Universität Bremen

Innovative Skills for an Old Vocation

Innovative Skills for New Materials

WP 04

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Content

1 Introduction

This manual is a joint product of all partners from the Erasmus+ project ”Innovative Skills for an Old Vocation” (ISOV, 2024-1-DE02-KA220-VET-000254492, https://isov-project.eu/). As all sectors, the sector of industrial footwear production faces the mega-trends of globalisation, digitalisation and sustainability. Main aims of the project are the development, pedagogical structuring and piloting of courses for apprentices, students and/or employees in industrial footwear production in Germany, Portugal and Romania, based on scientifically developed impact analyses on which of the dimensions of the trends influence which of the 18 Spheres of Activity (SoA) of the sector. The courses and the manuals refer to 12 chosen concrete SoA in which the participants are working, are supposed to work, or want to work.

Basic materials for the courses are the manuals. As the estimated impact of the dimensions respective sub-dimensions of the trends differ between partner countries and as the equipment of training providers with modern technology is differing, as well, the manuals follow a modular structure:

Chapter 2 documents the, partly shortened or updated, “state of the art” manual from previous projects “Integrating Companies in a Sustainable Apprenticeship System” (ICSAS, http://icsas-project.eu/) respective “Developing Innovative and Attractive Continuous Vocational Education and Training (DIA-CVET, https://dia-cvet.eu/).

Chapters 3-5 illustrate the expected impact of the various (sub-)dimensions of the 3 trends in the near future (up to 5 years) on the work-processes of the chosen SoA.

This approach has the huge advantage that, for example, if the sub-dimension “additive manufacturing” is estimated to have high impact on a certain SoA and a training provider has no 3-d printer, he can, with respect to this sub-dimension, rely on the “old” manual referring to subtractive manufacturing – but still impart the impact of other subdimensions, where the equipment is available.

Finally, chapter 6 offers a case study of apparent good practice, demonstrating not only what, but also exemplarily how to teach.

Or, to put it different, this manual should not be read as a “receipt”, where all condiments should be added or imparted in a fixed row and a defined quantity – but as a “toolbox”, aiming at inspiring trainers to impart not only “state of the art” knowledge, skills and competences (KSC) – but to prepare their apprentices, students or participants in continuous vocational education and training (CVET) for upcoming work-processes.

2 Manual from previous project New Materials

This manual was updated based on the training material titled **New Materials** developed in the framework of the project “Developing Innovative and Attractive Continuous Vocational Education and Training (DIA-CVET, https://dia-cvet.eu/)

2.1 New materials for upper

The footwear industry has to respond to consumers’ increasing demand for more durable, sustainable and innovative products. Durability translates into greater wear resistance and helps maintain features to reduce waste. Sustainability refers to non-toxic, recycled, recyclable, and reusable products and materials, and to efficient manufacturing processes that consume less energy and use alternative sources, aiming to reduce environmental impact as much as possible. Regarding materials, innovative products offer enhanced features and greater satisfaction.

Regardless of the nature of the materials, we have to consider the impact of their manufacturing processes on the environment and consumers’ health.

2.1.1 Leather

Natural leather is one of the most traditional and valued premium materials used in footwear manufacturing and is considered a by-product of the food industry. It is a very versatile natural material that, depending on the tanning process, is available in a wide range of finishes and with excellent characteristics such as flexibility, durability, tear resistance, wear resistance, and breathability.

Tanning is a complex mechanical and chemical process of transforming animal hides into leather. The tanning process uses large quantities of water and chemicals; therefore, the industry is constantly seeking innovative solutions to reduce pollution and obtain products with characteristics comparable to existing leather assortments, containing fewer chemicals and being easily disposed of.

Synthetic leather imitates the appearance of animal leather and is composed of natural and/or synthetic textiles (knitted, woven, or non-woven textiles) coated with a PU or PVC layer. It is generally considered that natural leather is superior to synthetic leather, but recent innovations (water-based synthetic leather, solvent-free synthetic leather, TPU synthetic leather, silicone leather, polyolefin leather, and so on) can offer higher performance, better health protection, and be animal- and eco-friendly.

2.1.2 New leather and leather-like materials

Alternatives like chrome-free leather, biodegradable leather, plant-based material, and bio-fabricated leather have a lower environmental impact than animal leather. These new materials are not completely eco-friendly, but have the potential to be a very good alternative to animal leather in the future.

Chrome-free leather

Due to the environmental damage caused by introducing metals into the ecosystem from the chrome tanning process, new chemicals are being researched.

One innovation is Ecotan Leather, manufactured by Silvateam, which uses plant-based tannins combined with synthetic additives. Another innovation comes from Conceria La Veneta, which developed a chrome-free-tanned leather certified as biodegradable.

Fig. 1: Conceria La Veneta biodegradable leather. Source: https://www.concerialaveneta.com/en/biodegradable-leather.html

Nano leather

Leather tanned or finished using nanotechnology can have excellent antimicrobial, self-cleaning, flame-retardant, water-resistant, and breathability characteristics. For example, silver-titanium dioxide nanoparticles are an ecological alternative to volatile organic biocides and organic solvents commonly used in leather, and they offer antimicrobial properties.

Plant-based materials

Plant-based material is made from mushrooms, pineapple, banana, apple, cactus, green tea, coffee grounds, and more, and is cruelty-free and climate-friendly, with a low environmental impact.

- **Pineapple material -** is made from pineapple leaf fibres, can be biodegradable is durable, flexible, soft, breathable, heat and water-resistant. **Piñatex Pineapple** www.ananas-anam.com/about-us/
- **Coconut material-** is made from waste products of the coconut industry and is biodegradable and compostable. **Malai Coconut** https://malai.eco/
- **Apple material -** is made from residues taken from industrial processing of apples, looks similar in appearance to real leather but has a paper-like feel, which makes it easy to obtain different backings and coatings. **AppleSkin** - https://www.appleleather.com/
- **Cactus materials -** are a sustainable alternative made from cactus leaves, which have similar texture and properties compared to animal leather. **Deserto Cactus -** https://desserto.com.mx/home

Fig. 2: Deserto- cactus material. Source: https://nordrepublic.com/de/desserto-cactus-leather/

Laboratory-engineered materials

- **Fungi -** Fungi-derived material is a sustainable and environmentally responsible alternative to animal leather. MYLO https://boltthreads.com/
- **Skin** - is engineered in the laboratory from skin cells and is marketed as having the same quality as traditional leather without the waste and harm to animals. Modern Meadow www.modernmeadow.com/

Fig. 3: MYLO. Source: www.dezeen.com/2020/10/08/mylo-consortium-adidas-stella-mccartney-lululemon-kering-mycelium/

2.1.3 Textiles

Textile fabrics are made from yarns and are available in a wide array of colours, varieties, styles and designs. Textiles are made from natural or man-made fibres and can be woven, knitted, or non-woven. Natural fibres are cellulosic or protein, and man-made fibres are made from various chemicals (synthetic) or are regenerated from natural sources (natural polymers). **Woven** fabrics are manufactured by interlacing two or more threads in a pattern that holds them together and creates the fabric. **Knitted** fabrics consist of a series of interlaced loops. In the footwear industry, warp-knitted fabrics such as tricot, locknit, and satin are primarily used. **Non-woven** fabrics are made from fibres bonded together by chemical, mechanical, heat or solvent treatment.

2.1.4 New textile fibres, yarns and fabrics

The textile industry is a major contributor to harmful environmental impacts and waste generation; therefore, most new textiles are developed as innovative solutions to address the need for more sustainable systems.

Examples of new textile fibres, yarns, and fabrics are listed below:

- **Polylana Fibre** - offers an eco-friendly alternative to acrylic fibres and is made from a mix of innovative polyester chips and recycled polyester. https://polylana-fiber.com/
- **Meryl nylon -** offers an eco-friendly alternative to cotton and addresses recycling options https://www.nylstar.com/
- **Seaqual -** is a fibre made entirely from recycled marine plastic. https://www.seaqual.org/
- **MATRYX fabric -** is made from recycled polyester and is light, breathable and abrasion-resistant. https://www.matryx-textile.com/en/
- **Tectec Performance** - are advanced coated and laminated fabrics that have enhanced properties. https://tectex.pt/
- **REMEANT** - is a sustainable textile fabric made from upcycled plastic used in packaging materials

Fig. 4: REMEANT textile fabric. Source: https://nat-2.eu/nat-2-reduceusecycle-line/

2.2 New materials for bottom components

The bottom part of the footwear supports and connects the bottom of the foot with the ground and has the main role of protecting the foot from mechanical actions and environmental agents, thus ensuring comfort.

Bottom complexity depends on the footwear type, model and characteristics. The main bottom components are the insole and in sock on the interior, the midsole as an intermediate layer and the sole and outsole in the exterior.

Fig. 5: Cork insole. Source: https://yoursole.com/blog/us/cork-footbed-collection

2.2.1 Natural materials for bottom components

Natural materials used for bottom components include leather, wood, cork, and natural rubber.

- **Leather** is mainly used for insoles and formal footwear soles.
- **Wood** soles are mainly used by designers and fashion labels, but they are also popular in some professions, providing protection.
- **Cork** is a versatile natural material with many applications. For soles, where durability is required, the material is usually mixed with synthetic materials such as PU and PVC.
- Soles made from **Natural Rubber (NR)** derived from the latex sap of the *Hevea brasiliensis* tree; it offers outstanding tensile strength, excellent tear and fatigue resistance, high elasticity, and superior heat dispersion, but has low resistance to ozone, UV light, oxygen, and petroleum-based oils. Therefore, natural rubber is usually mixed with other synthetic materials to improve its properties.

2.2.2 Synthetic materials for bottom components

Synthetic materials used for soles fall into the category of rubbers, plastics, thermoplastic rubbers and polyurethane mixtures:

Synthetic Rubber is processed through vulcanisation and consists of mixtures of plasticisers, antioxidants, active batches, fillers, colouring agents, activators, accelerators, crosslinking agents and specific additives:

- **Styrene-Butadiene Rubber (SBR)** - high elasticity, good tensile and abrasion resistance, high resistance to light and weathering, but lower resistance to tearing and repeated bending;
- **Butadiene Rubber (BR)** - very good resistance to low temperatures, high abrasion resistance, good resistance to wear and repeated bending and high elasticity;
- **Nitrile Butadiene Rubber (NBR)** - good tensile strength and resistance to ageing;

Thermoplastic Rubber (TR) has similar physical-mechanical properties to those of vulcanised rubber:

- **Styrene-Butadiene-Styrene (SBS)** - exceptional stability to water, alkalis, sulfuric, nitric and hydrochloric acids, ammonia, alcohols, low temperature, but limited resistance to mineral and vegetable oils.
- **Thermoplastic Polyurethane (TPU)** - exceptional resistance to abrasion, wear and tearing, high flexibility at very low temperatures, excellent resistance to oils, greases and many organic solvents, alongside superior shock absorption and high load-bearing capacity.

Plastics used for soles must provide flexibility, dimensional stability, bending resistance, wear-resistance and shock absorption:

- **Polyvinyl Chloride (PVC)** - flexibility and wear resistance;
- **Polyethylene (PE)** - low density, good resistance to low temperatures and good resistance to ageing.
- **Ethylene Vinyl Acetate (EVA)** - elasticity, reduced rigidity at low temperatures, no resistance to organic solvents and oils;

Polyurethane (PU) systems are composed of polyisocyanates and polyols (such as polyalcohols or polyesters), mixed with catalysts, blowing agents, crosslinking agents, flame retardants, stabilisers, and dyes. Soles obtained from these mixtures have good dimensional stability and the lowest specific density, for both compact and porous soles, compared with vulcanised rubber soles, thermoplastic rubbers, or plastics. Also, the soles are resistant to abrasion, bending, ageing, chemicals (hydrocarbons, acids, alcohols), fats and oils, and high temperatures, and have a high coefficient of friction on wet surfaces, thereby providing very good anti-slip properties.

A special category of materials comprises rigid soles and heels made from compact thermoplastic rubber, polyamide, polypropylene, polyethene, polycarbonate, polyformaldehyde, and polyurethane. Soles made from these polymeric mixtures must have good wear resistance, compression resistance, slip resistance, and good shock resistance and absorption.

2.2.3 New materials for bottom components

New materials for bottom components enhance footwear characteristics such as plantar pressure distribution, cushioning, shock absorption, balance and stability, slip resistance, softness and flexibility, bending and torsion and durability. Also, these new materials aim to reduce the environmental impact of footwear by focusing on natural and renewable resources, recycled and/or recyclable polymeric materials, biodegradable polymers, and the minimisation/elimination of hazardous and restricted substances.

- **Graphene foam –** graphene enhances the characteristics such as cushioning, shock absorption, slip resistance and durability. www.manchester.ac.uk/discover/news/graphene-foam-doubles-longevity-of-new-running-shoe/
- **Vibram N-oli** – made with more than 90% natural ingredients originating from plants and biological agricultural by-products without the use of solvents or chemical products. https://eu.vibram.com/en/technology/n-oil/

- **Eco TPU –** made with 60% material from renewable plant origin and having the same features as standard thermoplastic polyurethane. http://resimol.com/en/ecological-shoe-innovations/ecological-shoe-soles-ecotpu/
- **Indosole** – the material is made from recycled tyres and is waterproof and durable. https://www.indosoleeurope.com/
- **Eva Green –** a flexible, light and abrasion-resistant material composed of a resin produced from sugar cane, a renewable source that also contributes to reducing CO2 emissions. https://vapesol.com/eva-green/
- **Algae foam –** made from algae mixed with EVA. Reduces the amount of synthetic material used, cleans lakes of harmful algae, and prevents the release of CO2 into the atmosphere. https://www.bloommaterials.com/

Fig. 6: Bloom algae foam. Source: https://materialdistrict.com/material/algae-foam/bloom-foam-algae-foam-ona774-8/

2.3 Physical and chemical requirements

Materials have a significant influence on footwear; therefore, testing footwear materials, components, and footwear is essential for understanding footwear behaviour, quality, and performance. Materials can be tested and evaluated individually, as part of a system of materials (e.g., footwear components), or as part of finished footwear products.

The main physical tests for footwear materials are the following:

- **Abrasion resistance -** represents the ability to withstand the wear and tear of friction.
- **Adhesion resistance -** is the property that determines the strength of adhesion between two surfaces.
- **Colour fastness -** is the persistence of material colour under various conditions, such as contact with human perspiration or water.
- **Colour migration -** refers to the spreading of dye within the material or from one material to another, influenced by temperature, moisture and water.
- **Dimensional stability** - is the method that determines the dimensional stability of materials, for example, swelling after immersion in water, or shrinkage under high temperature.
- **Tear strength -** is a measure of how well a material can withstand the effects of tearing.
- **Tensile strength** - is defined as the ability of a material to resist a pulling force and refers to the breaking strength of the material.

- **Flex resistance -** is the ability of a material to withstand repeated flexing or bending.
- **Water resistance** - is the property of materials related to the penetration of water.
- **Water vapour permeability** - refers to materials' breathability and describes the ability to allow water vapour to pass.
- **Slip resistance** - is evaluated by determining the dynamic coefficient of friction between a sole and a surface. Slip resistance is related to a combination of factors, including the walkway surface, the footwear sole material and pattern, and the presence of foreign materials between them.
- **Compression energy** - influences the cushioning and shock absorption ability of bottom materials to absorb and to dissipate both the impact and push offloads that occur during walking or running
- **Delamination resistance -** refers to coating resistance to delamination from the substrate.

Fig. 7: Gore-Tex virtual footwear laboratory. Source: widget.gore-tex.com/3d/vlt/index.html?startscene=0&startactions=lookat(399.43,35.93,128.21,0,1)

2.3.1 Standards that establish footwear performance requirements

Various recognised standardisation organisations establish the requirements and test methods for footwear products. For example, **International Standards (IS)** or **Technical Specifications (TS)** establish performance requirements for footwear components across various footwear types (not for finished footwear), regardless of material. ISO standards for footwear are modern and focus on how the component *performs* (e.g., flexibility, tear strength), not what it is made of (leather, plastic, or rubber). The standards also establish the test methods for evaluating compliance with the requirements. ISO standards for general footwear and protective footwear are presented in the following tables:

ISO/TR 20879 Footwear — Performance requirements for components for footwear — Uppers
ISO/TR 20880 Footwear — Performance requirements for components for footwear — Outsole
ISO/TR 20881 Footwear — Performance requirements for components for footwear — Insoles
ISO/TR 20882 Footwear — Performance requirements for components for footwear — Lining and insocks

Tab. 1: ISO standards that establish the performance requirements for general footwear

ISO 20344 – Personal protective equipment — Test methods for footwear	
ISO 20345 - Personal protective equipment – Safety Footwear	
ISO 20346 – Personal protective equipment – Protective Footwear	
ISO 20347 – Personal protective equipment – Occupational Footwear	

Tab. 2: ISO standards that establish the performance requirements for protective footwear

The complete list of ISO standards for footwear can be found here www.iso.org/ics/61.060/x/p/1/u/1/w/0/d/0.

2.3.2 REACH - Registration, Evaluation, Authorisation and Restriction of Chemicals

The use of chemical substances is regulated by REACH, which aims to protect human health and the environment from chemical risks while enhancing the competitiveness of the EU chemicals industry. Companies from the footwear industry should ensure that their products do not contain restricted substances. The list of restrictions on the manufacture, placing on the market, and use of certain dangerous chemical substances, mixtures, and articles is set out in **REACH Annex XVII**, available at the following link: data.europa.eu/euodp/en/data/dataset/restricted-list-REACH.

2.3.3 CADS - Cooperation for assuring defined standards for shoes and leather goods

An exclusive list of Restricted Substances for the footwear industry was developed and is constantly updated by CADS which aims to secure the quality of footwear and leather goods, to distinguish footwear and leather goods whose quality is secured with a quality label, and to engage in public relations work for the manufacture and marketing of sustainable, non-toxic, environmentally compatible shoes, shoe materials and leather goods with social responsibility.

CADS list Restricted **Substances in Shoes is available** at the following link www.cads-shoes.com/en/documents.

The main substance groups regulated by CADS are the following:

- Azo dyes
- Biocides
- Chlorinated Phenols
- Allergenic dyes
- Carcinogenic dyes
- Heavy metals
- Organotin compounds
- Perfluorinated Substances
- Phthalates
- Polycyclic aromatic hydrocarbons
- Volatile Organic Compounds
- Chlorinated benzenes and toluenes
- Flame Retardants

For each restricted substance, there are tests designed to identify and quantify its presence in footwear.

3 Globalisation in New Materials

3.1 Global markets, consumers & economic drivers

Recent research highlights increasing environmental concerns associated with conventional footwear production, mainly due to intensive resource consumption and waste generation of materials (Harito et al.,2025[1]; Albano et al., 2022[2]; Alexandrescu et al., 2023[3]; Ghannadzadeh et al., 2025)[4]. Consumption patterns are undergoing profound transformations. Consumers are increasingly moving away from traditional ownership models toward more flexible and sustainable forms of consumption. Ellen MacArthur Foundation[5] highlights that circular economy strategies encourage practices such as renting, reselling, repairing, and recycling items, including footwear. These changes reflect a broader cultural shift toward sustainability and resource efficiency, which is reshaping demand across global markets.

Geopolitical conflicts are affecting the material supply. Shortages of rubber, leather, PU chemicals, EVA, and natural fibres push brands toward local biopolymers, regional rubbers, synthetic and recycled alternatives.

The war in Ukraine and related geopolitical tensions have driven uncertainty and exacerbated long-standing dependencies on critical raw materials, especially in the European leather and tanning industry, leading to potential shortages of crude and semi-finished hides and chemicals (De Clemente, 2022[6]). Footwear and leather brands are proactively diversifying their supply networks and investing in **local/regional solutions**. (Solca, 2022[7])

Recent **disruptions** in the **materials supply chain** (e.g., during 2020–2021) forced manufacturers to explore and adopt more sustainable materials out of necessity. According to industry case studies, such crisis-driven substitutions resulted in high-quality, low-impact products, more resilient supply chains, and positive environmental and community outcomes (Hokkanen, B., 2023[8]).

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[1] Harito, C., Martawidjaja, M., Chainando, N., & Simarmata, T. P. (2025). The current development of sustainable materials for a greener footwear industry: A review. IOP Conference Series: Earth and Environmental Science, 1488(1), 012008. https://doi.org/10.1088/1755-1315/1488/1/012008

[2] Albano F., Ferreira M. J., Costa, P., Machado, T., Pinto, V. (2022). Strategies to Make Footwear Sustainable and Circular: A New Walk towards the European Green Rules. https://doi.org/10.24264/icams-2022.iv.5

[3] Alexandrescu L., Georgescu M., Pantazi-Băjenaru M., Foiaşi, T. (2023). EEnvironment impact of eco-engineered versus conventional footwear. https://doi.org/10.5593/sgem2023/5.1/s20.13

[4] Ghannadzadeh, A., Ortiz-de-Montellano, C., G. -S, van der Meer, Y. (2025). Life Cycle Assessment and Circularity Assessment as Complementary Methods for the Circular and Sustainable Redesign of Multi-Material Products: A Case Study on Safety Industrial Footwear. No Journal. https://doi.org/10.55845/mbrq4782

[5] Ellen MacArthur Foundation (2025). Circular business models in fashion. Retrieved from https://www.ellenmacarthurfoundation.org/the-fashion remodel/learn#:~:text=Customer%20behaviour%20and%20norms%20are,5%20million%20in%20annual%20revenue.

[6] De Clemente, I. M. (2022). The New Challenge of the European Leather Supply Chain in the Current Geopolitical Environment. Scholars Journal of Economics Business and Management. https://doi.org/10.36347/sjebm.2022.v09i12.002

[7] Solca, L. (2022). Luxury leather goods and alternative leather: Risk and growth opportunities. Luxury Studies: The In Pursuit of Luxury Journal. https://doi.org/10.1386/ipol_00010_1

[8] Hokkanen, B., Mallek, J. Miller, J., Anderson, K., Norfleet K., Barry, L., Gathright, M., Glass, T. (2023). How the implications of force majeure resulted in the adoption of more sustainable materials. MRS bulletin, 48, 386 - 393. https://doi.org/10.1557/s43577-023-00533-4

Fig. 8: Nike materials supply chain failed during pandemic. Source: https://supplychainnuggets.com/why-nikes-supply-chain-failed-during-the-pandemic/

Footwear manufacturing uses various materials, such as rubber, leather, and synthetics, and relies on a network of international suppliers. As a result of its dependence on a global supply chain, the footwear industry is exposed to multiple disruptions throughout the production process. A clear example is **Nike**, which faced major difficulties during the pandemic when its highly efficient, fast-moving supply chain was suddenly disrupted.

Because the company relied heavily on manufacturing in countries like Vietnam, factory shutdowns brought production to a warehouse, while delays in global shipping significantly **increased delivery times and costs**. At the same time, since it had a low-inventory "just in time" model, it was limited by unpredictable interruptions, which caused shortages as these disruptions forced demand back. Then, the original decisions to reduce order amounts during declining demand would result in greater imbalance down the line, with products arriving either too early, too late, or in wrong quantities. Together, these factors led to both excess stock in some periods and product shortages in others, showing how tightly interconnected and fragile global footwear supply chains can be (Supply chain nuggets, 2025[9]; Eustochos, 2024[10]).

Global consumer behaviour, **innovation** and **competition** play a fundamental role in shaping the development of new materials in the footwear industry. Increasing demand for **comfort, performance, sustainability, and personalisation** has led to the emergence of advanced material categories such as engineered knits, bio-based polymers, and high-performance foams. Niinimäki et al., 2020[11]).

Consumers are increasingly prioritising **lightweight, breathable, and flexible materials**, particularly in athletic and lifestyle footwear. This shift has driven the development of materials such as **engineered mesh and knitted uppers**, which reduce weight while improving fit and comfort. For example, companies like Nike and Adidas have introduced technologies such as Flyknit and Primeknit, which use digitally engineered yarn structures to minimise material waste and enhance performance (Adidas Group, 2022[12]; Nike Inc., 2023[13]).

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[9] Supply chain nuggets. (2025). Why Nike's Supply Chain Failed During the Pandemic. Retrieved from: https://supplychainnuggets.com/why-nikes-supply-chain-failed-during-the-pandemic/

[10] Eustochos. (2024). Nike and the 2024 Supply Chain Disruption: A Case Study in Crisis Management. Retrieved from: https://eustochos.com/nike-and-the-2024-supply-chain-disruption-a-case-study-in-crisis-management/

[11] Niinimäki, K., et al. (2020). The environmental price of fast fashion. Nature Reviews Earth & Environment, 1(4), 189–200. https://doi.org/10.1038/s43017-020-0039-9

[12] Adidas Group. (2022). Primeknit technology and sustainability initiatives. Retrieved from https://www.sneakerfreaker.com/material-matters/material-matters-adidas-primeknit

[13] Nike Inc. (2023). Flyknit technology overview. Retrieved from https://www.adsport.store/nike/technologies/flyknit/

Fig. 9: Flyknit technology from Nike. Source: https://blog.size.co.uk/2016/01/24/27443/

Nike Flyknit is an advanced upper-construction technology developed by Nike, designed to create lightweight, form-fitting, high-performance footwear. Introduced in 2012, Flyknit uses high-strength fibres that are precisely engineered and digitally knitted into a single-piece upper, reducing material waste and improving structural efficiency. The technology enables targeted zones of support, flexibility, and breathability by varying the knit structure across the shoe. As a result, Flyknit provides a sock-like fit while maintaining durability and performance, making it particularly suitable for running and athletic footwear. Additionally, the process significantly reduces manufacturing waste compared to traditional cut-and-sew methods, contributing to more sustainable production practices.

3.2 Qualification, training and knowledge

In recent years, consumers have developed a stronger understanding of environmental issues, leading to increased expectations for transparency and accountability. According to Fani et al. (2023)[14], sustainability has become a priority not only for governments but also for consumers, who increasingly demand environmentally responsible products and **clear information about their impact**. People should know about sustainable materials so they can know what to ask and what to expect from a sustainable product that they're buying (Caniato, 2021[15]).

[14] Fani, V., Mazzoli, V., & Acuti, D. (2023). "I wanna be sustainable, but I don't wanna show it!": The effect of sustainability cues on young adult consumers' preferences. Business Strategy and the Environment, 32(6), 3344–3358. https://onlinelibrary.wiley.com/doi/full/10.1002/bse.3303

[15] Caniato, F., Caridi, M., Crippa, L. & Moretto, A. (2012). Environmental sustainability in fashion supply chains: an exploratory case based research. Int. J. Prod. Econ. 135, 659–670.

Fig. 10: Environmental sphere coding framework – sustainable materials. Source: Romero, M.J.M et al. (2024) [16]

Cross-border collaboration in footwear material development is evident in partnerships such as **Adidas and Parley for the Oceans**[17], which transformed marine plastic waste into performance materials, and **Adidas with Bolt Threads**[18] (a US-based biomaterials company that uses biotechnology to create sustainable, high-performance materials inspired by natural proteins), which introduced mycelium-based materials alternatives.

Additionally, **consortia like Korvaa**, bringing together companies such as **Modern Synthesis, Ecovative, and Ourobio,** demonstrate how multidisciplinary collaboration can generate entirely new biomaterial categories for footwear applications (Better Shoes Foundation, 2025[19]).

Universities play a key role too in footwear material innovation through collaborations with industry. For example, the **University of Manchester** collaborated with **inov-8** to create graphene-enhanced rubber for high-performance footwear (Fig. 11). These collaborations demonstrate how academic research supports the creation of new material categories in the footwear industry.

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[16] Romero, M.J.M., Kapsali, V., Wang, L. et al. (2025) An analysis of sustainability and performance indicators in Eco-Conscious trainers' brands. Sci Rep 15, 21581 (2025). DOI: https://doi.org/10.1038/s41598-025-04186-y

[17] Parley. (n.d). Parley ocean plastic. Retrieved from: https://parley.tv/future-material

[18] Adidas. (2021). Stan Smith Mylo. Retrieved from: https://news.adidas.com/originals/stan-smith-mylo--recreating-an-icon-made-with-underground-roots-of-mushrooms/s/3403a796-7db3-429c-8a3b-6378c2f962b0

[19] Better Shoes Foundation (2025). Korvaa consortium. https://www.bettershoes.org/korvaa-consortium

Fig. 11: University collaboration reveals world's first-ever graphene sports shoes. Source: https://www.manchester.ac.uk/about/news/university-collaboration-reveals-worlds-first-ever-graphene-sports-shoes/?

4 Sustainability in New Materials

4.1 Green awareness

Material identity & environmental disclosure

Due to growing pressure to reduce emissions and increase resource efficiency, many industries are changing in response to climate goals and regulations, such as the European Green Deal, leading to an increased emphasis on circularity and greenhouse gas emissions reduction. At the same time, integrated use of **Life Cycle Assessment (LCA), Material Circularity Indicators (MCI)**, and **environmental footprint methodologies** enables both companies and policymakers to evaluate and incentivise the adoption of sustainable materials and practices (Albano et. al., 2022[20]; Ghannadzadeh et. al., 2025[21]).

Digital transparency of materials

Sustainable approaches for **transparency** and the implementation of traceability mechanisms at the material level help ensure that information on environmental, social, and production attributes is disclosed, **thereby influencing trust** (Thibbotuwawa et al., 2024[22]). Production transparency, including cost breakdown and supply chain details, positively affects both overall brand equity and consumers' purchase intentions, provided that the information is perceived as fair (Rothenberg & Kim, 2019[23]). This situates transparency as a key extrinsic signal—external, visible, and thus effective for trust formation. However, transparency is rarely uniform across production tiers; many brands disclose information about immediate suppliers but less so about earlier stages of the supply chain (material sourcing, processes), which may limit the effectiveness of transparency mechanisms in building trust (Muratore & Marques, 2021[24]).

In this context, **Digital Material** and **Product Passports** (as described in the ISOV Design Manual), introduced by the European Commission under the Ecodesign for Sustainable Products Regulation, play an important role in improving **material transparency** in the footwear industry. It provides structured digital information on material composition, environmental impact, durability, and end-of-life options, enabling improved traceability and supporting circular economy strategies. From 2027, footwear products will be required to include such digital records, ensuring that **material data** is accessible across the entire product lifecycle (European Commission, 2025).[25]

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[20] Albano F., Ferreira, M. J. Costa, P., Machado, T., Pinto, V. (2022). Strategies to Make Footwear Sustainable and Circular: A New Walk towards the European Green Rules. No Journal. https://doi.org/10.24264/icams-2022.iv.5

[21] Ghannadzadeh, A., Ortiz-de-Montellano, C., G. -S, van der Meer, Y. (2025). Life Cycle Assessment and Circularity Assessment as Complementary Methods for the Circular and Sustainable Redesign of Multi-Material Products: A Case Study on Safety Industrial Footwear. No Journal. https://doi.org/10.55845/mbrq4782

[22] Thibbotuwawa, A., Weerasinghe, B., Perera, H. N., Madumali, S. (2023). Transparency in textile & apparel supply chains: a systematic review. Journal of South Asian Logistics and Transport. https://doi.org/10.4038/jsalt.v3i2.71

[23] Rothenberg, L., Kim, N. (2019). Is Honesty the Best Policy? Examining the Role of Price and Supply Chain Transparency in Fashion Marketing. No Journal, 76. https://doi.org/10.31274/ITAA.8230

[24] Muratore, A. P., Marques, L. (2021). Fashion supply chain transparency: do as I say not as I do. International Journal of Productivity and Performance Management. https://doi.org/10.1108/ijppm-02-2021-0110

[25] European Health and Digital Executive Agency. (2025). DigiPass: A digital materials and product passport in the domain of health and safety. Retrieved from: https://hadea.ec.europa.eu/news/digipass-digital-materials-and-product-passport-service-health-and-safety-2025-01-30_en

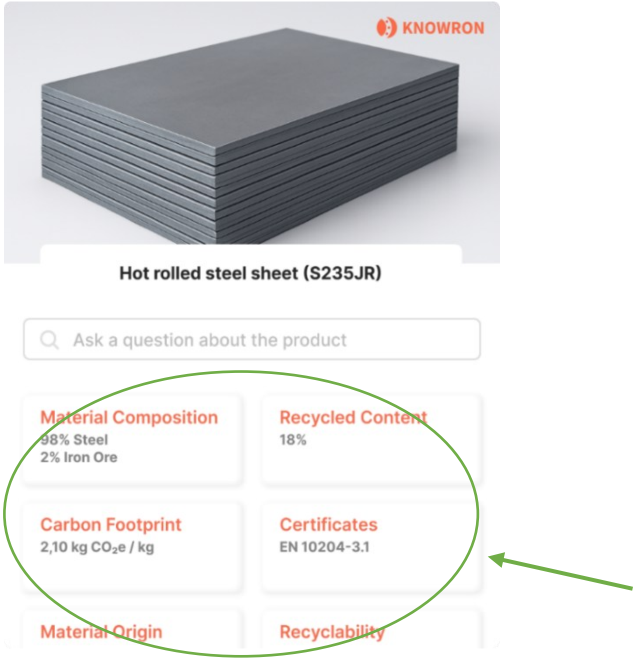

Fig. 12: Example of details of the materials that can be found in DPP from 2027. Source: https://www.knowron.com/digital-product-passport-product#consortium

An example of **material-level transparency** in the footwear industry is Camper, which demonstrates how brands can communicate detailed material information directly to consumers. The company's **Roku model**[26] provides information on each component, specifying both the **material composition and the percentage of recycled content** (e.g., upper, laces, insole), thereby offering a high level of product-level transparency.

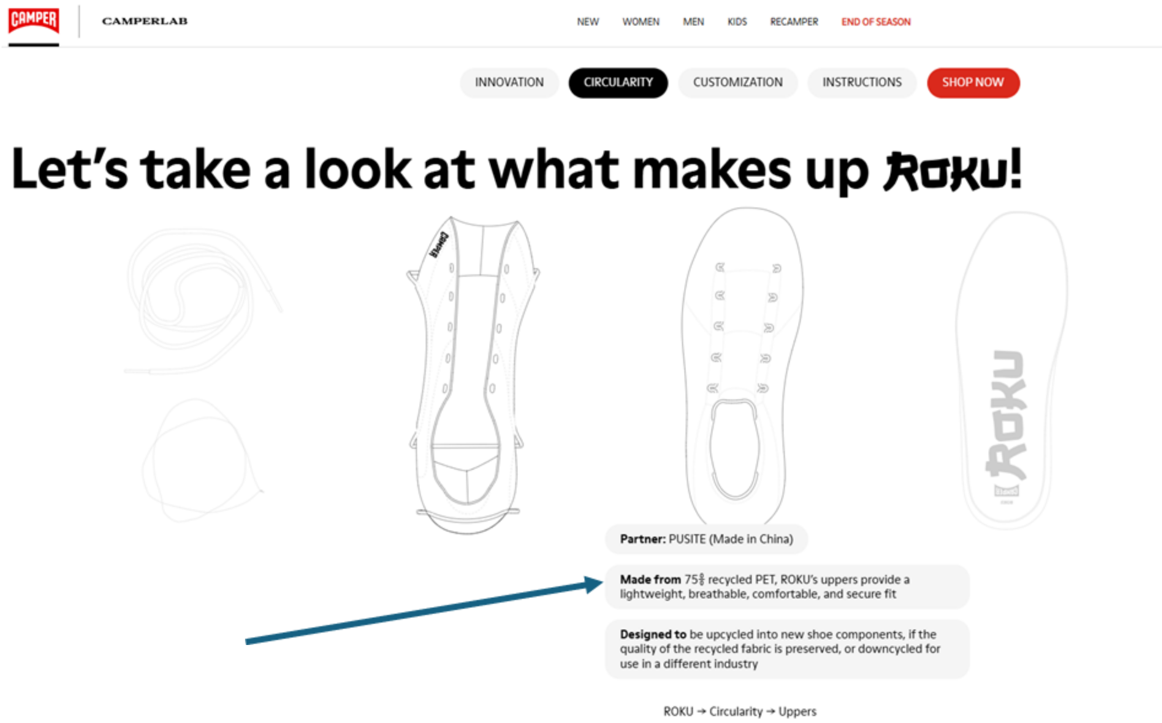

Fig. 12: Material transparency of ROKU model by CAMPER. Source: https://www.camper.com/en_RO/roku?section=circularity

[26] Camper. (2024). Sustainability: Product and materials. Retrieved from https://www.camper.com/en_RO/roku?section=circularity

The most **anticipated sustainable material trends** shaping the future of the footwear industry are categorised by the WORLD FOOTWEAR BUSINESS CONDITIONS SURVEY 2025 by Portuguese Shoes. Natural fibres are expected to lead footwear trends, followed by plant-based leather alternatives. Recycled plastics highlight a focus on sustainability, while innovative foams and compostable materials are emerging but are less dominant.

Material Type	Percentage (%)
Sustainable natural fibers	40
Plant-based leather alternatives	32
Recycled plastics	29
Innovative foam material	27
Compostable materials	20

Tab. 3: Trends in footwear materials. Source: WORLD FOOTWEAR BUSINESS CONDITIONS SURVEY 2025 2nd SEMESTER ISSUE 13 by Portuguese Shoes.

Eco-labelling requirements

Together with digital transparency, **eco-labelling** is another important mechanism that supports awareness of sustainable footwear**.** These tools allow consumers to access detailed information about materials.

In the European Union, the **EU Ecolabel**[27] for footwear products establishes environmental criteria for footwear throughout the product life cycle, including material selection, chemical use, durability, and consumer information. The label helps consumers identify products with reduced environmental impact while encouraging manufacturers to adopt more sustainable production practices.

Eco-certifications play a critical role in validating material sustainability. Key certifications relevant to footwear materials include:

- **OEKO-TEX®-** Chemical Safety and Material Compliance

OEKO-TEX®[28] certification systems, particularly **STANDARD 100** and **LEATHER STANDARD**, are widely applied in footwear to ensure that all material components are free from harmful substances. These certifications require that **every component of a product—such as uppers, linings, insoles, and outsoles—be tested for compliance with a comprehensive list of restricted chemicals.**

[27] European Commission. (n.d.). Footwear. European Commission, Environment. Retrieved from: https://environment.ec.europa.eu/publications/footwear_en

[28] Oeko tex. (n.d.) Oeko tex system. Retrieved from: https://www.oeko-tex.com/fileadmin/user_upload/Marketing_Materialien/Dachmarke/Modular_System/OEKO-TEX_modular_system_EN.pdf?

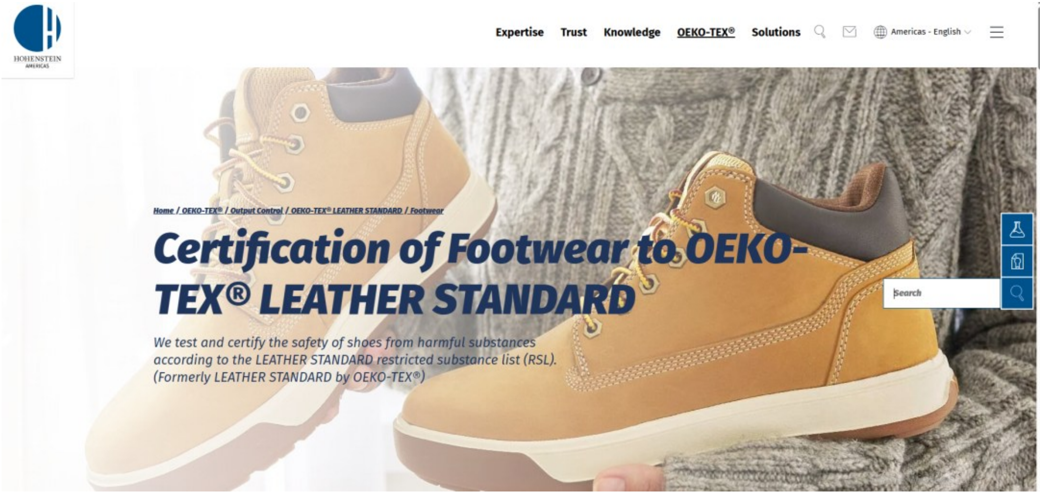

Fig. 13: OEKO-TEX® - Leather standard. Source: https://www.hohenstein.us/en-us/oeko-tex/output-control/leather-standard/certification-of-footwear?

- **Leather Working Group (LWG)**- Evaluates environmental practices in leather production.

The Leather Working Group (LWG) focuses specifically on the environmental performance of leather materials used in footwear. It evaluates tanneries based on criteria such as **chemical management, water use, energy consumption, and traceability**, directly influencing how leather materials are produced and processed (Hamm, n.d.[29]).

Membership in LWG ensures that leather used in footwear originates from environmentally responsible and transparent production systems, with many brands sourcing from LWG-certified "Gold-rated" tanneries to guarantee compliance with sustainability standards

- **Global Recycled Standard (GRS)**- Verifies recycled content in materials.

The Global Recycled Standard (GRS) is a certification that directly applies to the **material composition of footwear components containing recycled content**. It verifies both the **presence and percentage of recycled materials** and tracks the material flow from raw input to final product. It must contain at least 20% recycled material to be eligible for certification, and at least 50% to qualify for product-specific labelling (Texon, 2021[30]; Global Recycle Standard, n.d.[31]).

- **Cradle to Cradle Certified (C2C)**- Assesses material safety and circularity.

Cradle to Cradle Certified® is a comprehensive certification system that evaluates materials based on material health, circularity, and environmental impact. It requires that materials be designed for safe reuse, recycling, or biodegradation, fundamentally influencing material composition (Cradle to Cradle Products Innovation Institute, 2026[32]).

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[29] Hamm. (n.d.) Sustainability-Materials. Retrieved from: https://www.hamm-footwear.com/en/company/sustainability/materials

[30] Texon. (2021). Sustainability has always driven how we think, what we produce and who we work with. Retrieved from:https://www.texon.com/leading-the-way-with-first-rate-environmental-credentials/?

[31] Global Recycle Standard. (n.d.) Implementation Manual 4.2. Retrieved from: https://textileexchange.org/app/uploads/2021/02/GRS-v4.2-Implementation-Manual.pdf

[32]Cradle to cradle products innovation institute. (2026). Certifying products that are good for you and good for the planet. Retrieved from: https://c2ccertified.org/the-standard

4.2 Chemical safety

Harmful substances on the environmental impact

The footwear sector has made considerable progress in energy efficiency, material usage, and the removal of harmful materials from production over the past few years. Yet the results from the production phase have been negated by a huge increase in demand for shoes due to the rebound effect. The average lifespan of a pair of shoes is relatively short and declining due to rapidly changing markets and fashion trends across society. This short lifespan generates a massive flow of waste from worn-out shoes, which are discarded at the end of their functional life, with the vast majority ending up in landfills (Staikos et al., 2006[33]). Table 4 presents the main materials used in footwear production and their associated environmental pollutants.

Footwear materials	Environmental pollutants
Leather	Chromium, Aldehydes, Solvents
Syntethic Materials	Solvents, VOCs
Textiles	Process Chemicals, Biocides
Rubbers	Rubber Fume
PVC	Vinyl Chloride Monomer Cadmium, Plasticisers
Polystyrene	Styrene Monomer
Polyurethane	Isocyanates, (CFCs)
Adhesives	Solvents, VOCs, Chlorine

Tab. 4: The most harmful material pollutants found in the footwear industry. Source: Abbot S. & Wilford A. (1999).[34]

Emergence of new materials due to chemical restrictions

Table 5 presents a range of biodegradable materials that are increasingly being explored as alternatives to conventional petroleum-based materials in the footwear industry. These materials are derived from diverse renewable sources, including agricultural by-products, marine biomass, and microbial processes, reflecting a significant shift toward **bio-based and circular material systems.**

Name of biodegradable material	Primary raw material	PLA content
Pinatex	Pineapple fiber	Yes
AlgiKnit	Biopolymer from seaweed	No
Malai	Coconut water, bacterial cellulose, natural fibres	No
Nuatan	Bioplastics	Yes
Flax	Flax	Yes
MycoWorks	Mycelium	No
Bloomfoam	Algae	Yes
Vegetable-tanned leather	Animal skin	Yes

Tab. 5: Biodegradable materials for the footwear industry. Source: Zavodna, L., S. et. al. (2020)

[33] Staikos, T., Heath, R., Haworth, B. & Rahimifard, S. (2006). End-of-Life Management of Shoes and the Role of Biodegradable Materials. În: Bardos, P. (ed.) Proceedings of the 13th CIRP International Conference on Life Cycle Engineering (LCE), Leuven, Belgia. Loughborough: Centre for Sustainable Manufacturing and Recycling Technologies (SMART)

[34] Abbot S. & Wilford A. (1999). The Footwear Industry and the Environment. Modern Shoemaking, No. 56, 1999.

4.3 Energy, process and resources efficiency

Automation-ready materials are increasingly being developed to support advanced manufacturing systems such as robotic cutting, automated lasting, and automated bonding. A relevant example is the **LightSpray technology** developed by On, which demonstrates how material design and process innovation can be fully integrated into automated production.

The LightSpray system uses a **thermoplastic filament material specifically formulated for robotic processing**, enabling a fully automated manufacturing process in which a robotic arm sprays the material directly onto a shoe last to create a seamless upper. Unlike traditional footwear production, which involves up to 200 manual, multi-stage operations such as cutting, stitching, and bonding, this process reduces the process to a single automated step completed in approximately **3 minutes** (Innovation in Textile, 2025[35]).

In terms of efficiency, the LightSpray system significantly reduces resource consumption. By eliminating multiple manufacturing steps, it reduces **energy use, water consumption, and material waste**, and lowers carbon emissions by up to 75% compared to conventional footwear production methods (On, 2026[36]).

Fig. 14: On - Light Spray model of footwear with the upper done in 3 minutes.Source: https://www.gearpatrol.com/fitness/on-lightspray-running-shoes/

[35] Innovation in textile (2025). On's LightSpray pushes the automation envelope. Retrieved from: https://innovationintextiles.com/clothing-footwear/ons-lightspray-pushes-the-automation-envelope/

[36] On. (2026) LightSpray™. Find answers to your most commonly asked questions.https://www.on.com/en-pl/faq/lightspray-faqs?utm_source=chatgpt.com#what-makes-lightspray-tm-more-sustainable-than-traditional-manufacturing

5 Digitalisation in New Materials

5.1 Artificial Intelligence

The capacity of Artificial Intelligence (AI) systems to predict the **mechanical characteristics** of polymers, including, but not limited to, **tensile strength** and **elasticity**, through virtual methods rather than experimenting on an actual basis, is a major advancement (National Institute for Materials Science, 2024[37]) which will be an asset to footwear design by helping to ensure that the true performance capability of the footwear will be apparent when worn, even after repeated loads.

Furthermore, AI-based models can predict wear performance and durability in composite materials, supporting the development of footwear components such as outsoles that require high **abrasion resistance** (Kumar et al., 2025[38]).

AI systems can also work interactively with researchers by suggesting new material formulations based on desired properties. For example, AI-assisted design tools have been used to develop new polymers that combine **strength and flexibility**, properties that are typically difficult to achieve simultaneously, resulting in a rubber-like material (Heuring, 2025[39]).

Fig. 15: Chemists can discover new materials quickly with AI. Source: https://www.cmu.edu/mcs/news-events/2025/0922-machine-learning-polymer-discovery

5.2 Big Data

The footwear industry has developed many performance-specific databases to support the **precise selection of materials**, enabling designers to choose materials based on the mechanical and functional characteristics they require. One such database is Carbonfact's extensive database,

[37] National Institute for Materials Science. (2024). Machine learning can predict the mechanical properties of polymers. Retrieved from https://www.azorobotics.com

[38] Kumar, T. S., et al. (2025). Machine learning models based wear performance prediction of AZ31/TiC composites. Scientific Reports. https://doi.org/10.1038/s41598-025-33417-5

[39] Heuring, K., (2025). Chemists Can Discover New Materials More Quickly With AI. Retrieved from: https://www.cmu.edu/mcs/news-events/2025/0922-machine-learning-polymer-discovery

which contains specific **emission factors** for thousands of material categories used in apparel and footwear. These databases contain information on the **composition, durability**, and **processing methods** of a wide variety of materials, which will assist designers in evaluating the performance properties of these materials, such as their strength, flexibility, and wear resistance (Carbon Fact, 2026[40]).

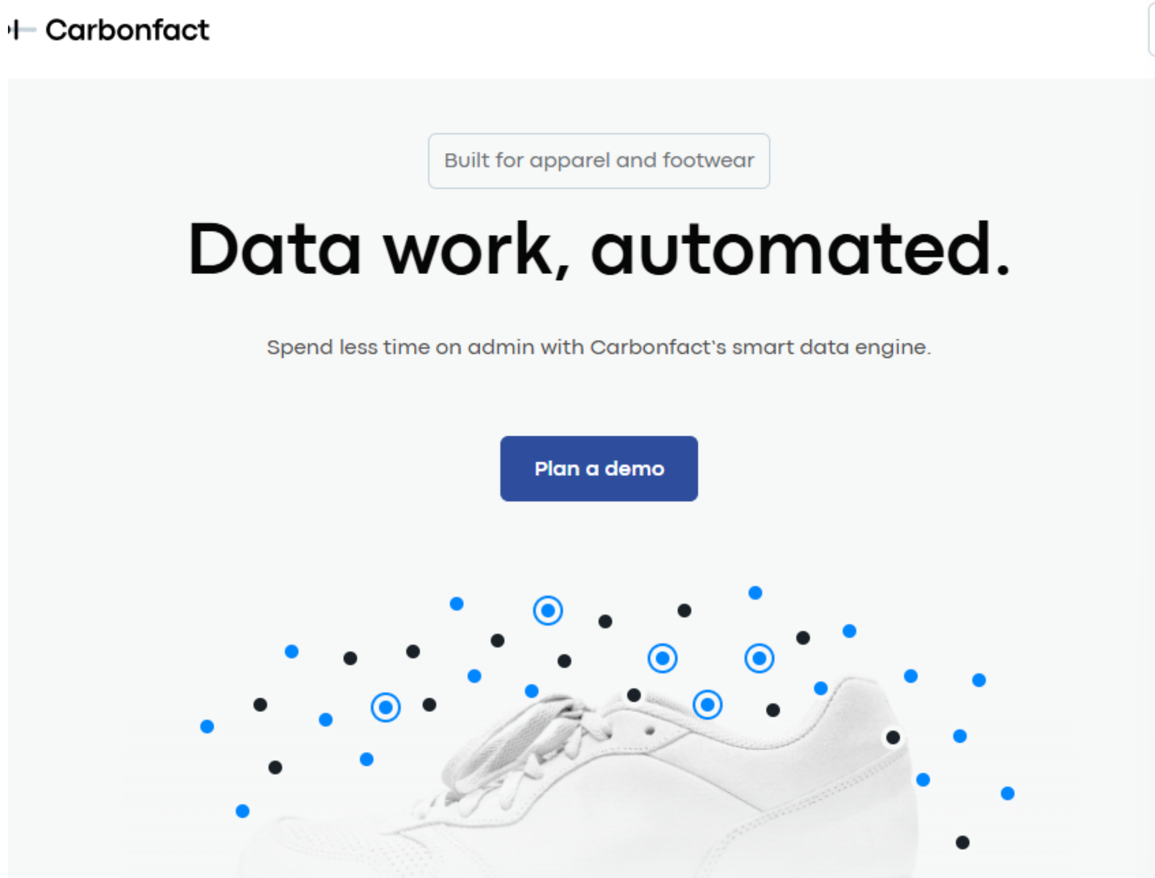

Fig. 16: A platform that manages big volumes of data about footwear and apparel. Source: https://www.carbonfact.com/data-management-software

5.3 3D Printing

3D Printing, also known as **Additive Manufacturing (AM)**, is revolutionising footwear production by enabling rapid prototyping and customised design. This technology allows companies to create complex structures that would be difficult or impossible to produce using traditional manufacturing methods (Luximon & Luximon, 2021[41]).

Among the most widely used materials for 3D printing footwear are **thermoplastic polyurethane (TPU)**, **thermoplastic elastomers (TPE)**, **polyamide (PA, nylon)**, and emerging **bio-based polymers** (Kingroon, 2024[42]). TPU, in particular, has gained significant attention due to its excellent

[40] Carbon fact. (2026). Data work, automated. Retrieved from:https://www.carbonfact.com/data-management-software

[41] Luximon, A., & Luximon, Y. (2021). New technologies—3D scanning, 3D design, and 3D printing. In A. Luximon (Ed.), Handbook of footwear design and manufacture (2nd ed., pp. 477–503). Elsevier. https://doi.org/10.1016/B978-0-12-821606-4.00019-3

[42] Kingroon (2024). 3D Printing Guides 10 Best 3D Printed Shoes. Retrieved from: https://kingroon.com/blogs/3d-printing-guides/3d-printed-shoes

combination of flexibility, abrasion resistance, and durability, making it suitable for midsoles, outsoles, and cushioning components (Covestro, 2019[43]; Chanhontech, 2025[44]).

Many major brands are also exploring TPU. For example, Nike's recent footwear product includes a fully 3D-printed shoe- the NIKE AIR MAX **95000** using TPU made by Zellerfeld (Zellerfeld, 2026[45]; All3dp, 2024[46]).

Fig. 17: 3D printed footwear for Nike by Zellerfeld from „zellerFOAM®. Source: https://ww.zellerfeld.com/products/air-max-95000?variant=56456711274831

This **zellerFOAM®** filament is not available for purchase, but other filaments are available and can be used to facilitate 3D printing at home.

Among these, flexible thermoplastic polyurethane (TPU) filaments such as **Filaflex Foamy Footwearology Edition** (Recreus, 2026[47]) developed by Recreus offer suitable properties for footwear applications, including elasticity, lightweight structure, and cushioning performance.

Additionally, **more sustainable options** are emerging, such as **BioCirflex by Balena**[48], which features DIN-certified bio-based content of 50–85% per ASTM D6866. These materials demonstrate that, despite the limited availability of proprietary filaments like zellerFOAM®, accessible alternatives can support the development of flexible, performance-oriented, and more sustainable 3D-printed footwear.

[43] Covestro. (2019) Effective shoe manufacturing with 3D printing. Fully recyclable shoes made from thermoplastic polyurethane. Retrieved from: https://www.covestro.com/press/effective-shoe-manufacturing-with-3d-printing

[44] Chanhontech. (2025) Thermoplastic Polyurethane (TPU) in 3D-Printed Footwear. Retrieved from: (https://chanhontech.com/thermoplastic-polyurethane-tpu-in-3d-printed-footwear/

[45] Zellerfeld. (2026). Product for selling page- Air Max 95000. Retrieved from: https://www.zellerfeld.com/products/air-max-95000?variant=56456711274831

[46] All3dp. (2024). Design & 3D-Print-to-Order Your Own Shoes. Retrieved from: https://all3dp.com/4/design-3d-print-to-order-your-own-shoes/

[47] Recreus. (2026) TPU 3D printing filament (FOAMY FILAFLEX). Source: https://recreus.com/products/filaflex-foamy-footwearology-edition?variant=46281390260483

[48] Balena (2026). BioCir®flex by BALENA from Bio-Based Content DIN-certified 50–85% bio-based (based on ASTM D6866). Retrieved from: https://balena.science/pages/biocirflex-1

a) **b)**

Fig. 18: a.) TPU 3D printing filament (FOAMY FILAFLEX). Source: https://recreus.com/products/filaflex-foamy-footwearology-edition?variant=46281390260483 , b) BioCir®flex by BALENA from Bio-Based Content DIN-certified 50-85% bio-based (based on ASTM D 6866). Source: https://balena.science/pages/biocirflex-1

Evaluating 3D-printed materials requires a systematic approach to testing their weaknesses, given the layer-by-layer manufacturing process.

The mechanical characterisation of a material should reflect its **anisotropic tensile** and **compressive properties** by testing and evaluating **directional differences in strength** for both tensile and compressive properties of the material. The sample's **interlayer adhesion** should be tested by performing **fracture and tensile tests** perpendicular to the build direction.

Because many AM components are subjected to repeated loading, it is also necessary to evaluate the **materials' fatigue behaviour** using **cyclic tests** in which crack initiation occurs at the layer interface and within internal defects.

The material's ageing under environmental conditions (UV, humidity, temperature) should also be tested to evaluate any changes in mechanical properties over time.

Additionally, complementary evaluations of **surface roughness, porosity**, and **dimensional accuracy** should be performed, as they also affect the fatigue life and long-term reliability of the AM component.

Tests and standards that establish performance requirements for materials and footwear should be considered (see Section 2.3).

Due to the type of materials used in 3D printing, additional standards could be taken into consideration:

- ISO 527- Plastics — Determination of tensile properties.
- ASTM D638- Standard Test Method for Tensile Properties of Plastics.
- ISO/ASTM 17295- Additive manufacturing- part positioning, coordinates and orientation.
- ASTM D779- Standard Test Method for Uniaxial Fatigue Properties of Plastics.
- ISO 4892-Plastics — Methods of exposure to laboratory light sources.
- ISO 21920- Geometrical Product Specifications (GPS) — Surface texture: Profile— Terms, definitions and surface texture parameters.

6 Case Study and Project Work

6.1 Case study – CONDUR by alexandru

CONDUR by alexandru is a Romanian footwear brand with over 35 years of artisanal craftsmanship. Founded by Alexandru, the brand operates as a boutique workshop dedicated to women who appreciate authenticity, quality, and refined aesthetics. Its business model is characterised by small production batches and a direct, personalised relationship with its customers.

The brand's philosophy combines the **technical heritage of traditional leather craftsmanship** with an **openness to material innovation** and **artistic collaboration** — an approach that positions CONDUR by alexandru among the leading independent European luxury footwear brands.

In the field of material innovation, CONDUR by alexandru developed the **Magic Blue footwear collection** using **digitally printed leather**. The material is made from high-quality natural leather onto which a unique graphic pattern is applied using high-resolution **digital printing technology**.

The **digital print** applied to the leather was created through a **collaboration** between **CONDUR by alexandru** and the **visual artist Hamid Nicola Katrib**. The graphic motif evokes broad, expressive brushstrokes and features a rich chromatic palette dominated by electric blue, lime green, yellow, and accents of red and magenta, creating the illusion of moving waves or feathers. As a result, each pair becomes a unique wearable object positioned at the intersection of footwear design and applied art.

Pointed-toe shoe with a cylindrical block heel in patent blue leather, featuring double straps and golden metal buckles. The upper combines digitally printed leather with navy-blue patent leather inserts, creating a highly impactful chromatic and textural contrast. The silhouette balances classic femininity with a contemporary attitude, making it directly relevant for formal and semi-formal occasions.

Fig. 19: Double-strap high-heeled shoe. Source: CONDUR by alexandru

High ankle boot with a square toe, front lacing through golden metal eyelets, cobalt-blue satin ribbon bow, side zipper, and metallic gold stiletto heel. The construction evokes a Victorian-inspired aesthetic reinterpreted in a luxurious and contemporary manner, combining traditional construction techniques with the brand's distinctive decorative elements.

Fig. 20: Lace-up ankle boot with metallic stiletto heel. Source: CONDUR by alexandru

The material production process involves several specific **technological stages**:

Digital pattern creation	• The artist provides the original artwork, which is converted into a high-resolution vector or raster format (minimum 300 DPI).
Preparation of the leather layer	• Surface treatments are applied to ensure optimal ink adhesion, including degreasing and primer application.
Digital printing	• UV printing systems or flexible pigment-based inks specifically designed for leather are used to achieve high chromatic fidelity and an extended color palette, including electric blue, lime green, yellow, red, and magenta.
Protective finishing	• A flexible polyurethane top-coat is applied to provide resistance to abrasion, UV exposure, and repeated flexing during wear.

Fig. 21: Main technological stages in digitally printed leather production

Digitally printed leather represents an application of digitalisation in the materials industry. The technology lies at the intersection of digital colour management, advanced surface-finishing processes, and the philosophy of customised small-series production.
This approach **eliminates the limitations of traditional methods**, **reduces material waste**, and allows **small-scale customisation**. In the case of CONDUR by alexandru, digitalisation does not replace craftsmanship, but amplifies it — the substrate remains natural leather, the construction remains artisanal, and the added value derives from the uniqueness of the pattern.

Compared to conventional leather colouring methods (bath dyeing, solvent-based lacquering), digital leather printing presents documented sustainability advantages:

Reduced chemical consumption	• Inks are applied precisely, eliminating dye baths with excess colorants and auxiliary substances
Zero dye waste in effluents	• Digital printing generates minimal quantities of colored wastewater
Natural bovine leather substrate	• A by-product of the food industry, with European traceability — in line with Leather Working Group (LWG) and REACH Annex XVII requirements
High product longevity	• The quality of artisanal construction and unique aesthetic value discourage premature replacement, counteracting fast fashion logic
Small production series without overproduction	• The CONDUR by alexandru boutique model excludes mass production and stock waste

Fig. 22: Sustainability advantages of digital leather printing

The CONDUR by alexandru — visual artist partnership illustrates a **multidisciplinary collaboration model for material innovation**. The artistic pattern gives the product a distinct and industrially irreproducible cultural identity — a genuine competitive advantage in global luxury markets, where consumers seek authenticity and uniqueness.

The digitally printed leather used as a footwear upper material satisfies the following **technical standards**:

Property	Test method	Required performance
Colour fastness to rubbing (wet/dry)	ISO 11640	Minimum 4/5 on the grey scale, critical for preventing color transfer during wear
Flex resistance of the finishing layer	ISO 17694	Minimum 50,000 cycles without cracking or print detachment
Adhesion of the printing layer	ISO 11644	Minimum 3 N/10 mm, essential for durability
Resistance to artificial light	ISO 105-B02	Minimum 4, preventing pigment fading/photodegradation
Elongation at break	ISO 3376	Compatible with the deformation specific to footwear uppers
Water vapour permeability	ISO 1426	Maintaining breathability, essential for natural leather
Restricted substances	REACH Annex XVII / CADS	Verification of inks: absence of heavy metals, hazardous azo dyes, and phthalates

Tab. 5: Technical performance requirements of digitally printed leather for footwear uppers

6.2 Structure of the project work

Topic/Theme: Explore, select and analyse New Materials for footwear products or footwear collections based on sustainability, globalisation and digitalisation trends.

Material exploration

- Explore at least 5 innovative/sustainable materials, such as:
  - Bio-based materials (e.g., mycelium, algae-based polymers);
  - Recycled materials (e.g., recycled PET, rubber);
  - Circular materials (e.g., mono-materials, recyclable composites);
  - Smart or advanced materials.

Material comparison and analysis

- Compare and evaluate the materials based on:
  - Visual appearance;
  - Mechanical performance;
  - Sustainability (recyclability/biodegradability, renewable content, environmental impact of processing, and end-of-life scenarios);
  - Comfort-related properties;
  - Durability;
  - Manufacturing process compatibility;
  - Cost.

Final material selection

- Select the optimal material (or combination of materials). Justify based on:
  - Product function (how these materials will improve footwear performance);
  - User needs (how these materials will improve user experience);
  - Manufacturing feasibility;
  - Environmental impact.

7 List of Figures and Tables

8 References

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