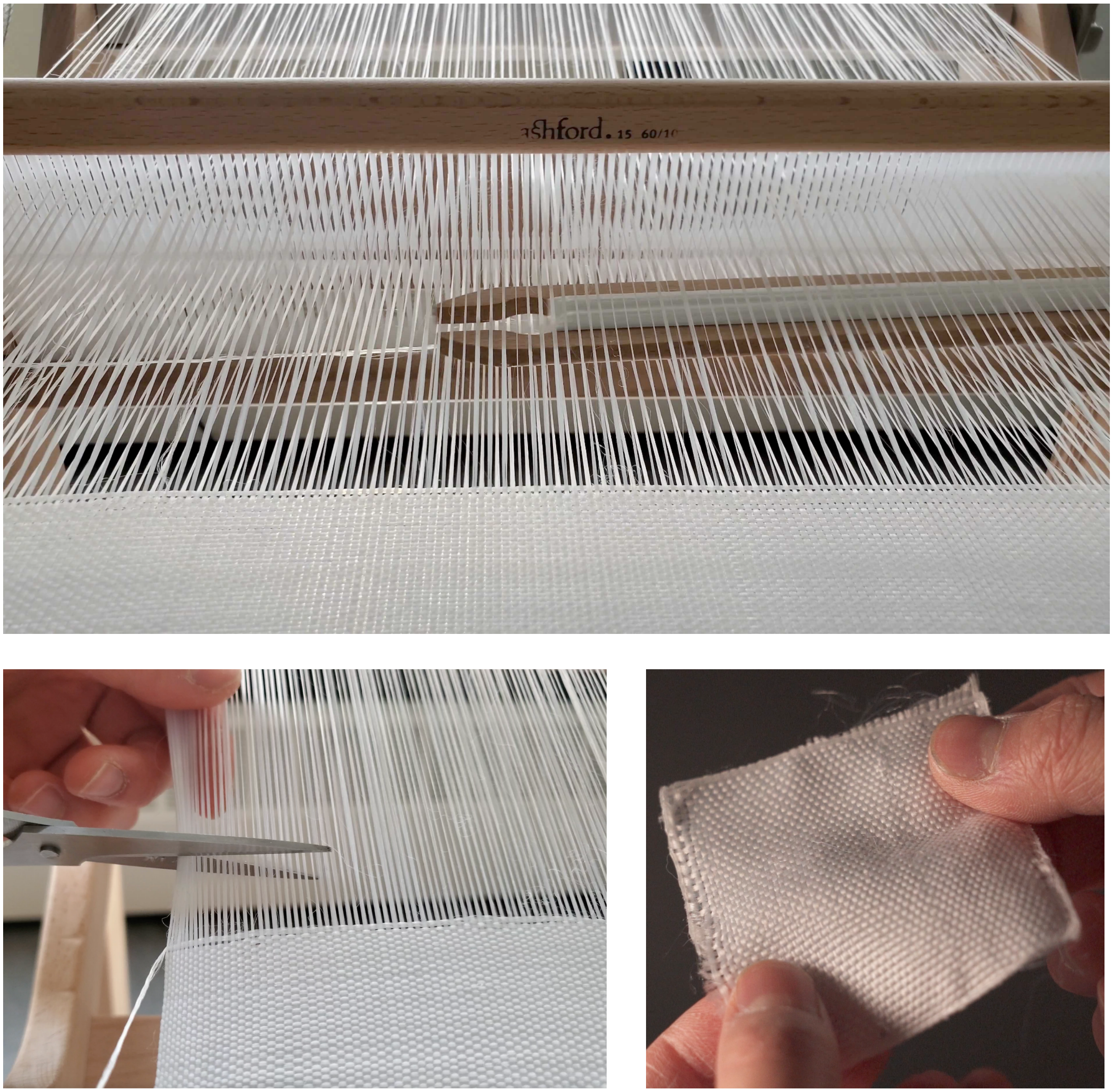

Figure 12: (Top, bottom left) Weaving PE fabric on an Ashford 16” rigid heddle loom; (Bottom right) Sample swatch of plainweave PE fabric.

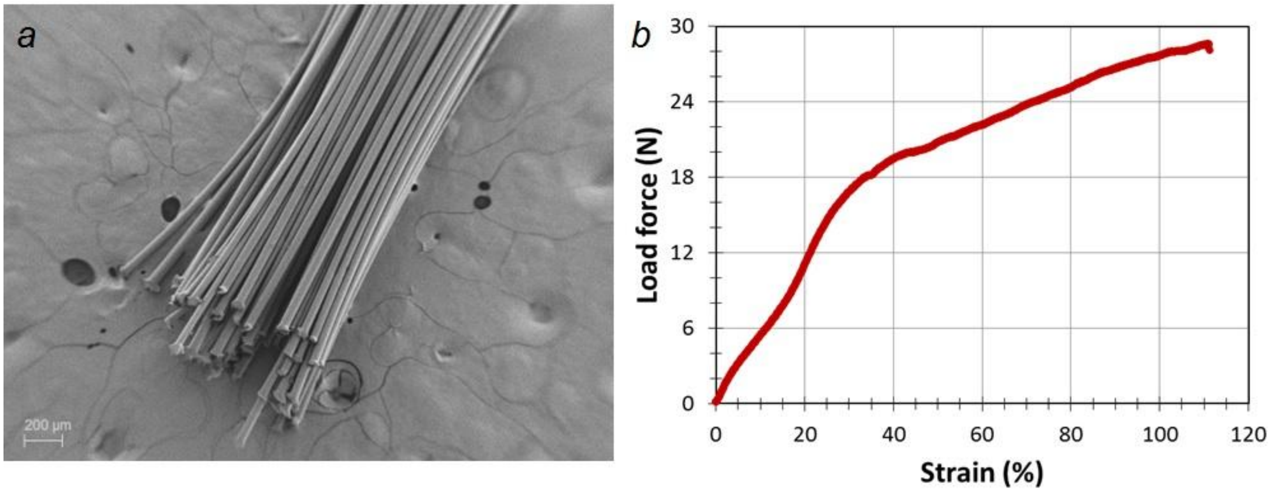

Figure 13: (Left) Scanning electron microscopy (SEM) image (a) of the HDPE yarn with diameter of 872±60 µm. Representative load force - strain curve (b) for this yarn; breaking is exhibited at 110% elongation at break with a breaking force of 28N.

Using a standard clothes iron, indirect heat was applied to pre-shrink the fabric. In this pre-shrinking process, a muslin fabric sheet was laid over the PE fabric; subsequently, an iron set between 135-150 degrees Celsius was moved over the muslin fabric. The pre-shrunk fabric was then secured to the glass bed of an Ultimaker 2+ printer using double-sided kapton tape (Fig. 14). The printing material, an uncolored, 2.85mm HDPE filament (Canadian Maker Series), was extruded at 195 degrees Celsius. The printer bed was heated to 70 degrees Celsius.

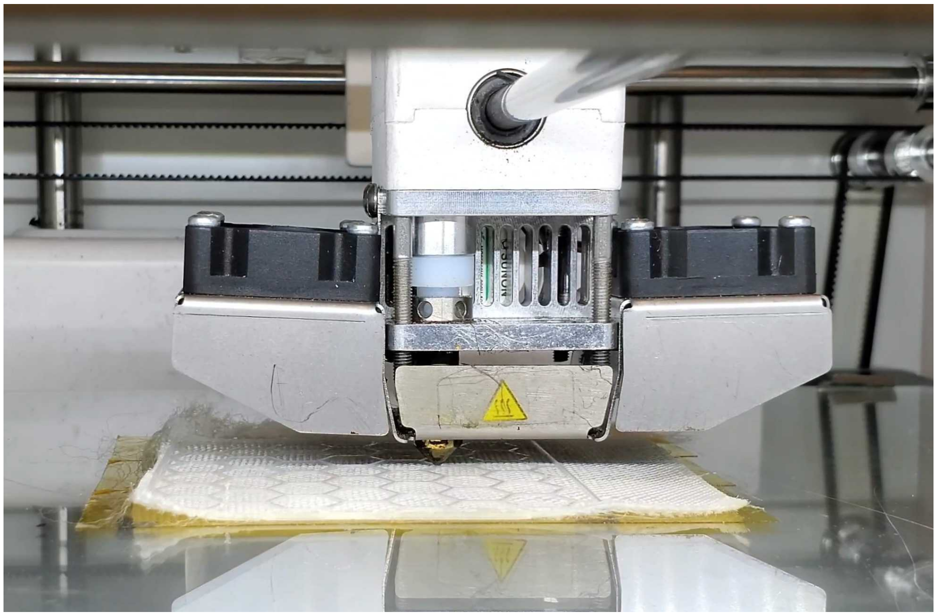

Figure 14:

3D printing HDPE filament onto PE fabric sample using Ultimaker 2+. The fabric is adhered to the printer bed using double-sided kapton tape.

A variety of different printable structures modeled using Rhino and Grasshopper were designed for prototyping, demonstrating a number of textile transformations that can be achieved (Fig. 15). Further design possibilities of specific relevance to sneaker manufacture range from the direct printing of a rigid sneaker component, such as eyelets and the heel counter, to printing overlays that serve to reinforce the fabric while adding an opportunity for aesthetic experimentation. This range of 3DPPOT sneaker design opportunities may be integrated into a one-piece, 3D-printable upper: two simplified prototypes illustrating this approach can be seen in Fig. 16.

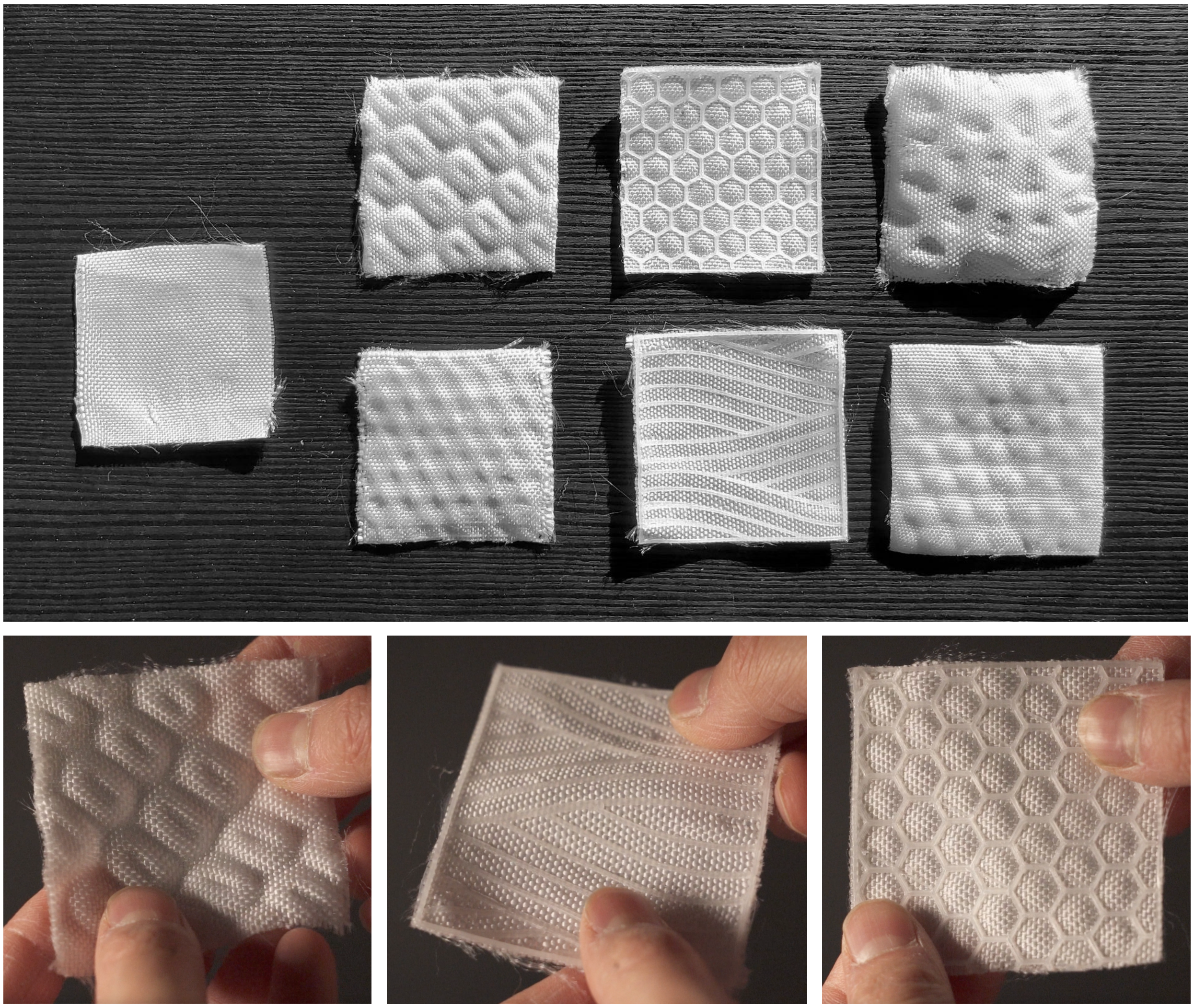

Figure 15: Sample swatches of PE fabric 3D printed with a variety of different HDPE structures.

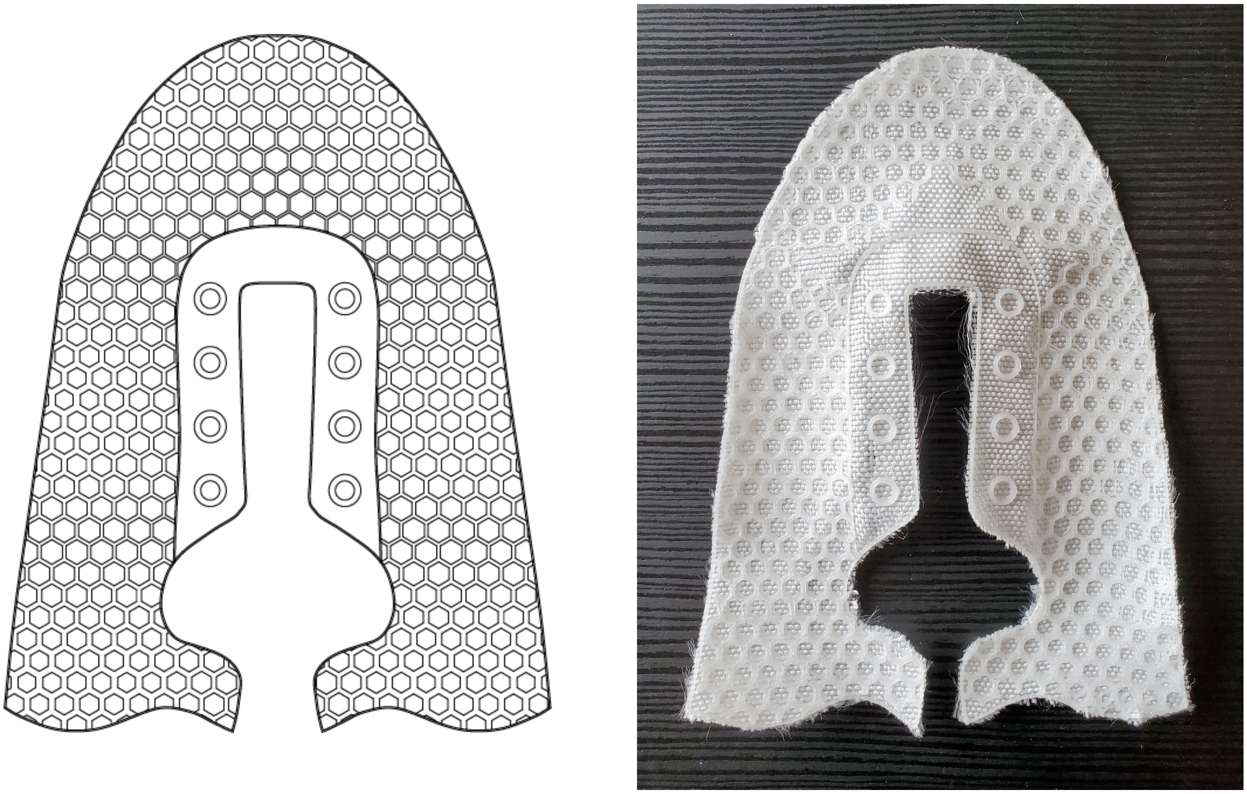

Figure 16: (Left) Sample 3D printable sneaker upper pattern with variegated hexagonal pattern,;(Right) fabricated mono-PE 3D-PPOT sneaker upper pattern.

While not within the scope of exploration undertaken for this demonstration, future work may involve quantifying and optimizing the flexural strength and adhesion of printed parts onto fabric. A previous study that investigated deposition of PLA filament onto plain-woven PLA fabric found that the pairting resulted in a high adhesion force, especially compared to PLA on nylon fabric[77]. The researchers hypothesized that this was due to the chemical similarity of and interpolymer interactions between the two surfaces, indicating that a similar result is likely to be quantified for an HDPE/HDPE pairing.

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[77] Hashemi Sanatgar, Campagne, and Nierstrasz, "Investigation of the Adhesion Properties of Direct 3D Printing of Polymers and Nanocomposites on Textiles."

Opportunity #2: Reinforcement through design and recycling of mono-PE material blends

Background

Dyneema (UHMWPE) for reinforced sneaker uppers

While polyethylene may not be commonly found in most sneakers, one specific PE formulation has seen recent and notable use in a few high-performance shoe models: yet, for reinforcement rather than recycling. This formulation is known as Dyneema, a branded ultra-high weight molecular polyethylene (UHMWPE) fiber. Dyneema fiber is said to be 15 times stronger than steel, lightweight, and highly-abrasion-resistant; yet, can be woven in textiles that do not compromise on aesthetics[78]. The high cost of Dyneema means that use of the fiber has thus far been limited to the uppers of high-end trail running sneakers, like the Norda 001 (which utilizes a bio-based Dyneema)[79] and Speedland SL: HSV[80]. However, Dyneema could be a more cost-effective option for sneaker designs if limited to areas of the upper that undergo the highest wear, or if utilized for a ripstop weave; a traditional weaving pattern that is resistant to ripping and tearing.

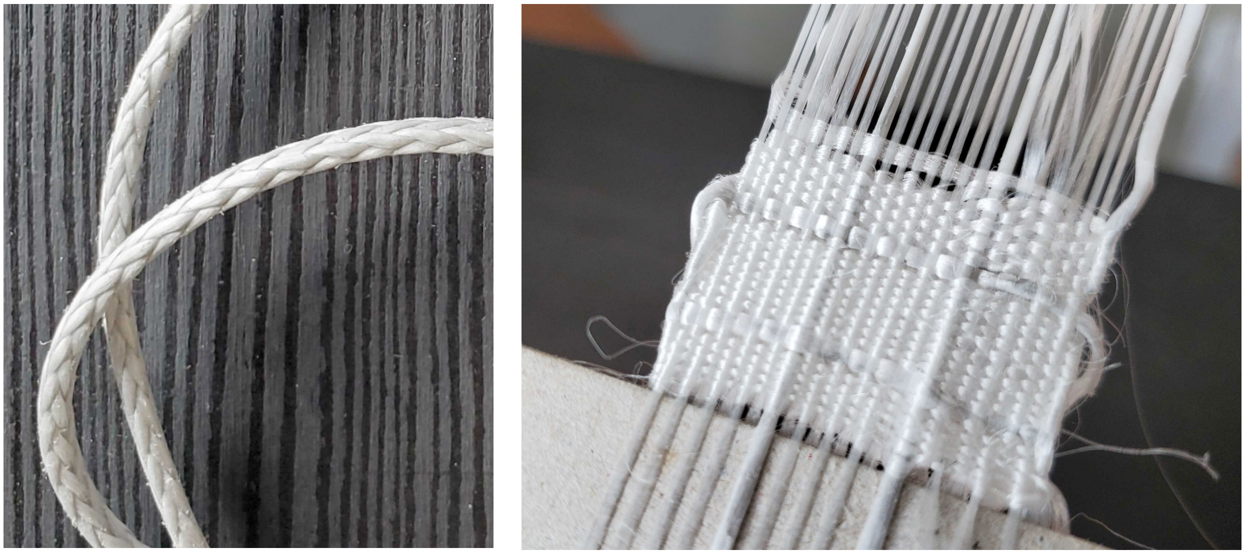

Figure 17: (Left) Commercial Dyneema rope; (Right) Strands of commercial Dyneema rope being used to fabricate ripstop PE fabric swatch (pictured on the loom)

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[78] DSM, "Dyneema® Fiber."

[79] Myaing, "Norda's Trail Runners Are the 1st Bio-Based Dyneema Trail Runners."

[80] "SL:V | Speedland."

There is a clear argument for utilizing UHMWPE fibers to enhance the wear durability of a sneaker upper for a product that can then be marketed for its performance advantage. However, the case for UHMWPE fibers in a mono-PE shoe design goes beyond slowing material loops: a recycled polyethylene blend containing UHMWPE could play a significant role in enabling closed-loop material circularity. Such a blend would also improve the manufacturability of UHMWPE, which is otherwise difficult to extrude and process due to its high viscosity[81].

Upgrading material performance with UHMWPE-reinforced blends

Past research exploring blends of UHMWPE with other densities of polyethylene has produced enhanced mechanical properties such as higher elongation at break, slower crack growth, and higher tensile strength[82]. Ferreira et. al demonstrated that blends of HMWPE with 10% and 20% UHMWPE exhibited wear resistance exceeding that of pure UHMWPE, indicating the potential for a synergistic effect[83]. This improvement to mechanical performance was even shown to be even greater at lower percentages of UHMWPE by weight. When a mono-PE "composite" is formed from a PE matrix reinforced by discontinuous UHMWPE fibers, thus producing a fiber-reinforced plastic, superior mechanical performance is further demonstrated[84].

Dyneema reinforcement to retain value of mono-PE sneaker recyclate

As previously discussed, a key barrier to the recycling of plastics for a circular sneaker economy concerns the degradation of material properties upon repeat cycles of mechanical recycling. Thus, there lies significant design opportunity in creating products composed of a selection of materials that would form a reinforced blend when subjected to the grinding and re-extrusion processes of mechanical recycling.

In the context of a mono-polyethylene sneaker, this could be realized as a majority-HDPE shoe design that utilizes small amounts of Dyneema fiber or textile for reinforcement in high-wear regions, such as the toe area. Not only would this design present durability and performance benefits during the initial lifespan of the shoe, but it would further

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[81] Changhui et al., "Customized UHMWPE Tibial Insert Directly Fabricated by Selective Laser Sintering."

[82] Lim et al., "High-density Polyethylene/Ultrahigh-molecular-weight Polyethylene Blend. I. The Processing, Thermal, and Mechanical Properties"; Zhang and Liang, *Extrusion Processing of Ultra-High Molecular Weight Polyethylene*; Mészáros et al., "Novel, Injection Molded All-Polyethylene Composites for Potential Biomedical Implant Applications."

[83] Ferreira and Fechine, "High Abrasive Wear Resistance Polyethylene Blends."

[84] Jacobs et al., "Sliding Wear Performance of HD-PE Reinforced by Continuous UHMWPE Fibres"; Stern, Teishev, and Marom, "Composites of Polyethylene Reinforced with Chopped Polyethylene Fibers."

take advantage of the standard mechanical recycling process to produce a PE recycate with maintained or upgraded properties.

The hybrid textile-solid construction of sneakers presents a unique opportunity for the production of a discontinuous Dyneema fiber-reinforced composite as output of the mechanical recycling process, provided that this process can be performed above the melting temperature of HDPE and below the melting temperature of Dyneema (130-144 degrees C)[85]. However, even if this range proves too narrow in practice, the performance advantages derived from a Dyneema fiber-reinforced PE formulation may still be achieved. Boscoletto et. al demonstrated that in blends of HDPE and UHMWPE up to 20%wt exhibited only 3% dissolution of UHMWPE in the PE matrix; however, an additional reinforcing effect was realized due to the dual filler effect provided by the non-dissolved UHMPWE.

Demonstrating Dyneema reinforcement in practice

To validate the concept of "upgrading through recycling" in practice, a Dyneema fiber-reinforced HDPE blend was fabricated through small-scale and manual simulations of mechanical recycling processes, then mechanically tested. A visualization of this fabrication workflow can be seen in Fig. 18.

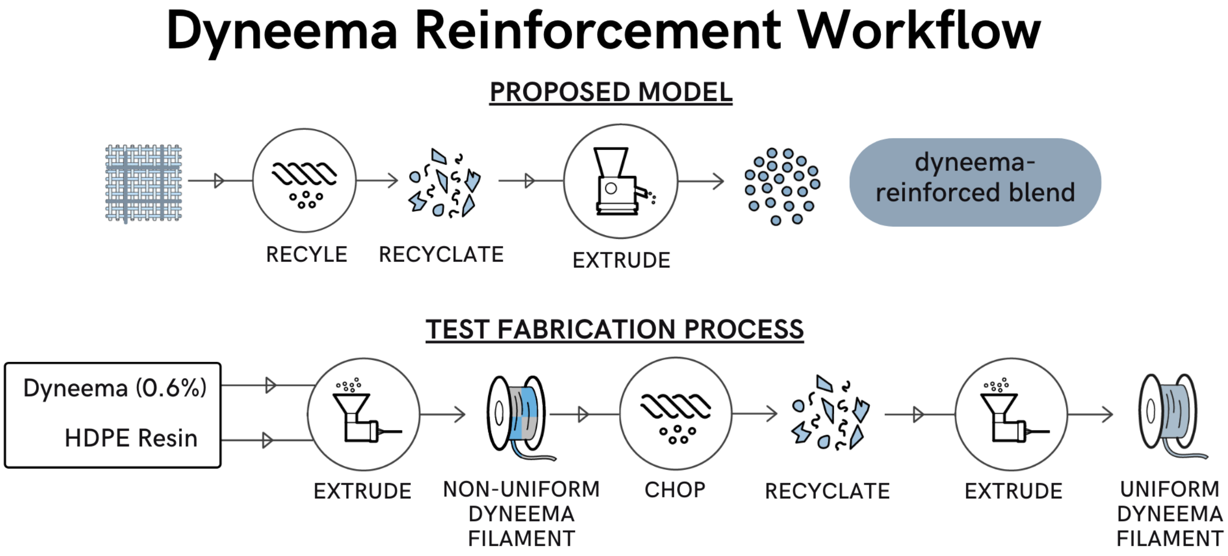

Figure 18: Visualized workflow for dyneema reinforcement of PE recyclate; both the proposed model utilizing Dyneema-reinforced ripstop fabric (top) and the process undertaken during fabrication and validation (bottom).

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[85] FibrXL, "Dyneema®."

Based on literature, a blend containing a low weight percentage (0.6%) of Dyneema was selected. Validating the reinforcing effect of Dyneema at a low weight percentage also presents a benefit in light of the high price of Dyneema, mitigating the cost of integrating Dyneema content into a shoe upper. Dyneema fibers were sourced from a commercially available braided Dyneema winch rope (WROUGH) and cut into lengths of 10-15mm to reflect the shortening of fibers that typically occurs during recycling of textiles. This is the same Dyneema fiber from which the Dyneema-HDPE ripstop sample in Figure 17 was woven.

Two cycles of melt-extrusion of a blend consisting of cut fibers mixed with HDPE resin (DOW) at a ratio of 0.6%-Dyneema by weight were then performed with a small-scale filament extruder (Filabot EX2) (Fig. 19), as well as a preliminary procedure in which the fiber was directly melted with a small amount of the HDPE resin. Following each melting procedure, all of which were performed at 200 degrees Celsius, the manufactured filament was cut into 4-7mm pieces in order to be fed back into the extruder hopper, This multi-step procedure helped to both enable a more uniform dispersal of the Dyneema in the HDPE and mimic the grinding and heating procedures typical of the mechanical recycling of polymers.

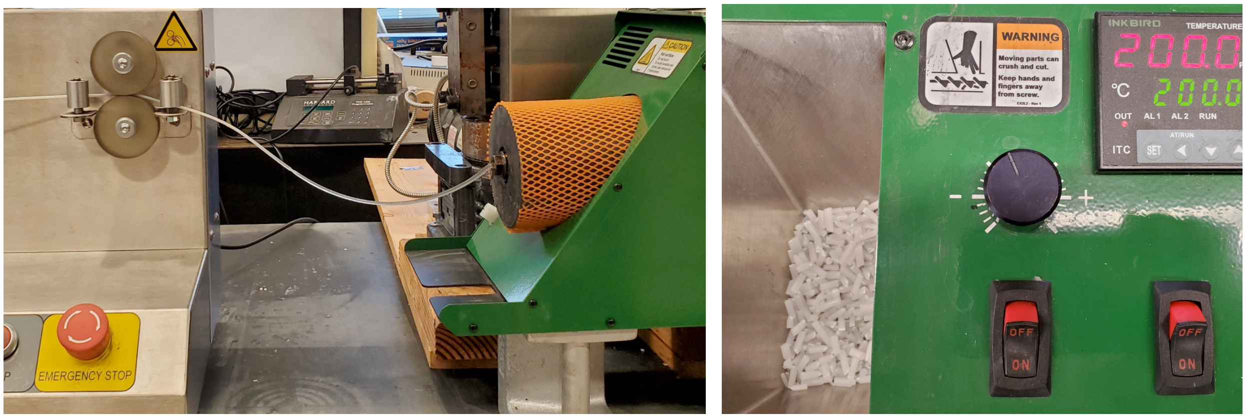


Figure 19: Second round extrusion of Dyneema-reinforced HDPE blend.

Lengths of the Dyneema fiber-reinforced HDPE filament (diameter 2.5 mm) were subjected to uniaxial tensile testing on a Zwick mechanical tester loaded with a 10 kN force cell; from this data, ultimate tensile strength (UTS) and Young's modulus were obtained (Fig. 20). For comparison, an analogous filament manufactured from the same HDPE resin (diameter 2.57 mm) was subjected to tensile testing; the stress-strain curve for the HDPE filament is also presented in Fig. 20.

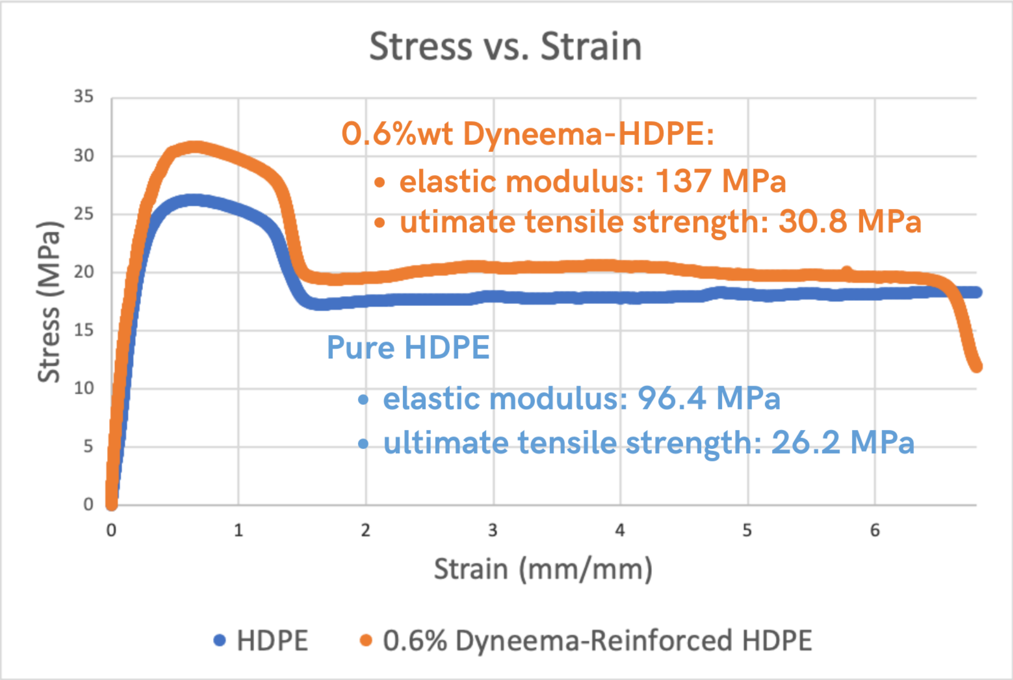


Figure 19: Stress-strain curves of the 0.6%wt Dyneema-HDPE and the pure HDPE filament, as well as the corresponding elastic moduli and ultimate tensile strength. The Dyneema-reinforced HDPE exhibits superior performance with respect to both of these qualities, though does show a lower elongation at break.

As can be seen from the tensile testing results, the 0.6%wt Dyneema-reinforced HDPE filament is observed to have an elastic modulus that is 42.1% greater than that of the pure HDPE filament, as The Dyneema-reinforced blend also exhibits as an ultimate tensile strength that is 17.5% greater, though has a notably lower strain at break. Nevertheless, especially in light of the multiple heat cycles through which the Dyneema-HDPE blend entered during manufacture, these results support the proposal of utilizing small amounts of Dyneema in a PE product to produce a recyclate with upgraded qualities.

Thermal analysis was also performed on the blend using a TA Instruments Discovery differential scanning calorimeter (DSC), allowing for the measurement of the average melting temperature and the calculation of the degree of crystallinity of the blend. The measured and calculated data from these two tests are described in Fig. 20.

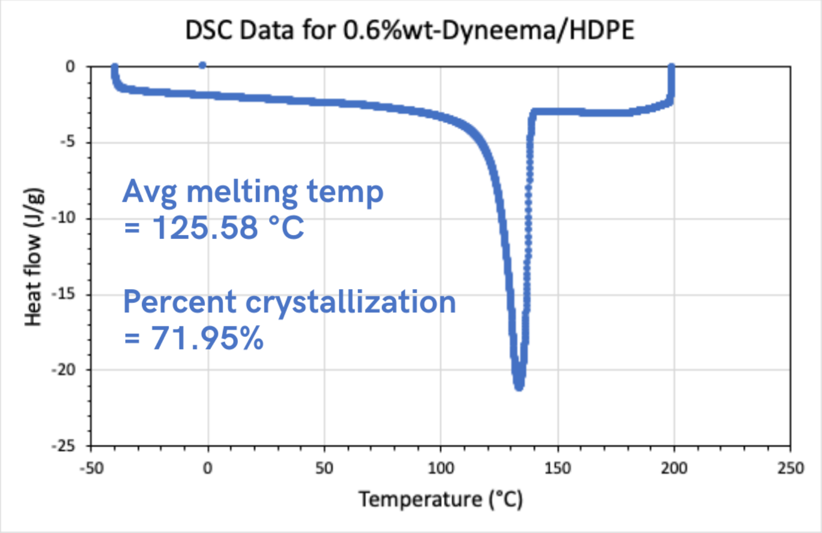


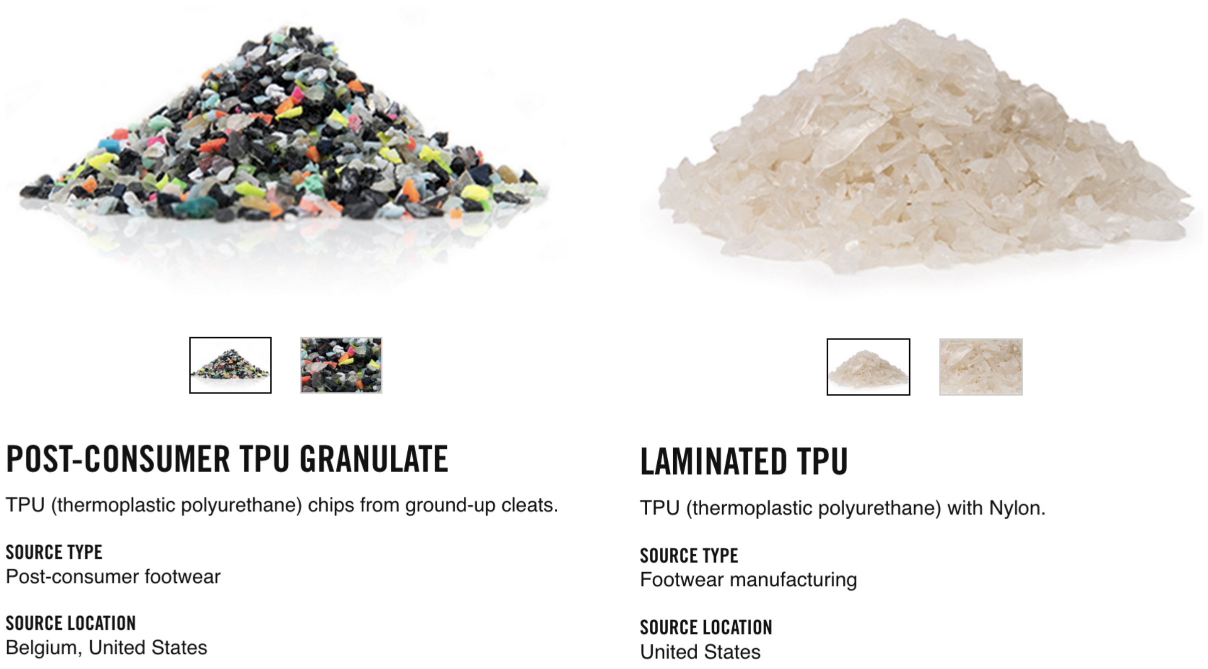
Figure 20: DSC curve for 0.6%wt Dyneema-reinforced HDPE blend.

Circular pathways for a Dyneema-reinforced PE blend

To make an argument for the Dyneema-reinforced PE blend, the means through which the blend is directed back into production must be considered. The reinforced recyclate could re-enter the manufacturing process for a new PE sneaker, contributing to a closed-loop product economy: a path taken by Adidas with their Loop shoe. However, another pathway more closely aligned with the system challenges to shoe circularity could be to divert the recyclate for use in the local production of high-performance and high-value plastic products. As evident from the fabrication and testing above, it is possible for the recycled blend to be upgraded with respect to some mechanical properties but not to others. In this case, material value may be retained more fully if the recyclate can be used for applications where such upgraded properties are desirable, even if those applications extend beyond the shoe.

Expanding beyond the sneaker industry and creating end-market potential for the upgraded material could present a clear economic argument for a shoe circularity. This argument grows more compelling in the scenario that the recyclate is sold to manufacturers in the same geographic region in which the sneakers are recycled, avoiding any complications presented by China’s waste import regulations.

Nike Grind is a successful example of the sale of repurposed shoe waste as raw material for other products outside the footwear space, primarily sport surfaces (tracks, playgrounds, etc.) and flooring. While Nike Grind is marketed alongside the brand vision for circularity and zero waste, it should be recognized that the majority of materials used for Nike Grind come from factory scraps rather than post-consumer footwear[86]. Moreover, given the multi-material composition of most Nike Grind blends, Nike Grind is primarily suited for downcycled applications. Still, the scale of the Nike Grind business model, especially from a company otherwise known for selling finished consumer goods, is to be recognized as an innovative, positive step towards circularity.



POST-CONSUMER TPU GRANULATE

TPU (thermoplastic polyurethane) chips from ground-up cleats.

SOURCE TYPE
Post-consumer footwear

SOURCE LOCATION
Belgium, United States

LAMINATED TPU

TPU (thermoplastic polyurethane) with Nylon.

SOURCE TYPE
Footwear manufacturing

SOURCE LOCATION
United States

Figure 21: Examples of downcycled Nike Grind recyclates available for purchase.

Certainly, creating a viable end-market for upgraded PE would require large feedstocks of the recycled material. Given the widespread use of polyethylene plastic, this could present a collaborative business opportunity for sneaker brands to join efforts with another product industry to grow the volume of PE recyclables.

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[86] Nike, “About Nike Grind.”

CONCLUSION

The modern sneaker is ingrained in a linear take-make-dispose model that is gravely unsustainable and begets an irreversible loss of material value from the 20+ billion pairs of shoes produced by the footwear economy each year. Designing for sneaker circularity presents an opportunity to recover materials at their highest value and utility, however, the complexity of this task is reflected in the intricacy of both sneaker constructions and the system context in which they operate. Neglecting this complexity yields unsuccessful attempts towards circular sneaker design.

This thesis first sought to develop a systems-aligned framework through which to understand the many barriers to transitioning towards a circular sneaker economy through design. These barriers were uncovered through direct consultation with the footwear industry and its closest collaborators; specifically through a wide-reaching questionnaire and a series of in-depth expert interviews. Mapping these product-oriented barriers along the dimensions of resources, technology, regulations, business, and the consumer set the basis for a systems-thinking, materials-centric approach to designing for sneaker circularity.

Secondly, this thesis demonstrated this new systematic ethos to designing for materials circularity through the example of a mono-polyethylene sneaker, with focus on the traditionally-complex upper component. The versatility of polyethylene presents many performance and sustainability advantages, especially in a textile embodiment. Expanding beyond traditional textile manipulations, this research explored new techniques for mono-material polyethylene design. These techniques, mono-PE 3D printing on fabric and recyclate reinforcement through the design of PE blends, directly addressed the system challenges to sneaker circularity while also illustrating novel functionality and aesthetic possibilities.

In closing, this thesis presents the potential of a holistic design approach grounded in materials consideration to set the sneaker industry on a path towards circularity. While this research operates primarily on the materials level, a key future step will be to translate this work to a fully-realized sneaker embodiment. Nevertheless, it is evident that there exists no singular design solution to the ideal of a circular sneaker. Rather, to realize sneaker circularity, the complexity of sneaker designs and systems necessitates an comprehensive series of integrated materials design strategies.

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