THE FIRST ENVIRONMENTAL EVALUATION OF 3D-PRINTED FOOTWEAR

February 2022

A team of graduate students at Yale's Center for Business and the Environment worked with HILOS and with data provided by our supply chain partners - BASF Forward AM and AMT - to examine each piece of our environmental impact. We then benchmarked the results against traditional footwear supply chain emissions to answer the following questions:

How does 3D-printed footwear compare to legacy shoemaking?

Where does the technology have the potential to deliver the greatest environmental impact?

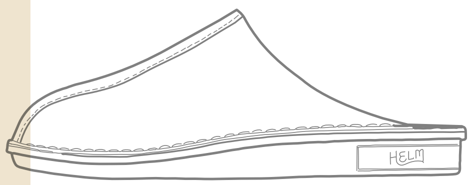
Where are the greatest opportunities for future improvement, and how do we get there?

Our mission is to stop waste before it starts, pioneering 3D-printed shoes made on-demand, without inventory or waste.

After launching our first line in 2021, we teamed up with footwear brand HELM to showcase a new collaboration model for the industry. Designed by HELM and made on-demand by HILOS, the Emmett slip-on mule became the focus for this case study.

HELM by HILOS

Key findings



Emmett, a HELM by HILOS collaboration

The footprint/pair

11.1 kg CO_2	89.2 liters water	1 gram glue

The impact (compared to traditional manufacturing)

WATER — 99% reduction

CO_2 — 48% reduction

CO_2 reductions breakdown

On-demand production **20%**

Circularity **7.2%**

Part reduction **29%**

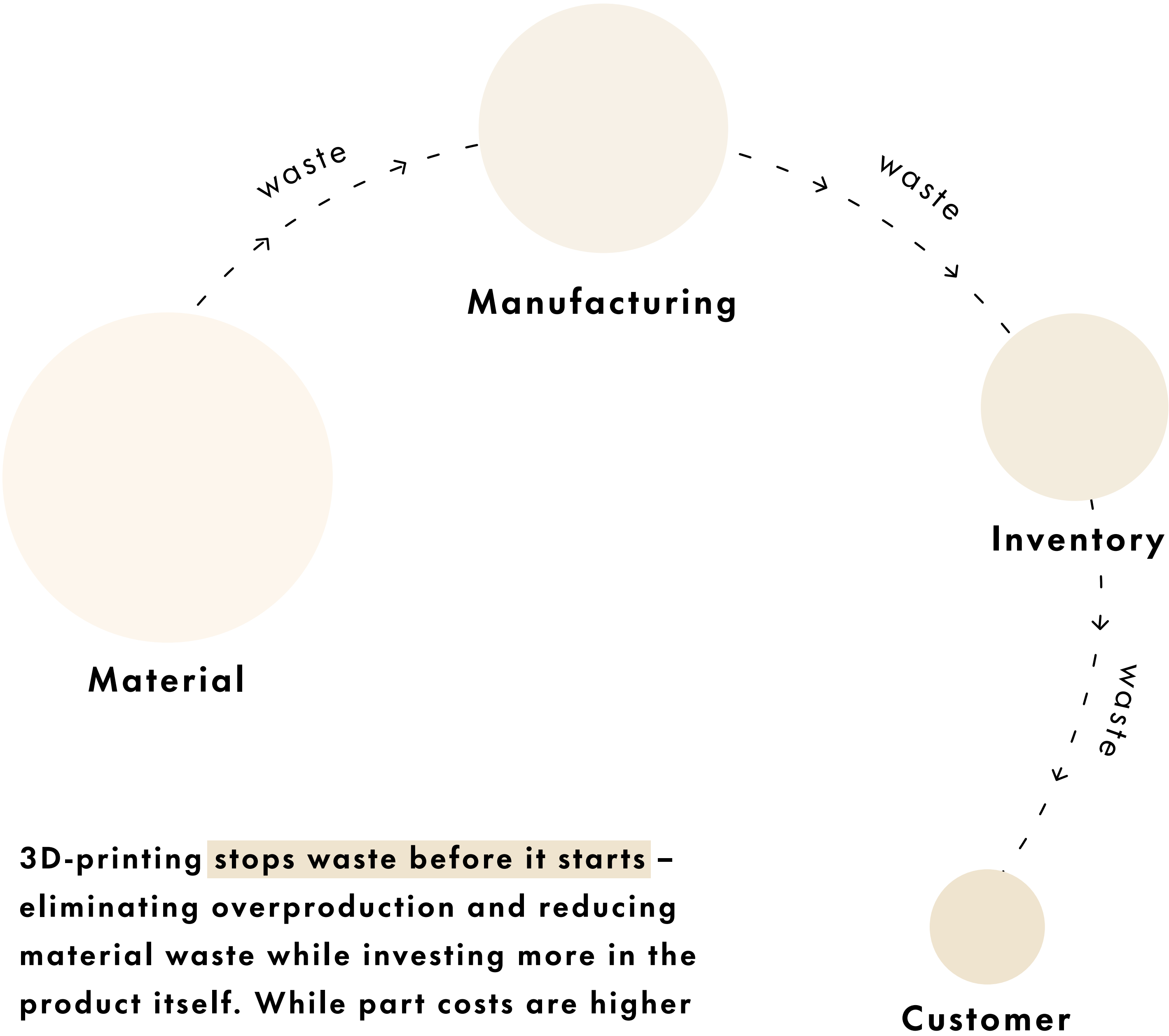
WHY 3D-PRINTING?

Almost every shoe today is made from a layered construction. 3D printing allows us to take what was formerly different materials glued together and instead print a single part on-demand, reducing overproduction and material waste while enabling recyclability.

HILOS

Paradigm Shift

Legacy industrial manufacturing depends on overproduction and material waste. Brands are paying to make things no one will buy, in some cases overproducing up to 35% and wasting 76% of material. What most of us don't realize is that we're subsidizing that waste with our purchase.



3D-printing stops waste before it starts – eliminating overproduction and reducing material waste while investing more in the product itself. While part costs are higher than for traditional manufacturing, this model enables brands to sell more while making less.

System Bounds and Methodology

This initial review focused on supply chain (scope 3) CO_2 emissions and water usage. The scope of data collection covered the raw material extraction of polyurethanes for printing and the raw material treatment of leather hides through to transport to HILOS, manufacturing, end-of-life return, and component recycling.[1]

The carbon displaced from recycling was derived from a comparative analysis of the energy required to return the shoes to HILOS, transport its component parts to HILOS' partners and to repurpose the materials themselves (the debit side of the balance sheet) together with the carbon emissions avoided by displacing the equivalent virgin materials and reintroducing these materials back into the supply chain (the credit side of the balance sheet).[2]

Defining sustainability is by nature a relative exercise. It depends on understanding the costs not only of current operations but also of viable alternatives in order to consciously define a direction for reducing the default environmental impact of a business. **Our intention with this evaluation is to assess 3D-printed shoes as an alternative to traditional industrial shoemaking.**

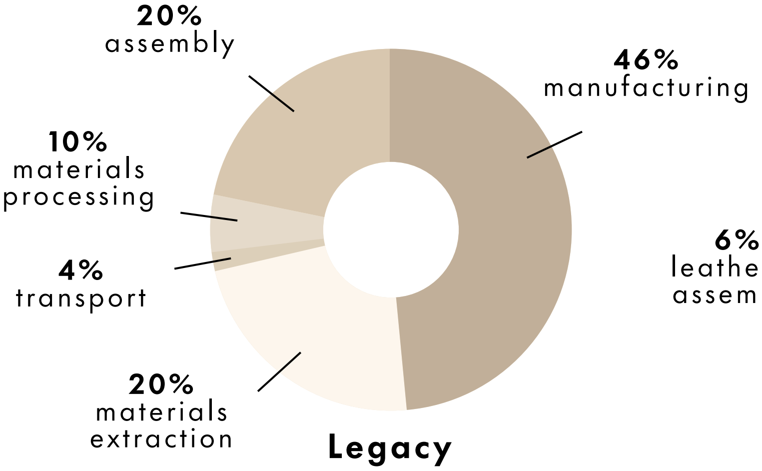
Unfortunately, it remains very difficult to gather comparative data for traditional scope 3 emissions in this industry. Brands will often publish headline statistics, such as total carbon emissions, and sometimes attributions by scope and even process (raw materials, manufacturing, shipping), but it is difficult to find out how these numbers were reached, what they encompass, and what this means on a per product basis, therefore we used the data available at the time of this study.

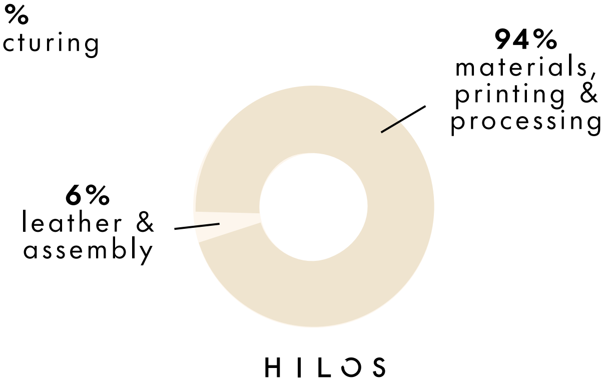
Veja Esplar

For comparative purposes, HILOS benchmarked against **Veja's Esplar full leather style**, a comparative construction in terms of outsole and leather upper with a recently publicized carbon footprint. We are very grateful to Veja for the level of detail and transparency in their sustainability reporting. Water usage was benchmarked against leather footwear as a category, supplied by DHI Water Group. For performing the analysis of HILOS's environmental footprint, we would like to thank Dr. Marian Chertow and the work of her students, Michaela Kerxhalli-Kleinfield, Victor Seau, Prachi Sharma, and Angela Xue, as well as our partners at BASF Forward AM, HP, and AMT for providing data.

Carbon Emissions

Traditional footwear supply chains encompass raw material extraction, processing, assembly, packaging, transportation, and end of life. HILOS utilizes BASF Ultrasint® TPU powder and HP Multi Jet Fusion 3D printers to produce a shoe's insole, midsole, outsole, and heel as a single component part which is then treated using AMT technology and assembled with traditional veg-tanned leather liners and uppers. 94% of HILOS carbon emissions can be attributed to the raw materials, printing, and processing of these 3D-printed parts.





Interestingly, when comparing this 3D printed component with an injection molded outsole and midsole on a part-to-part basis, overall emissions are actually 10-17% higher for 3D printing. Only when a complete assembly of the shoe is taken into account does the overall carbon efficiency of 3D printing stand out. Due to the high number of parts and energy-intensive assemblies of traditional manufacturing, injection molded midsoles and outsoles make up a smaller percentage of overall emissions. By reducing part count and streamlining product assembly, 3D printing **reduces overall emissions by 48%** even with lower economies of scale.[3]

Cradle to cradle product emissions

	Legacy	HILOS
kG CO_2/pair	21.5	15.2
Recycling displacement	--	(1.1)
On-demand displacement	--	(3.0)
Total kG CO_2/pair	21.5	11.1

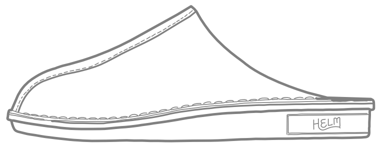
Injection molding vs. 3D printing of soles

	Legacy	HILOS	Delta
kG CO_2/pair	12.2 - 12.9	14.3	+10% - 17%
Water usage	393.5	84.1	-78%

This suggests that **the right design and application of 3D printing is critical for overall carbon reduction**.

Traditional footwear assemblies can utilize up to 65 discrete parts requiring 360 steps for assembly.[4] By contrast, the Emmett has five component parts per shoe assembled in twelve steps. Part and material reduction due to streamlined forms of shoemaking accounted for a 29% reduction in emissions.

Traditional assembly	Digital manufacturing
65 components	**5** components
360 steps	**12** steps
	29% emissions reduction



On-demand production

Circularity is only one half of the equation to enable more sustainable production to meet demand. While 71% of total emissions can be the result of raw materials, 76% of these emissions are the result of material waste.[5] HILOS makes every pair only after a customer orders, eliminating overproduction in an industry where one out of every five shoes made goes unsold.[6] While raw materials are still held in inventory, they are not materials specific to a given size or even style, allowing for flexibility and no material waste. 3D printing recaptures over 98% of material needed for production at a reuse rate up to 80%.

Selling the same amount of shoes while actually producing less has an enormous impact on supply chain efficiency across every step of the process, avoiding both the initial material usage as well as the accompanying waste resulting from each step.

For instance, if the yield from a textile process is 80%, and the yield from a stitching process is 95%, making one less product will not just displace that specific product's footprint but 120% of its textile footprint and 105% of its manufacturing footprint.

We don't factor this wider efficiency gained into our calculations, only focusing on the number of products no longer needing to be produced and amortizing this across each product as a 20% reduction in CO_2 and water usage per pair. This is very likely a conservative calculation.

Water Usage

When only comparing an injection-molded midsole and outsole with a 3D-printed HILOS platform, the 3D-printing process represented a 78% reduction in water usage. This is largely due to the poor yield efficiencies of injection molding when compared with 3D-printing. When the complete shoe is taken into account, accounting for reduced materials required for construction and assembly, 3D-printing reduced water consumption by 99%.[7]

Cradle to cradle water usage

	Legacy	HILOS
Water liters/pair	8000	111.5
Recycling displacement	--	not calculated
On-demand displacement	--	(22.3)
Total water liters/pair	8000	89.2

Circularity

HILOS products are engineered to be disassembled into their main component parts: TPU platforms and leather uppers and liners. Veg-tanned leathers are sourced from tanneries with a gold rating from the Leather Working Group and above a 90% transparency rating that are **able to be completely recycled and renewed** for use in other products, while the BASF Ultrasint® TPU can be **ground up with zero material degradation** and used for injection molding of traditionally made shoe soles and TPU products.

Recycling HILOS' Georgia

Overall, HILOS product circularity only accounted for a 7.25% reduction of CO_2 emissions per pair.[8] This is largely because the energy required to reprocess the materials nearly canceled out any gain from renewing the materials themselves. For comparison, if reprocessing itself was carbon neutral, product circularity would have credited 3.4 kg CO_2/pair, a 22% carbon reduction. **Increasing the efficiency of material renewal and reprocessing is key to leveraging the full potential of carbon savings from product circularity.**

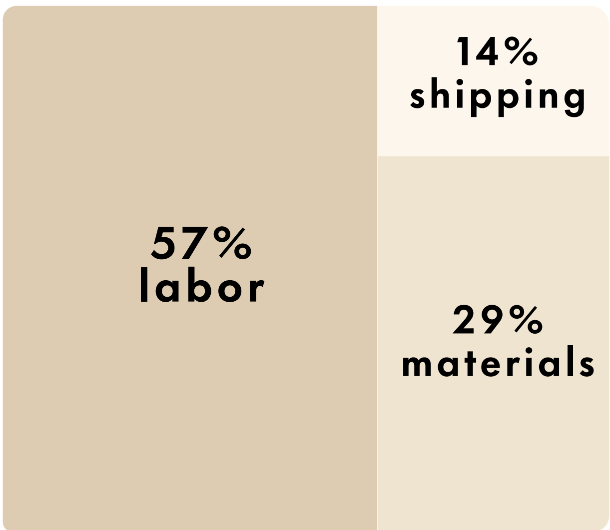
Rather than see more circularity as always better , it is probably best to be selective about which parts to recycle, which to repurpose, and which should be diverted from the landfill in other ways, such as organic composting.

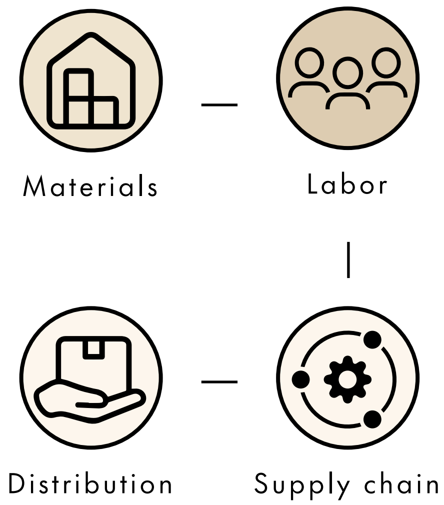
HILOS' focus for the future of product circularity will be evaluating overall carbon efficiency across each component parts' end of life while also sourcing more efficient methods for material renewal.

Parts and labor

HILOS' cost structure is significantly different from legacy manufacturing, which relies on large economies of scale and incentivizes overproduction. On a per part basis, traditional manufacturing is less expensive than digital manufacturing. For the average leather shoe manufacturer, 29% of costs are attributed to materials, 57% to labor, and 14% to shipping. Brands pay for product made at 20-25% of retail price in order to absorb hits to margin from inventory and carrying costs, discounting, and returns. This model has come under increasing pressure over the past two years, as brands bear the cost of not having product in the right place at the right time while having too much elsewhere.

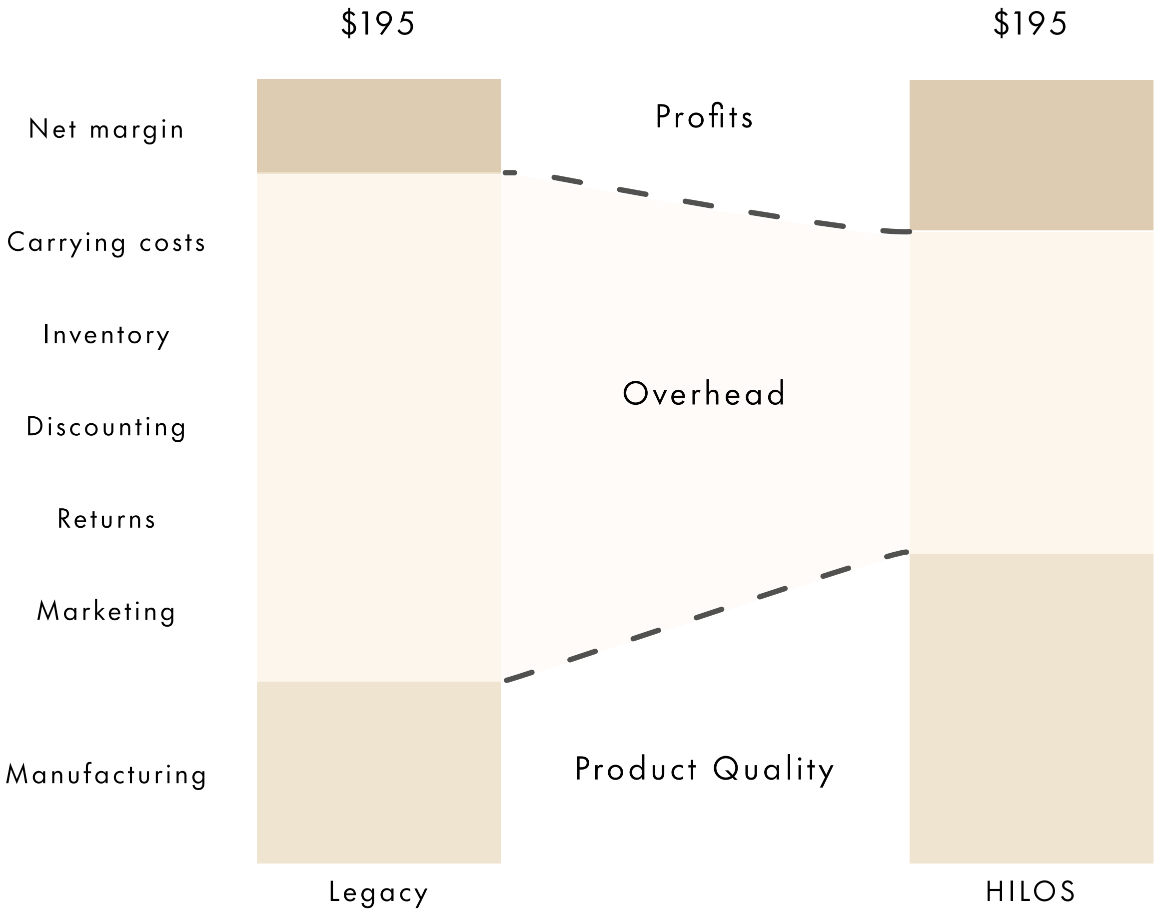
Legacy cost structure





A model that reduces or eliminates these costs entirely can afford to reinvest this margin back into manufacturing, **in turn increasing the quality, durability, and longevity of product delivered and further reducing returns.** This virtuous cycle is the antithesis of the current focus on cheaper material costs across traditional supply chains that challenge the adoption of more sustainable materials and efficient production processes.

73% of HILOS costs are attributed to materials, 19% to labor, and 8% to shipping. Despite higher wages paid to a Portland-based workforce, HILOS spends less on labor costs per product due to new forms of shoemaking developed using digital manufacturing. Reduced labor requirements enable domestic manufacturing (90% of footwear sold in the USA is currently made overseas) and potentially mitigates unethical labor practices.[9] HILOS also benefits from reduced shipping costs due to localization of production close to market. These savings in turn are absorbed by higher material costs from 3D printing.



There are additional benefits from digital manufacturing that were not factored into a direct cost comparison but included in Yale's review. **3D-printing allows for the production of new product SKUs at 85-95% less marginal cost and up to 86% faster than legacy operations.** This could enable an entirely new diversity of product lines taken far quicker to market without the accompanying waste of traditional supply chains.

Conclusions

We believe that advances in material science and 3D printing are beginning to profoundly transform how we make things, in what will be the largest fundamental shift since industrialization. These changes will allow brands to rapidly launch new products into market without traditional design and development cycles, eliminate inventory needs by replacing forward-stocking with forward-making, and meet aggressive sustainability goals through zero-waste production and product recyclability.

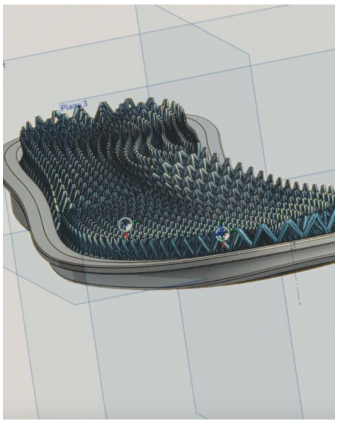
We began this evaluation by noting that sustainability is by its nature a relative exercise. The help of our partners at Yale, BASF Forward AM, HP, and AMT enabled us to objectively weigh the strengths and weaknesses of an on-demand digital supply chain for footwear against the most readily available alternatives. This initial exercise reveals the pronounced benefits from adopting 3D-printing for footwear, from reduced carbon emissions and water usage to more efficiently meeting demand and bringing manufacturing closer to market. **Critically, the very business model for 3D-printed footwear encourages greater investment in materials and an emphasis on efficiency.**

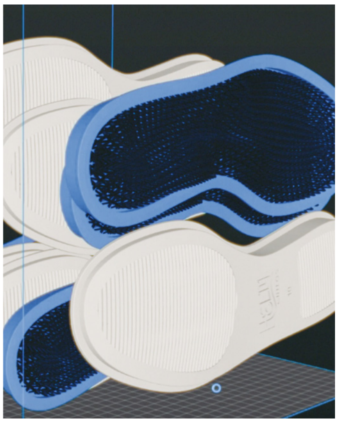
There remain considerable challenges ahead. Injection molded parts can reach such high volumes that on a per-part basis they become more carbon efficient than 3D printing. Increasing energy efficiency in printing needs to be an ongoing focus for the industry. The energy required to recapture and recycle component parts can in some cases erode much of the benefits of displacing new virgin materials. Sourcing more efficient processes for material renewal will decisively increase the impact of product recycling.

Conclusions

Our most significant finding related to on-demand production and the resulting reduction of material waste, introducing efficiencies across the entire supply chain in a way that a more sustainable material or recycling process could not. The opportunity for both material and financial savings for brands is encouraging for the future of digital manufacturing and its ability to radically reshape legacy supply chains.

These findings illuminate striking insights to take into account when designing and developing the next generation of product lines. There has never been such a rich array of tools with which to evaluate, test, and adopt new materials and technologies for product creation. This initial evaluation continues to inspire our own use of this technology. We hope it will serve as a resource to our industry's continuous evolution.





Endnotes

[1] HILOS uses a minimal amount of glue (1 gram per pair) as part of the assembly process prior to stitching. The carbon footprint for glue usage was estimated and water consumption for glues and transportation is not accounted for in this assessment.

[2] To be conservative, HILOS included the energy required to grind down the BASF Ultrasint TPU for reprocessing, even if virgin material processing also requires grinding, which depends on the supplier and the application.

[3] HILOS emission data from Yale exercise, "HILOS: Manufacturing Footwear for Circularity." Benchmarked data using the emissions from Veja's Esplar full leather style. Accessible at https://project.veja-store.com/en/single/emissions/

[4] Cheah Lynette, Natalia Duque Ciceri, Elsa Olivetti, Seiko Matsumura, Dai Forterre, Richard Roth, and Randolph Kirchain. "Manufacturing-Focused Emissions Reductions in Footwear Production." Journal of Cleaner Production 44 (April 2013): 18–29.

[5] From "Veja Carbon Footprint", accessed https://project.veja-store.com/assets/files/keyword/emissions/VEJA_CO2_EMISSIONS_PDF.pdf

[6] The co-founder of Moda Operandi estimates fashion brands overproduce 30-40% per season. We conservatively estimate a 20% overproduction rate for footwear. Magnusdottir, Aslaug. "How Fashion Manufacturing Will Change After the Coronavirus." Forbes, (May 13, 2020): Accessed: https://www.forbes.com/sites/aslaugmagnusdottir/2020/05/13/fashions-next-normal/?sh=710913f578f3

[7] Water consumption data for traditional manufacturing was not included by the Yale team in their report, outside of component part benchmarking for injection molding. Total water consumption was benchmarked against remarks delivered by Hans Enggrob, head of innovation at the DHI Water Group, at a 2008 conference. According to DHI, 8000 liters of water are used to produce a single pair of leather shoes.

[8] This is assuming a 100% product return rate. HILOS has not yet reached the natural end of life for any of its lines, so we don't have any historical product return data to factor into our assumptions. By assuming a 100% product return rate we are able to assess the overall impact of product circularity under ideal conditions.

[9] Cheah et al. 2013