



Innovative Skills for an Old Vocation

Innovative Skills for STEM

WP 04



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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

2.1 STEM in the Footwear industry

How can footwear manufacturers reduce waste and energy consumption while remaining competitive? How can brands verify the origin and sustainability of materials across increasingly complex global supply chains? How can quality issues be identified before defective products reach consumers? And how can new footwear concepts be developed faster while improving comfort, fit, and performance?

These are some of the key challenges facing the footwear industry today. Addressing them requires more than traditional craftsmanship and manufacturing expertise. It demands a combination of scientific knowledge, technological innovation, engineering solutions, and data-driven decision-making, all of which are at the heart of STEM (Science, Technology, Engineering, and Mathematics).

Although STEM may not immediately seem connected to traditional footwear functions such as quality management, sustainability, production planning, or technical development, by now it plays a crucial role throughout the entire footwear value chain. STEM enables the development of innovative and sustainable materials, the use of 3D printing for prototypes and moulds, and the implementation of robotics and automation in cutting, stitching, and assembly processes. It also supports advanced quality control systems, data-driven production planning, supply chain transparency, and emerging digital tools such as Digital Product Passports (DPPs). In addition, STEM contributes to biomechanical research and movement analysis, helping companies design footwear that enhances comfort, foot health, and athletic performance.

As footwear manufacturing becomes increasingly digital, sustainable, and technology-driven, STEM competencies are becoming essential for professionals across virtually every area of the industry.

Because STEM applications span the entire footwear lifecycle, this manual does not aim to provide a comprehensive overview of all STEM-related topics. Instead, it highlights selected examples and emerging areas of application that demonstrate how STEM is shaping the future of footwear design, manufacturing, quality assurance, sustainability, and product innovation. Through practical case studies and real-world examples, the manual seeks to stimulate curiosity, broaden perspectives, and encourage learners, educators, and industry practitioners to explore new approaches and opportunities within the footwear sector.

2.2 Automation and Robots

Which footwear manufacturing processes can be automated? How can automation improve product quality and consistency? Can robotics contribute to more sustainable production? How do automated systems affect productivity and workplace safety? And which tasks still require human expertise?

These questions are becoming increasingly important as footwear manufacturers face pressure to improve efficiency, reduce waste, maintain consistent product quality, and respond more quickly to changing consumer demands.

Historical Development and Industry Roots

Although automation is often perceived as a recent development, robotics has been used in footwear manufacturing for over four decades. For example, cooperation between machinery specialist DESMA Schuhmaschinen and ABB Robotics began in the 1980s, marking an early industry turning point that demonstrated the feasibility of automated direct soling technologies in the shoe

production^{1,2}. Following successful early pilots, the partnership scaled rapidly- delivering 70 robots by 1990 for applications such as roughing, spraying release agents, and applying adhesives. Today, over 1,700 ABB robots operate within DESMA customer facilities globally.

Another notable early pioneer was Brightwood, a Florida-based athletic shoe manufacturer. Brightwood integrated Stäubli RX90 industrial robots into its manufacturing line to automate cementing (gluing) and roughing operations³. This setup demonstrated high-volume throughput, achieving a production rate of 1,800 pairs of lasted shoes per eight-hour shift. Together, Brightwood, DESMA, and ABB prove that automated shoe production is not a recent innovation, but an established evolution built over decades.

By the 1990s and 2000s, robotic systems were increasingly investigated for specific footwear operations. Adhesive application was a primary target because it is labour-intensive, requires strict consistency, and involves worker exposure to solvent fumes and hazardous chemical compounds. Today, automation is successfully applied throughout many stages of footwear production^{4,5}. Computer-controlled cutting machines optimize material utilization and reduce waste. Robotic systems can apply primers, adhesives, and release agents with high precision, ensuring consistent quality while reducing material consumption. Automated direct-soling systems combine moulding and assembly operations, improving efficiency and repeatability. Vision systems and AI-assisted quality control technologies can detect defects earlier than traditional inspection methods, helping manufacturers reduce rework and product returns. Modern robotic solutions also improve workplace safety by taking over repetitive, physically demanding, or chemically sensitive tasks.

2.2.1 What is a robot

Industrial robots are increasingly used across manufacturing industries to automate handling and production processes. According to ISO 8373:2021, an industrial robot is a "programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation or positioning." Other commonly cited definitions are largely consistent with this interpretation. VDI-Richtlinie 2860 defines industrial robots as "Industrial robots are universally applicable automatic movement machines with several axes, the movements of which are freely programmable regarding the sequence of movements and paths or angles (i.e., without mechanical or human intervention) and, if necessary, are sensor controlled.



Fig. 1: 6-axis robot with gripper © PFI

¹ ABB Robotics. (2025, December 3). *ABB robots help DESMA pioneer the future of automated footwear manufacturing*. ABB News Center. <https://new.abb.com/news/detail/131559/cstmr-abb-robots-help-desma-pioneer-the-future-of-automated-footwear-manufacturing>

² Vogel Communications Group GmbH & Co. KG/ ABB Press Release. (2026, February 2). *ABB robots and DESMA are shaping the future of automated shoe production*. <https://www.all-about-industries.com/abb-robots-shape-the-future-of-automated-shoe-production-a-c3c4ede7486dfaf08900ecaa49b12b52/>

³ Kochan, Anna. "Actis and the shoe industry." *Assembly automation* 16.3 (1996): 30-31.

⁴ Dias, P. A., Petry, M. R., & Rocha, L. F. (2024, September). The role of robotics: Automation in shoe manufacturing. In 2024 20th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA) (pp. 1-8). IEEE.

⁵ Intech Vietnam. (n.d.). Automation in footwear production: The key to improving production capacity. <https://intechvietnam.com/news/tech-news/automation-in-footwear-production-the-key-to-improving-production-capacity-1455/>

They can be equipped with grippers, tools or other production means and can carry out handling and / or production tasks.” Similarly, the Robotic Industries Association⁶ (now rebranded as Association for Advancing Automation) defines a robot as “A robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks.” These definitions consistently highlight the key characteristics of industrial robots, namely programmability, multifunctionality, and the ability to autonomously perform a wide range of handling and production tasks. However, despite the various definitions, the actual common understanding of **a robot is a programmable device that has at least three freely movable axes.**

The adoption of industrial robotics has grown substantially over recent years^{7,8,9}. According to data published by the International Federation of Robotics (IFR, 2026), global operational stock stood at roughly 3.0 million units in 2020 and grew to approximately 4.66 million units (reaching around 5 million overall). In 2024, worldwide installations reached 542,000 new units. Asia continues to drive this growth, accounting for nearly three-quarters of all new deployments. China led global installation numbers, representing 54% of all new robot deployments (approximately 295,000 units) and maintaining an operational stock of around 2 million units in its manufacturing sector.

Robots are increasingly being adopted in the footwear industry to automate labour-intensive and repetitive manufacturing operations. Current robotic applications include roughing, adhesive application, and cementing of shoe uppers and soles, as well as direct injection moulding where polymer materials are injected directly onto the upper. Additional applications encompass three-dimensional scanning of shoe components, automated trajectory generation for manufacturing processes, and the handling and manipulation of footwear parts during assembly. Researchers have demonstrated robotic systems capable of replacing manual operations in upper and sole manufacturing—including both glued assembly and direct injection processing—improving process consistency and reducing worker exposure to noisy and hazardous environments¹⁰. Other studies have shown the feasibility of using industrial robots for automated glue deposition on shoe uppers, achieving high-quality adhesive application while supporting more flexible and efficient production systems¹¹. In addition, robotic workcells (a self-contained automatic unit performing a specific task) have been developed for shoe sole digitization, material dispensing, and automated component handling as part of the transition toward Industry 4.0 footwear manufacturing¹².

⁶ American National Standards Institute. (n.d.). Industrial robots: Safety and production. ANSI Blog. <https://blog.ansi.org/ansi/industrial-robots-safety-production-ria/>

⁷ Richter, F. (2026, September 24). Rise of the robots [Infographic]. Statista. <https://www.statista.com/chart/26210/operational-stock-of-industrial-robots/>

⁸ International Federation of Robotics. (2026). Industrial robots. <https://ifr.org/industrial-robots>

⁹ International Federation of Robotics. (2026, April 8). Robot density surges in Europe, Asia, and Americas. <https://ifr.org/ifr-press-releases/news/robot-density-surges-in-europe-asia-and-americas>

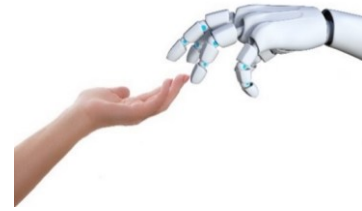
¹⁰ Kim, M. G., Kim, J., Chung, S. Y., Jin, M., & Hwang, M. J. (2022). Robot-based automation for upper and sole manufacturing in shoe production. *Machines*, 10(4), 255.

¹¹ Castelli, K., Zaki, A. M. A., Dmytriyev, Y., Carnevale, M., & Giberti, H. (2020). A feasibility study of a robotic approach for the gluing process in the footwear industry. *Robotics*, 10(1), 6.

¹² Oliver, G., Gil, P., Gomez, J. F., & Torres, F. (2021). Towards footwear manufacturing 4.0: shoe sole robotic grasping in assembling operations. *The International Journal of Advanced Manufacturing Technology*, 114(3), 811-827.

2.2.2 Human-Robot Collaboration

In the past, robots and humans mainly worked separately from each other. This separation is still relevant today in many areas of production and is made clear by complex barriers and safety precautions. These are intended to prevent a person from entering the working area of an active robot and being injured or even killed by its movements.



The various options for securing work areas of robots against unauthorized entry include, for example, cages with monitored security doors, light barriers or even access restrictions for entire rooms or halls. Triggering these protective measures generally means stopping the affected machines immediately in conjunction with an optical and / or acoustic alarm.

Despite the inherent risks that industrial machinery can pose to humans, advanced technological solutions enable safe, close-proximity collaboration between humans and machines. When a robot is explicitly designed and certified for this purpose, it is known as a **cobot (collaborative robot)**.

To ensure workplace safety, a cobot system must be engineered to prevent harmful collisions. This is achieved through two primary methods:

1. **Inherent Safety:** Designing the robot to be physically incapable of exerting force that could cause injury (e.g., lightweight materials, rounded edges, and power/force limiting joints).
2. **Functional Safety:** Implementing a network of intelligent, redundant safety measures that monitor the environment and immediately alter or halt the robot's movement if a human worker approaches.

Modern safety ecosystems rely on a combination of overlapping sensor technologies, including:

- **Tactile and Touch Sensors:** "Smart skins" and torque sensors that instantly register physical contact and trigger an immediate stop.
- **Proximity and Ultrasonic Sensors:** Localized sensors that detect the close presence of a worker to slow down operations.
- **Laser Distance Sensors & 3D Scanners:** LiDAR and scanning devices that map out precise, multi-tiered safety zones around the workspace.
- **AI-Powered Machine Vision & Video Systems:** Advanced camera systems paired with deep learning algorithms. Unlike traditional vision, these systems don't just detect motion; they actively distinguish humans from objects, predict worker trajectories, and dynamically adjust the robot's speed and path in real time.

Such systems are highly complex, and even small errors can lead to a complete halt of the machine, since human safety always takes priority. This complexity is also reflected in the cost, both in terms of acquisition and maintenance.

- **Base Hardware vs. Total Integration:** A standard industrial cobot arm typically costs between \$25,000 and \$50,000¹³. However, the complete integrated system—including 3D vision sensors, custom shoe-lasting grippers, software integration, and certified safety compliance testing—ranges from \$50,000 to \$400,000+ per workstation.
- **Operational & Maintenance Costs:** Advanced sensor suites require periodic recalibration, software updates, and specialized technician support.

¹³ Reeman Robot. (15. June 2026). How much does an industrial robotic arm cost? Complete pricing guide. <https://reemanbot.com/posts/how-much-does-an-industrial-robotic-arm-cost-complete-pricing-guide>

Intelligent robots can be regarded as an advanced form of collaborative robots (cobots), combining human-robot interaction with enhanced perception and autonomous decision-making capabilities. Based on the robot classification framework developed by the former Japan Industrial Robot Association (JIRA), intelligent robots represent a higher level of autonomy, as they are able to perceive environmental conditions, process sensory information, and adapt their actions in response to changing circumstances. Consequently, intelligent robots extend the traditional cobot paradigm beyond primarily safety-oriented collaboration by incorporating adaptive control, environmental awareness, and real-time decision-making^{14,15}.

Feature	Traditional Industrial Robot	Conventional Cobot System	Intelligent AI-Driven System
Physical Isolation & Safety	Strict Separation: Operates inside locked safety cages or behind light curtains. Completely stops if a human enters the cell.	Passive Stopping: Operates without cages, but halts or slows down immediately when physical contact or close proximity is detected.	Active Adaptation: Operates safely alongside humans by dynamically adjusting speed, orientation, and trajectory in real time.
Environmental Perception	Blind execution of hardcoded trajectories; cannot detect human presence without external interlocks.	Detects presence/distance or force via torque/proximity sensors (binary or zone-based detection).	Identifies context: Uses AI machine vision to distinguish between a human worker, a shoe component, and factory equipment.
Shoe Factory Example	Executes rapid, high-force sole pressing or rubber injection inside a physical cage. If an operator opens the cage door, the entire line triggers a hard shutdown to prevent severe injury.	During an automated upper-stitching process, a worker reaches into the workspace to adjust a misplaced leather piece. The cobot immediately triggers an emergency stop, requiring a manual reset before resuming production.	The system's AI vision detects the worker's hand approaching the upper. It predicts the hand's path, slows down, and smoothly repositions its arm to work on the opposite seam, resuming normal speed once the worker clears the area—avoiding downtime entirely.

Tab. 1: Evolution of automation.

2.2.3 Different types of robots

If you think of industrial robots the most common model you can imagine will be similar to the one shown in the chapter “What is a robot”. It’s a five to six axis arm like structure with a tool at the tip. This type is the most versatile construction and can handle various tasks from handling parts and feeding other machines to assembly of products or even milling, welding or (3D-) printing. A six-axis robot can reach any point in its space with its tool oriented in any direction necessary. With five axis the orientation of the tool is partially limited and depends on the position the robot is reaching for.

¹⁴ Nof, S. Y. (Ed.). (1999). Handbook of industrial robotics. John Wiley & Sons.

¹⁵ Oh, J. (2025). Towards cognitive collaborative robots: Semantic-level integration and explainable control for human-centric cooperation. arXiv preprint arXiv:2505.03815.

Another common model is a so-called SCARA robot. It's mostly used for pick and place tasks, where speed and precision must be achieved at moderate costs. The kinematic of a SCARA robot is limited to a plane, with a height adjustable manipulator. With this limitation it's easier to reach a high degree of stiffness and precision, while maintaining speed and moderate costs.



Fig. 2: Scara Robot © PFI

The last typical participant in the field is the Delta (or parallel) robot. Like the SCARA robot, it is mainly used for pick and place activities where speed and cost efficiency are more important than precision and versatility. Like the SCARA robot the tool axis is fixed and remains perpendicular to the working plane.



Fig. 3: Delta Robot © PFI

2.2.4 How does a robot function?

An industrial robot's primary job is to precisely position a tool or workpiece in three-dimensional space in order to perform a specific task. In the footwear industry, for example, a robot may be used to apply adhesive to a shoe upper, manipulate a sole during assembly, or transport components between manufacturing stations. To perform these tasks accurately and repeatedly, the robot relies on three interconnected systems:

The Software (Control and Motion Planning): The robot's rigid links and joints form a kinematic chain. The control software calculates the movements required for each joint so that the tool reaches the desired position and orientation. From the user's perspective, this allows complex movements to be programmed easily while ensuring that manufacturing operations are carried out accurately and consistently.

The Electronics (Closed-Loop Control): Actuators (motors) execute movements based on software commands, while sensors continuously monitor the robot's actual position and operating conditions. This feedback enables the controller to compare the intended and actual motion and immediately correct any deviations. Sensors are therefore essential for maintaining accuracy, compensating for disturbances, ensuring repeatability, and supporting safe operation, particularly when robots work in changing environments or close to human operators.

The Mechanics (Structure): The physical structure, typically made from aluminium, steel, or cast iron components, provides the rigidity required to withstand operational forces and torques. At the same time, the design seeks to minimize weight to enable higher speeds and energy efficiency. The mechanical structure ultimately determines the robot's payload capacity, reach, workspace, and installation footprint.

The interaction of these three systems enables robots to perform manufacturing tasks with a high degree of precision, repeatability, and efficiency. In practical applications, such as footwear production, this can improve product quality, reduce manual handling, and automate repetitive or ergonomically demanding processes.

2.2.5 Programming a robot

There are different methods to tell a robot what to do. The choice of programming method depends on the complexity of the task, the required flexibility, the frequency of product changes, and the available expertise. In footwear manufacturing, for example, robots may be used for operations such as adhesive application, sole handling, roughing, polishing, or material transport. Selecting the appropriate programming approach can improve efficiency, product quality, and sustainability by reducing setup times, minimizing waste, and ensuring consistent process execution.

Manual Programming

In manual programming, a specialized programmer writes the robot's code directly. Unlike CNC machines, which commonly use G-Code, industrial robot manufacturers utilize proprietary high-level programming languages such as ABB's RAPID, KUKA's KRL, or FANUC's KAREL. These languages allow the implementation of complex logic, sensor integration, communication with external devices, and safety functions.

Manual programming offers the highest degree of flexibility and control and is therefore particularly suitable for complex applications where the robot must perform sophisticated decision-making or interact with multiple systems. Examples include automated production cells with vision systems, quality inspection stations, or highly customized assembly processes. In the footwear industry, manual programming may be used for advanced robotic adhesive application systems where the robot's movement, glue flow, and sensor feedback must be precisely coordinated.

While modern development environments provide syntax support and programming tools, manual programming requires considerable expertise and can be time-consuming. However, for demanding applications it remains indispensable because it enables optimization of cycle times, process quality, and resource utilization.

Teach-in (and Lead-Through)

The Teach-In process is a highly intuitive method for programming a robot. Using a handheld device called a teach pendant, an operator manually moves the robot to specific positions and stores these locations as points within a program sequence. A variation of this approach is Lead-Through programming, which is particularly common with collaborative robots (cobots). In this case, the user physically guides the robot arm through the desired motion, and the robot records the trajectory.

These methods require only limited programming knowledge and allow rapid setup, making them well suited for simple and repetitive tasks or applications that change frequently. For example, a cobot used to transport shoe components between workstations or perform simple polishing operations can often be programmed within minutes using lead-through programming.

The main advantage is ease of use and reduced programming effort. This allows smaller manufacturers to implement robotic automation without requiring specialized programming personnel. However, as task complexity increases, teach-in methods may become less efficient than more advanced programming approaches.

Offline Programming (OLP) & Simulation

Instead of programming the physical robot directly on the factory floor, Offline Programming (OLP) uses specialized software to create a virtual model of the robot and its environment. Depending on the application, this may range from CAM-supported systems that automatically generate paths for robotic machining processes to sophisticated simulation platforms capable of modelling complete production lines.



Fig. 4: CAM-System DEScom by DESMA; Programming of a roughing cycle based on 3D-CAD data; visualizing of tool path and orientation. (Picture by DESMA)

This approach is particularly advantageous for complex manufacturing systems because programs can be developed, tested, and optimized without interrupting ongoing production. Potential collisions, reachability issues, and cycle times can be evaluated before the program is transferred to the physical robot.

In the footwear industry, OLP can be used to generate adhesive application paths on digital shoe models or to simulate robotic sole-handling operations before production begins. For manufacturers producing many shoe variants, offline programming significantly reduces setup times while improving process consistency and reducing material waste. As a result, OLP is widely regarded as the standard programming approach for advanced robotic manufacturing systems.

Different programming methods therefore address different industrial needs. Teach-in and lead-through programming offer simplicity and rapid deployment, manual programming provides maximum flexibility and control for complex tasks, and offline programming enables efficient implementation and optimization of sophisticated production processes. Together, these approaches allow manufacturers to balance productivity, quality, flexibility, and sustainability according to their specific application requirements.

2.2.6 Existing automated processes in the industry

One of the earliest participants in the field of automation and robots in the shoe industry was the company **DESMa**. As stated in the introduction, in 1980 the installed the first machine for moulding soles directly onto the uppers. Meanwhile they offer complete automation solutions for the shoe industry, as seen in the picture below. A carousel with multiple stations for injection moulding is fed by robots with the uppers, and the finished product is also automatically removed and placed on a conveyor band for further processing.

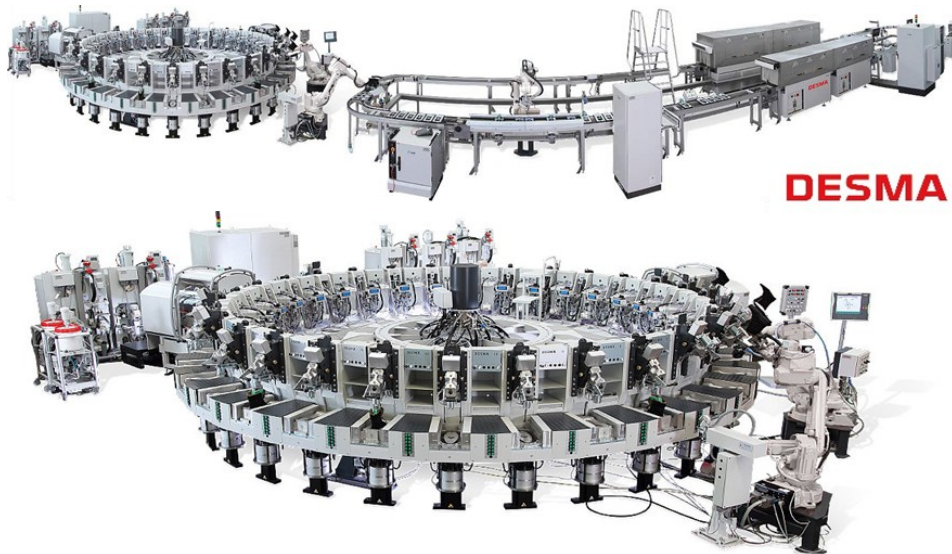


Fig. 5: Highly automated injection moulding system by DESMA (Pictures provided by DESMA)

2.3 3D-Printing – Additive Manufacturing

Traditionally, manufacturing processes in industry have been predominantly subtractive processes, where the desired geometry is created by removing material from a raw stock. Common examples include turning, milling, and cutting. In recent years, however, additive manufacturing has become increasingly important in both industrial and consumer applications. Falling equipment costs and continuous improvements in printable materials have made these technologies accessible for a growing range of products.

3D printing is an additive manufacturing process in which material is deposited layer by layer to create a desired geometry. Depending on the process, the raw material can be supplied as a filament, powder, liquid resin, or other forms. Material solidification occurs through thermal or chemical mechanisms.

The major advantage of 3D printing is the relatively short time required to transform a CAD model into a physical part, particularly for highly complex geometries. Unlike conventional manufacturing processes, component complexity has only a limited influence on production effort. This enables the fabrication of intricate lattice structures, internal channels, and customized designs that would be difficult or impossible to manufacture conventionally.

For the footwear industry, additive manufacturing offers additional benefits. It enables rapid prototyping of shoe components, customized orthotic devices, individualized midsoles, and the production of complex cushioning structures tailored to specific performance requirements. As products can be manufactured directly from digital designs, development cycles can be shortened and design iterations can be implemented more efficiently.



Fig. 6: left: subtractive process (dark blue: desired Part, light blue: removed material) | right: additive process (dark blue: base layer, green: added up layers) © PFI

2.3.1 Overview of different techniques

In the field of 3D-printing, there are different approaches to target the material application.

Stereolithography

BEST FOR: Functional prototyping, patterns, moulds and tooling

Definition: Stereolithography is one of the oldest 3D-printing technologies, patented in 1984. In this process, a liquid photosensitive resin is selectively cured layer by layer using ultraviolet (UV) light to create the desired geometry. Modern systems typically use either a laser, an LCD screen that masks a UV light source, or a UV projector. After printing, parts must be cleaned to remove excess resin and subsequently post-cured under UV light to achieve their final material properties.

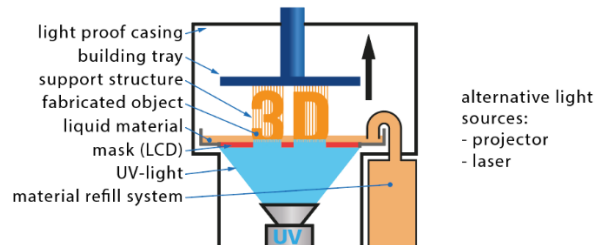


Fig. 7: Schematic of an SLA-printer with LCD-light source © PFI

Applications in the Footwear Industry: SLA is primarily used for design verification, functional prototypes, moulds, and tooling. It can also be used to evaluate sole geometries and customized footwear concepts before mass production.

Key Benefits: The process offers excellent dimensional accuracy, smooth surface finishes, and the ability to produce highly detailed structures. Flexible materials are possible. Various companies in the shoe industry experiment with this method to print soles with specialized structures dedicated to variable damping properties

Sustainability Perspective: Compared with subtractive methods, material waste is generally reduced. However, resin materials require careful handling and disposal, and many photopolymer resins are not easily recyclable.

Fused Deposition Moulding

BEST FOR: basic proof of concept models and simple prototyping.

Definition: Maybe the most common 3D-printing method uses molten plastics to create the part. The raw material is fed into a heated extruder, where it melts and can then be pressed through a nozzle at the desired position. The extruder and the nozzle are guided by a CNC-like machine, which could also be a robot. A heated base plate serves as the printing surface for the first layer. All other layers are applied on top of each other. Because the material is extruded layer-by-layer, the printer requires a surface beneath it to deposit plastic. If a part features

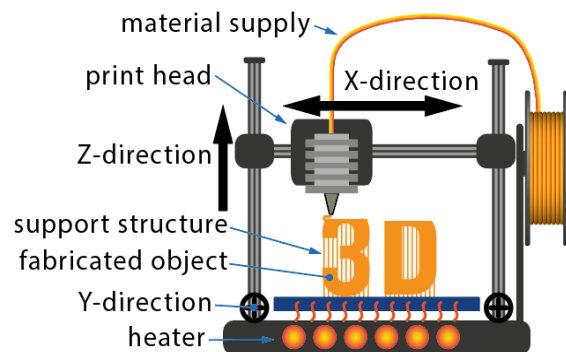


Fig. 8: Schematic of an FDM-printer © PFI

overhangs or bridges, the machine must print support structures.

While standard supports can be tedious and messy to remove manually during post-processing, modern "slicing" software can automatically generate optimized tree-like (organic) supports that break away easily. Advanced dual-extruder printers can even use soluble support materials (like PVA) that completely dissolve in water, leaving a flawless surface finish.

The quality of the parts depends heavily on the settings used for printing. For optimal settings the user needs some experience especially if many different materials are used. A few degrees Celsius more or less on the extruder can mean the difference between good parts and a failed print.

Applications in the Footwear Industry: FDM is mainly used for proof-of-concept models, design verification, orthotic prototypes, and the production of jigs, fixtures, and tooling aids.

Key Benefits: FDM is the most affordable and widely available 3D-printing technology. It enables rapid and cost-effective prototyping, allowing designers to quickly evaluate and modify footwear concepts. Entry level printers are in a price range between 150\$ to 300\$.

Sustainability Perspective: As material is only deposited where needed, FDM generates less waste than many subtractive manufacturing processes. It can also reduce the need for physical tooling during development, although support structures and failed prints still produce material waste.

Selective Laser Sintering or Selective Laser Melting

BEST FOR: functional prototyping and end-use production.

Definition: SLS and SLM are additive manufacturing processes belonging to the Powder Bed Fusion family, where selective areas of a powder bed are fused together using thermal energy. After a layer is scanned, the bed lowers, a roller or recoater blade applies a fresh layer of powder, and the process repeats. The energy is introduced into the preheated powder by a laser that tracks the cross-section of the component.

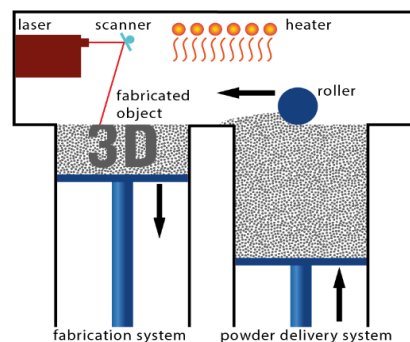


Fig. 9: Schematic of SLS / SLM system © PFI

Despite their similarities, the process diverges significantly based on the material used:

SLS primarily uses polymer powders (like Nylon/Polyamide). A major advantage of SLS is that the surrounding, unfused powder acts as a natural support structure for overhanging geometries. Because of this, no dedicated support structures need to be printed, allowing for incredible geometric freedom and nesting multiple parts in a single build volume. Post-processing simply involves shaking or blasting away the excess powder.

SLM uses metal powders (like titanium, aluminum, or stainless steel) and fully melts them into dense components. Unlike SLS, metal SLM prints absolutely require printed support structures. These anchors pull heat away from the part and physically clamp it to a heavy metal build plate to prevent severe warping caused by thermal stress. Post-processing is intensive: the entire plate must undergo a thermal stress-relief cycle in a furnace, the parts must be cut off the plate via wire EDM or a bandsaw, and the metal supports must be machined or ground away.

The surface finish of powder-bed parts is inherently grainy (mat) but can be bead-blasted, tumbled, or chemically smoothed. The mechanical integrity of these parts is outstanding, offering nearly isotropic strength (equal strength in all directions), making the layers virtually invisible. Materials range from flexible elastomers (TPU) to ultra-rigid metals and carbon-composite plastics.

Applications in the Footwear Industry: SLS is widely used for functional prototypes, customized insoles, orthotics, and midsoles with complex lattice structures. It is also suitable for low-volume production of end-use footwear components. SLM is mainly used for tooling, mould inserts, and specialized manufacturing equipment rather than for shoe components themselves.

Key Benefits:

A major advantage of SLS is that no dedicated support structures are required, enabling the production of highly complex geometries such as customized insoles and lattice-based midsoles. The technology provides excellent mechanical properties and is suitable for both functional prototypes and end-use footwear components. SLM, while less commonly used for footwear products themselves, is valuable for manufacturing tooling, mould inserts, and specialized production equipment with complex geometric features. Although industrial SLS and SLM systems typically cost between USD 100,000 and USD 500,000 or more they enable the production of highly customized, high-performance components that are difficult or impossible to manufacture using conventional methods.

Sustainability Perspective Compared with subtractive manufacturing, powder bed fusion processes can reduce material waste because unused powder can often be recovered and reused. In addition, the ability to produce customized parts on demand can reduce inventories and overproduction. However, the process requires significant energy and specialized equipment, which increases its overall environmental footprint.

Material Jetting

BEST FOR: functional prototyping with focus on haptic and design

Definition: Material Jetting is similar to an inkjet printer, but instead of ink, droplets of a photosensitive polymer are deposited and immediately cured using UV light. Multiple print heads can dispense different materials or colours simultaneously, allowing parts with varying material properties to be produced in a single print. Like a typical desktop printer, which usually prints with four colours (cyan, magenta, yellow and black) a material jet printer also has separated printing heads which can be utilized in different ways. This can be the same material in different colours but can also be materials with different properties.

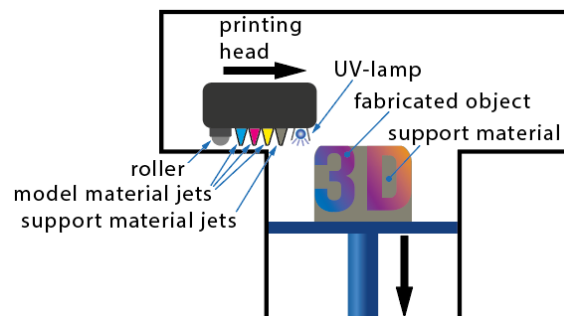


Fig. 10: Schematic of material jetting printer © PFI

Applications in the Footwear Industry: Material Jetting is mainly used for design validation, appearance models, and prototypes where colour, surface finish, and tactile properties are important. It allows footwear designers to evaluate the look and feel of a product before tooling and production.

Key Benefits: The main advantage of Material Jetting is its ability to combine multiple materials, colours, and levels of flexibility within a single component. The technology also produces highly detailed parts with excellent surface quality and requires only minimal post-processing. These capabilities make it particularly suitable for design-focused and haptic prototypes.

Sustainability Perspective: Material Jetting can reduce waste associated with traditional prototype manufacturing by producing highly realistic models directly from digital designs. However, the process relies on photopolymer materials that require appropriate handling and disposal, and the materials are generally less recyclable than common thermoplastics used in other additive manufacturing processes.

Binder Jetting

BEST FOR: functional prototyping with focus on design and end-use production

Definition: The binder jetting technique is something like a combination of selective laser sintering and material jetting. In this case a printing head is injecting a binding agent layer by layer in a powder bed to form the final part. Like other powder bed procedures, no support structures are needed. This procedure is faster than the SLS, while capable of photorealistic colouring but the parts are brittle without special postprocessing. Also, metals are processable, but a proper post sintering procedure is necessary to achieve real metal-like material properties.

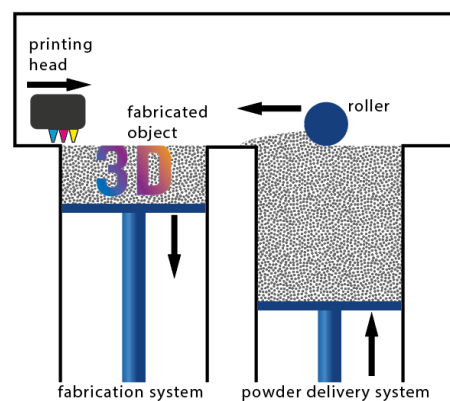


Fig. 11: Schematic of a binder jetting printer © PFI

Applications in the Footwear Industry: Binder Jetting is primarily used for design prototypes, concept models, mould development, and customized footwear components where colour and appearance are important. The technology can also be used to produce tooling and, after additional processing, metal parts.

Key Benefits: The process is faster than SLS, can produce full-colour parts, and does not require dedicated support structures because the surrounding powder supports the component.

Sustainability Perspective: Unused powder can often be recovered and reused, reducing material waste. However, additional post-processing steps and energy consumption associated with sintering must be considered when evaluating the overall environmental impact.

2.3.2 Print preparation / slicer

Preparing a 3D model for printing significantly impacts production time and part quality via three core steps:

- **Import & Orientation:** The 3D model is loaded into a slicer software. The user manually optimizes the part's orientation to balance surface finish, mechanical strength, and the need for temporary support structures (shown below in blue).
- **Adjusting Settings:** Key parameters are configured, primarily layer height:
- **Thin layers:** Fine details and smooth surfaces, but slower print times.
- **Thick layers:** Coarse structures and visible layer lines, but faster print times.
- **Other variables** (like temperature and infill density) are typically managed using software presets like "Draft" or "High Quality."
- **Slicing & Preview:** The software slices the model into layers to generate machine-readable code (G-code). A 3D viewport allows the user to preview the print layer-by-layer to catch potential errors before manufacturing begins. The preparation of a 3D-part for printing is relatively simple but can have a big impact on the required printing time and quality of the part.

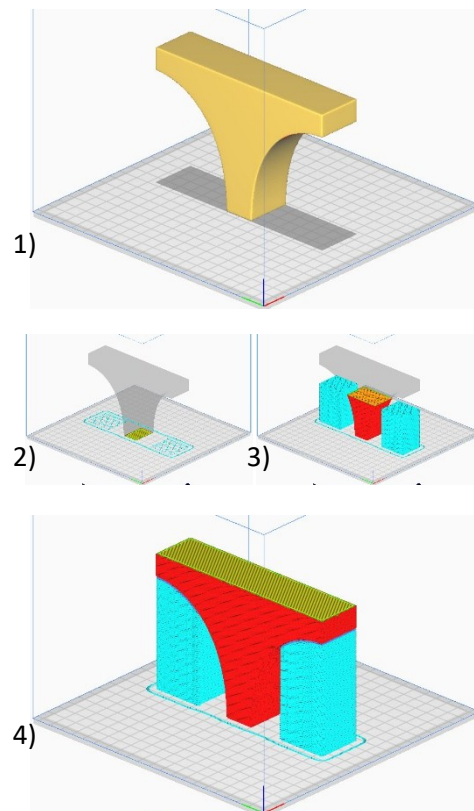


Fig. 12: Slicer for an FDM-based print. © PFI

1) placed part; 2) preview of first layer; 3) mid-print with infill visible (orange); 4) finished part

2.3.3 Problems and difficulties

Although 3D printing opens up new possibilities and provides designers with unprecedented geometric freedom, it is still a developing manufacturing technology. This is particularly evident in material science, where the market is constantly being shaped by new materials and formulations.

These developments are important because the material properties of printed parts ultimately determine whether a component can be used only as a prototype or as a durable end-use product. Depending on the printing technology, properties such as strength, flexibility, wear resistance, and heat resistance may differ significantly from conventionally manufactured parts. In addition, some processes produce anisotropic components, meaning that the mechanical properties can vary depending on the build direction.

In the footwear industry, these limitations are particularly relevant. Insoles, midsoles, orthotics, and other load-bearing components are exposed to repeated mechanical stresses during daily use. Therefore, printed components must provide not only the desired geometry and customization

but also sufficient durability, comfort, and long-term performance. As a result, material selection, process parameters, and post-processing remain critical factors when implementing additive manufacturing in footwear production.

From a sustainability perspective, 3D printing can reduce material waste, shorten development cycles, decrease the number of physical prototypes required, and support on-demand manufacturing. However, the environmental impact of printing materials, energy consumption, and recyclability at the end of a product's life remain important considerations for the future development of the technology.

2.3.4 Overview

Criteria	SLA/DLP	FDM	SLS	SLM	Material Jetting	Binder Jetting
Surface Quality	High	Low-Medium	Medium	Medium	High	Medium
Dimensional Accuracy	High	Low-Medium	High	High	High	Medium
Mechanical Performance	Medium-High	Medium	High	High	Low-Medium	Low-Medium
Colour Capability	Single colour	Limited colours	Single colour	Single colour	Multi-colour	Multi-colour
Support Structures Required	Yes	Yes	No	Yes	Yes (typically soluble)	No
Printing Speed	Medium	Medium	Medium	Low	Medium	High
Typical Machine Cost	Medium	Low	High	Very High	High	High
Material Cost	Medium	Low	Medium	High	High	Medium
Operational Complexity	Medium	Medium	High	Very High	Low	Medium
Typical Footwear Application	Design prototypes, tooling	Concept models, orthotic prototypes, fixtures	Customized insoles, orthotics, lattice midsoles	Tooling and mould inserts	Design and haptic prototypes	Concept models and coloured design prototypes
Sustainability Benefits	Reduced prototyping waste	Low material consumption, reduced tooling	Powder can be reused	Lightweight tooling, long service life	Reduces physical prototype iterations	Powder reuse and rapid design validation

Tab. 2: Overview of 3D printing technologies.

2.4 Machine Vision

Machine vision systems are increasingly used in footwear manufacturing to automate inspection, process control, and quality assurance. Typical applications include the detection of scratches or contamination on leather, verification of stitching quality, identification of material defects, guidance of robotic handling systems, and final product inspection. Depending on the task, either conventional rule-based image processing or modern AI-based systems can be used.

To better understand these applications, the following questions should be considered:

- How can a camera detect defects that are difficult to identify manually?
- Why is lighting often more important than the camera itself?
- When is rule-based image processing sufficient, and when is artificial intelligence required?
- How can machine vision improve product quality and reduce waste in footwear manufacturing?

2.4.1 What is Machine Vision?

Machine Vision describes the process of capturing and analyzing image data in order to obtain information for process control, quality assurance, or automated decision-making.



In the footwear industry, machine vision is commonly used to inspect incoming materials, detect contamination or scratches on leather surfaces, verify adhesive application, check stitching quality, identify assembly errors, and support robotic pick-and-place systems^{16,17,18}.

2.4.2 What is an image?

To a computer, an image is a numerical matrix representing colour intensities across three primary channels: Red, Green, and Blue (RGB). This mirrors human vision, which relies on three corresponding eye receptors to interpret the visible spectrum. In standard 8-bit digital imaging, each pixel channel holds a value from 0 (zero intensity) to 255 (maximum intensity), allowing millions of colour combinations through additive mixing.

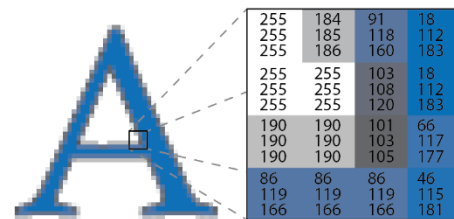


Fig. 13: RGB-colour values of the different pixels © PFI

These values can be processed and analysed to identify shapes, colours, textures, dimensions, or defects.

¹⁶ Aslam, M., Khan, T. M., Naqvi, S. S., Holmes, G., & Naffa, R. (2019). On the application of automated machine vision for leather defect inspection and grading: a survey. *IEEE Access*, 7, 176065-176086.

¹⁷ Zetamotion. (n.d.). Automated visual inspection for shoes and footwear. Retrieved September 29, 2026, from <https://zetamotion.com/product/shoes-and-footwear/>

¹⁸ Bai, J., Wu, D., Shelley, T., Schubel, P., Twine, D., Russell, J., ... & Zhang, J. (2025). A comprehensive survey on machine learning driven material defect detection. *ACM Computing Surveys*, 57(11), 1-36.

2.4.3 Key components

The following components are required for image processing:

Light

Lighting is often the most important component of a machine vision system. Proper illumination enhances relevant features and suppresses unwanted effects such as shadows or reflections. In footwear manufacturing, Optimized lighting can make scratches, wrinkles, contamination, or stitching defects clearly visible. Industrial systems rely on specialized artificial lighting rather than volatile ambient light.

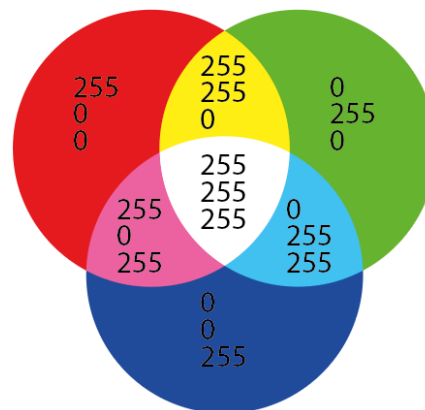


Fig. 14: Additive colour mixing © PFI

Lens

Optics focus reflected light onto the sensor. High-quality lenses minimize distortions like chromatic aberration (color fringing caused by uneven light refraction), which can otherwise degrade software accuracy.

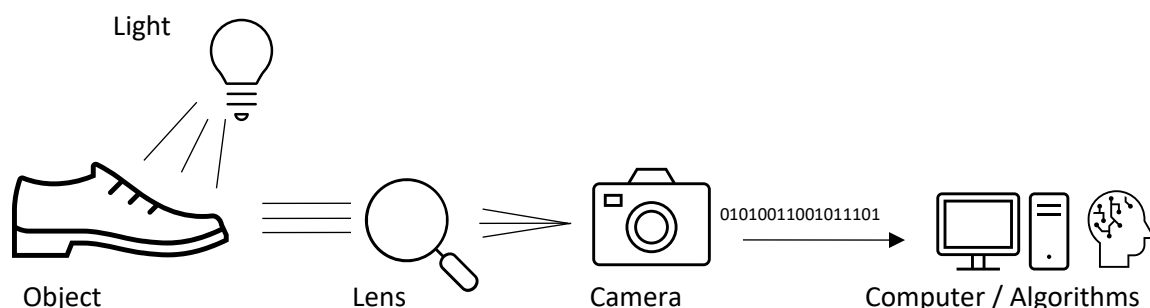
Camera sensor

A matrix of light-sensitive pixels that converts photons into digital data.

Monochrome (Black & White) Sensors: Measure overall light intensity without filtering. They offer superior light sensitivity, lower noise, and sharper edge accuracy because they require no pixel interpolation.

Color Sensors: Utilize a Bayer Filter grid (50% Green, 25% Red, 25% Blue) over the pixels. A software process called demosaicing interpolates the missing colour data for each pixel, which inherently reduces absolute edge sharpness.

Resolution & Size: Larger sensors capture more light and offer better dynamic range but require more expensive optics. For resolution, industrial engineering follows the rule: "As much as necessary, as little as possible" to keep data volumes manageable and processing speeds high.



2.4.4 Computer Analysis: Rule-Based vs. AI-Powered Vision

Rule-Based Vision

Traditional machine vision relies on rule-based algorithms. An engineer writes explicit code defining exact contrast thresholds, geometric features, or colour values. While highly effective for precise measurements, rule-based vision struggles with variability, surface textures, and organic shapes.

Typical footwear applications:

- Measuring component dimensions
- Verifying hole positions
- Checking alignment of shoe parts
- Reading printed labels or codes

Advantages:

- Fast and reliable
- Easy to validate
- Well suited for repetitive tasks with clearly defined criteria

AI-Powered Vision

Modern systems increasingly integrate AI and Deep Learning (Convolutional Neural Networks). Instead of rigid programming, an AI vision system is trained on thousands of sample images labelled "good" or "defective."

Typical footwear applications:

- Detection of scratches or contamination on leather
- Identification of stitching defects
- Classification of material quality
- Inspection of complex textured surfaces
- Detection of cosmetic defects in finished shoes

Advantages:

- Handles natural material variability
- More tolerant of shape and texture variations
- Enables automated inspection tasks that previously required human operators.

Summary: Overall, machine vision enables higher product quality, improved process consistency, and reduced inspection effort in footwear manufacturing. Rule-based systems remain the preferred choice for precise and repeatable measurements, while AI-based systems excel at detecting complex defects and evaluating natural materials such as leather and textiles.

From a sustainability perspective, machine vision can reduce material waste by identifying defects earlier in the production process and preventing defective products from progressing through subsequent manufacturing steps. Improved process control can also reduce scrap, rework, and unnecessary material consumption, thereby contributing to a more resource-efficient footwear production process.

2.5 Anatomy and biomechanics

2.5.1 Locomotor system

The locomotor system is also called the musculoskeletal system. It consists of:

- the skeleton,
- skeletal muscles,
- tendons,
- ligaments,
- joints,
- cartilage
- other connective tissue.

The nervous system (brain and nerves) sends signals to activate the muscles and allows for voluntary movements.

The study of the structure, function and motion of the mechanical aspects of organisms is called biomechanics. Biomechanical studies are used to gain a comprehensive understanding of movements and the forces generated by and acting on the body. Key areas of biomechanics are: dynamics, kinematics, kinetics and statics.

2.5.2 Foot anatomy

The foot is part of the locomotor system and bears the load when standing and moving. It is a complex structure with 28 bones, 33 joints and many muscles, tendons and ligaments, which is able to adapt to unevenness and at the same time has sufficient rigidity to propel the body forward. Foot anthropometry is influenced by many factors such as age, gender, region, mobility, and health. Shoes should be designed that they support the natural foot movement and do not restrict and confine the foot significantly. Foot deformities are often rooted in unsuitable footwear during the early development stages. Problems such as flat, skewed feet often manifest in adults due to wrong footwear, insufficient exercise and unhealthy lifestyles.

2.5.3 Gait Cycles

Walking and running are dynamic, periodic movements during which forces are generated that have to be supported by the musculoskeletal system. During the different phases in the gait cycle the load and function of the foot varies. During initial contact the impact needs to be dampened, the load needs to be supported over the stance time and during push off the body needs to be propelled forward. The load exceeds the body weight and can reach up to 2.8 times of the body weight during running.

2.5.4 Measurement methods

There are a number of static and dynamic measurement methods to investigate movement, pressure distribution and forces generated over the course of the gait cycle. Variables that are measured may be temporal, kinematic (position, displacement, velocity, acceleration), kinetic (force, energy, work, power) or related to muscle activity, metabolic measurements.

Measurement equipment includes force plates, high speed cameras, pressure sensor mats, pressure sensor insoles, EMG-Sensors, IMU-Sensors, GPS- Sensors, gas analysers.

2.6 Sensors

Sensors are the foundation of modern biomechanical measurement systems. In the footwear industry they are used to objectively quantify parameters such as plantar pressure, gait patterns, foot movement, impacts during walking or running, and environmental conditions. The collected data can support footwear design, orthotic development, clinical assessment, and quality control by providing objective measurements that cannot be obtained reliably through visual observation alone.

2.6.1 What can be measured?

Sensors enable the objective measurement of physical properties and environmental conditions. While many of these properties can also be perceived by humans, sensors provide quantitative, unbiased, and repeatable data. In addition, sensors can detect phenomena that are beyond human perception, such as magnetic fields, radio waves, or infrared radiation.

In the footwear industry, sensors are used to measure parameters such as plantar pressure, gait velocity, acceleration, ground reaction forces, and foot orientation. These measurements provide objective data for biomechanical assessments, footwear development, and the customization of orthotic devices.

Examples of measurable physical quantities include:

- Distance
- Velocity
- Acceleration
- Time
- Pressure
- Temperature
- Magnetic fields
- Brightness
- Force
- Humidity
- Etc.

2.6.2 How can sensors measure?

Distance

Distance measurement can be used in footwear manufacturing and development to determine the position, dimensions and geometry of objects without physical contact. Triangulation-based laser sensors are particularly suitable for 3D scanning of feet, lasts and footwear components, supporting digital last development, customised footwear and quality inspection. Time-of-flight sensors can additionally be used for position detection and process monitoring in automated production and robotic handling, for example to detect the position of footwear components during assembly.

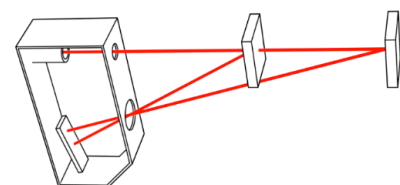


Fig. 15: Triangulation-based distance sensor © PFI

Velocity

Velocity describes the change in position over time and is measured relative to a reference frame. While speed describes only the magnitude of motion, velocity also includes its direction. Velocity can be determined by measuring the distance travelled over a known period of time, or indirectly using sensors that measure position, acceleration or rotation. In the shoe industry, velocity measurement is used to analyse foot and shoe movement during walking and running, for example in gait and biomechanical testing. It is also relevant for monitoring and controlling the movement of components, machinery and robots in automated footwear production, as well as for defined-motion tests such as abrasion, flexing and slip-resistance testing.

Acceleration

Acceleration sensors are particularly important in the footwear industry because they enable the analysis of gait patterns, running mechanics, impact loading, and foot movement outside of laboratory environments. Wearable acceleration sensors can continuously record movement during daily activities and sports, providing valuable information for footwear development and orthotic assessment.

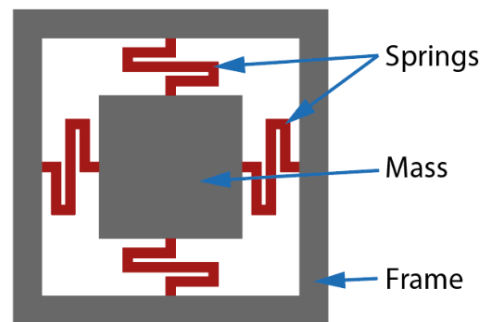


Fig. 16: Schematic of an acceleration sensor © PFI

Acceleration is typically measured by tracking the inertial force that a known mass experiences when its velocity changes. Using MEMS (Micro-Electro-Mechanical Systems) technology, a tiny mass is suspended on microscopic spring elements. When the sensor moves, inertia causes the mass to shift, and this displacement is measured electronically and converted into an acceleration value.

Gyroscope

Gyroscopes complement acceleration sensors by measuring rotational movements of the foot and lower limb. In footwear biomechanics, they are used to analyse foot orientation, pronation and supination behaviour, stride characteristics, and overall gait mechanics.

Similar to acceleration sensors, gyroscopes measure motion without requiring an external reference. Modern gyroscopes are also based on MEMS technology and are often integrated together with accelerometers.

Temperature

Temperature sensors can be used to monitor thermal conditions inside a shoe or at the foot–shoe interface. Excessive temperatures may affect comfort, material performance, and moisture management. Temperature monitoring can be particularly relevant for people with diabetes, as elevated or abnormal foot temperatures may indicate localized areas of increased mechanical stress or inflammation and can therefore support the early identification of potential foot problems¹⁹.

Various measurement principles exist, but many electronic temperature sensors rely on the temperature-dependent electrical resistance of specific materials to determine temperature. In smart footwear, temperature sensors can therefore be combined with pressure or other biomechanical sensors to provide additional information about the condition of the foot and the footwear environment.

¹⁹ Borg, M., Mizzi, S., Farrugia, R., Mifsud, T., Mizzi, A., Bajada, J., & Falzon, O. (2025, July). An Investigation of Foot Temperature Deviations in Individuals with Diabetes: Insights from Wearable In-Shoe Technology. In 2025 47th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) (pp. 1-7). IEEE.

Magnetic fields

Magnetic field sensors help determine the orientation of wearable systems used for gait analysis. When combined with accelerometers and gyroscopes, they improve the accuracy of motion tracking by providing a reference to the Earth's magnetic field.

These sensors measure magnetic fields using electronic components that react to the interaction between electric currents and magnetic forces.

Pressure / Force

Pressure and force measurements are among the most important sensor applications in the footwear industry. Pressure sensors are used in pressure platforms, insoles, and biomechanics laboratories to evaluate plantar pressure distribution, identify areas of excessive loading, and support footwear and orthotic design.

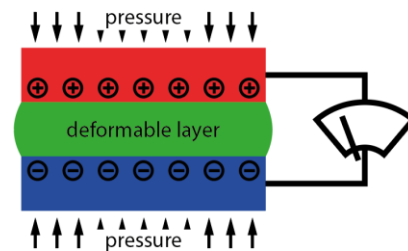


Fig. 17: Principle of a capacitive senso © PFI

There are different physical properties that can be measured, but most of the sensors have a deformable layer between two conductive layers. For example: If the layer is insulating, the other two result in a capacitor, the capacitance of which depends on the distance between the two outer layers. This capacitance is measured and converted into the applied pressure; therefore, this sensor type is called a capacitive sensor.

2.6.3 Inertial measurement unit (IMU)

Inertial Measurement Units (IMUs) are increasingly used in the footwear industry because they enable gait and movement analysis outside of specialized laboratories. Small wearable IMUs can be attached to the shoe, foot, or lower leg to measure parameters such as foot orientation, stride characteristics, walking speed, and gait symmetry during everyday activities. This allows movement patterns to be assessed in real-world environments rather than only under laboratory conditions.

An IMU combines an accelerometer, gyroscope, and magnetometer (compass) into a single sensor unit. By combining rotational measurements with information from the Earth's gravitational and magnetic fields, the IMU can determine its three-dimensional orientation with good accuracy.

However, estimating the actual position of the sensor is significantly more challenging. Position must be calculated by integrating acceleration data over time. Even very small measurement errors accumulate during this process, leading to gradually increasing position deviations, a phenomenon known as sensor drift.

For this reason, IMUs are often combined with external reference systems such as optical motion capture systems, GPS signals, or known gait events to improve long-term accuracy and compensate for drift. While IMUs generally do not provide the same level of positional accuracy as laboratory-based motion capture systems, they offer important advantages in terms of portability, ease of use, and the ability to collect data in real-world environments. Consequently, IMUs are frequently used as a complementary measurement tool or, where ultra-high precision is not required, as a practical alternative to laboratory-based assessments.

A practical application in the footwear industry is gait analysis during walking and running. IMUs attached to the shoe or foot can measure parameters such as foot orientation, pronation, foot

strike location, and ground contact time in real-world environments, providing objective information about movement patterns outside specialized laboratories^{20,21}.

2.6.4 Stationary Sensors

Stationary sensors are integrated into fixed measurement systems, such as instrumented treadmills, force plates, pressure platforms, or complete gait laboratories. Unlike wearable sensors, they remain permanently installed within a controlled environment and measure the interaction between the subject and the measurement system.

These systems offer the advantage of high measurement accuracy, repeatability, and long-term stability. Because the sensors are permanently installed and regularly calibrated, measurement uncertainties can be minimized. In addition, the controlled laboratory environment reduces external influences that might affect measurement quality.

In the footwear industry, stationary sensor systems are widely used for biomechanical assessments, footwear development, and orthotic evaluation. For example, pressure platforms can measure plantar pressure distribution during walking and identify regions of excessive loading under the foot. Force plates can quantify ground reaction forces and loading rates, while instrumented treadmills enable continuous gait analysis over multiple gait cycles. Such measurements provide objective information for footwear design, orthotic customization, and clinical decision-making.

A key limitation is that measurements are restricted to the laboratory environment and may not fully reflect movement patterns during everyday activities. For this reason, stationary systems are increasingly complemented by wearable sensor technologies such as IMUs.

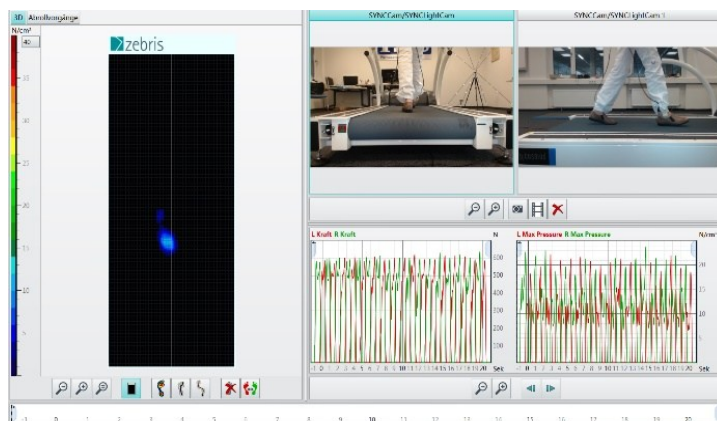


Fig. 18: Software interface of a sensor equipped treadmill; left: overview of treadmill surface; top right: camera view; lower right: visualisation of captured data. © PFI

2.6.5 Mobile sensors

Mobile sensors are carried directly by the user and record data either locally for later analysis or transmit information wirelessly via technologies such as Bluetooth or Wi-Fi. Unlike stationary systems, mobile sensors enable measurements outside the laboratory and therefore provide

²⁰ Young, F., Mason, R., Wall, C., Morris, R., Stuart, S., & Godfrey, A. (2022). Examination of a foot mounted IMU-based methodology for a running gait assessment. *Frontiers in Sports and Active Living*, 4, 956889.

²¹ Lewin, M., Price, C., & Nester, C. (2023). Can a shoe-mounted IMU identify the effects of orthotics in ways comparable to gait laboratory measurements?. *Journal of Foot and Ankle Research*, 16(1), 54.

insight into movement patterns during everyday activities. However, they generally require attachment to the body or footwear and often require calibration before use.

Common examples include:

- Inertial Measurement Units (IMUs)
- Electromyography (EMG) sensors
- Pressure and force sensors integrated into insoles

Feature	Mobile Sensors	Stationary Sensors
Measurement Environment	Real-world conditions	Controlled laboratory
Mobility	High	Fixed installation
Measurement Duration	Long-term possible	Usually short-term
Ease of Use	Requires attachment	Immediately available
Force and Pressure Measurement	Possible (e.g., instrumented insoles)	Highly accurate
Motion Analysis	Excellent for daily-life monitoring	High accuracy under controlled conditions
Measurement Accuracy	Moderate to high	High
Typical Footwear Application	Wearable gait monitoring, activity tracking	Pressure analysis, force measurements, footwear and orthotic development

Tab. 3: Comparison of Mobile and Stationary Sensor Systems.

Both stationary and mobile sensor systems play important roles in footwear biomechanics. Stationary systems provide highly accurate and repeatable measurements under controlled laboratory conditions and are often considered the reference standard for biomechanical assessments. Mobile systems, in contrast, enable measurements in real-world environments and provide insight into natural movement patterns during everyday activities.

In practice, the two approaches are complementary. Stationary systems are often used during footwear and orthotic development, while mobile sensors enable the subsequent evaluation of performance under realistic usage conditions. Together, they provide comprehensive biomechanical information to support footwear design, orthotic customization, and clinical assessment.

Sustainability Perspective

By providing objective information on gait patterns, plantar pressure distribution, movement asymmetries, and footwear performance, these systems can support the development of footwear and orthotic solutions tailored to individual needs. This contributes to **SDG 3: Good Health and Well-Being** by promoting mobility, reducing injury risks, and supporting preventive and rehabilitative healthcare.

In addition, objective biomechanical data can improve the efficiency of footwear and orthotic development processes by reducing the number of physical prototypes, wear trials, and design iterations required. As a result, material consumption, development time, and associated resource use can be reduced while maintaining or improving product performance and user outcomes.

2.6.6 Use of sensors in shoes

The use of sensors in shoes offers a wide range of possibilities, from simple pedometers in everyday life to biometric gait analysis in science and research. Medicine can also benefit from data

on the walking and running behaviour of patients and better adapt treatment methods to the respective situation. With all this, however, the disposal and recycling of the electronic components in shoes and clothing must not be neglected.



Fig. 19: a) Insole with humidity sensor and temperature sensor b) Zoom view of the humidity sensor. PFI (2022–2024). Safety of footwear containing electronic components under the Electronic Equipment Act (IGF project 22292 N).

3 Digitalisation in STEM

The modern footwear manufacturing sector is undergoing a profound paradigm shift, evolving from a historically labour-intensive, tactile craft into a highly automated, data-driven domain of STEM application. Digitalization acts as the primary catalyst in this transition, fusing advanced engineering, computational sciences, and innovative material manufacturing. By integrating cyber-physical systems across the value chain, the industry is establishing agile production models capable of addressing contemporary consumer demands for extreme personalization, localized manufacturing, and verifiable sustainability.

3.1 New Era of Robots

Traditional footwear assembly has long resisted total automation due to the non-rigid, flexible nature of materials like leather, mesh, and textiles, which present significant handling challenges for classic industrial robotics. However, a new era of advanced robotics, driven by vision-guided systems and soft-robotics grippers, is transforming the factory floor. High-precision automated systems are now standard in material cutting, automated lasting, and sole-bonding processes, drastically reducing manual error and operational throughput times²².

A prominent contemporary manifestation of this technological evolution is the scaling of robotic chemical-spraying systems. For instance, footwear brand On expanded its "LightSpray" technology by deploying a fully automated, 32-robot production matrix capable of constructing a complex, monolithic running shoe upper within minutes without a single piece of stitching.



Fig. 20: On LightSpray Factory Busan - Photo by SeongYoun Vhae - 2026

These multi-robot systems operate in synchronized, computerized cells, coordinating real-time paths to apply bio-based polymers directly onto a shoe last. This shift toward intelligent robotic ecosystems eliminates traditional assembly-line dependencies, paving the way for hyper-localized micro-factories that minimize shipping distances and global carbon overheads.

3.2 Artificial Intelligence (AI)

Artificial Intelligence (AI) has emerged as a disruptive framework optimizing both the creative design and structural execution phases of footwear engineering (Minaoglou et al., 2024)²³. Through algorithmic creativity and generative design networks, AI engines allow engineers to input specific mechanical constraints—such as target weight, torsion resistance, and ventilation parameters—to generate hundreds of optimal geometric iterations. These computational architectures utilize

²²Huang, Y.-Y., Lai, J.-T., & Wu, H.-H. (2025). Real-time 3D vision-based robotic path planning for automated adhesive spraying on lasted uppers in footwear manufacturing. *Applied Sciences*, 15(11), 6365. <https://doi.org/10.3390/app15116365>.

²³ Minaoglou, P., Tzotzis, A., Efklidis, N., & Kyratsis, P. (2024). Integrating artificial intelligence into the shoe design process. *Engineering Proceedings*, 72(1), 7. <https://doi.org/10.3390/engproc2024072007>.

genetic algorithms combined with Convolutional Neural Networks (CNNs) to optimize the shoe structure for specific athletic outputs, validating performance virtually before any physical sample is moulded.

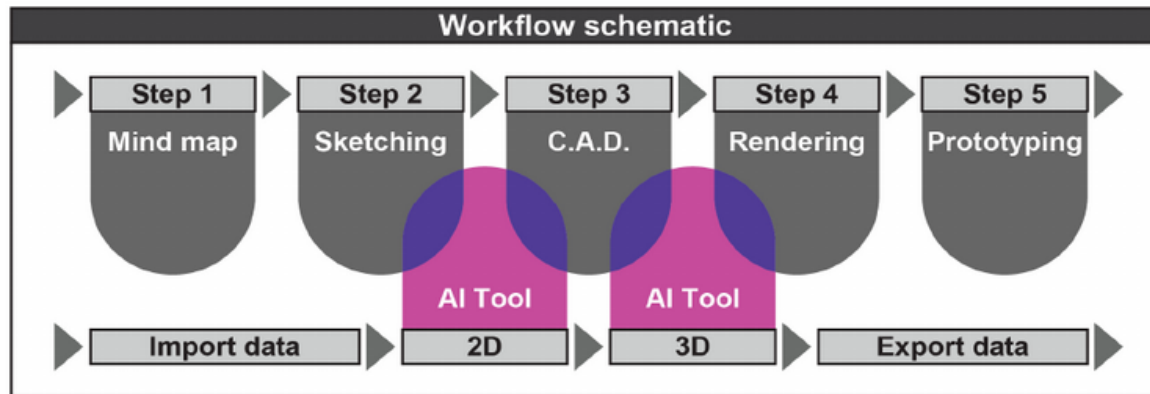


Fig. 21: Description of the entire process. Minaoglou et al., 2024.

On the production floor, AI-driven machine learning algorithms have substantially minimized material waste and operational downtime. In material processing, intelligent cutting systems utilize computer vision to instantly map out nested patterns on irregular leather hides, achieving optimal yield and drastically reducing scrap rates. Furthermore, AI controls integrated into automated injection-moulding equipment continuously monitor variables like pressure, viscosity, and temperature. By analysing real-time fluctuations, these systems automatically adjust chemical formulations—such as polyurethane blends—ensuring batch uniformity, eliminating defective outputs, and driving predictive maintenance protocols that protect capital equipment from catastrophic²⁴.

3.3 Big Data

The convergence of the Internet of Things (IoT) and Big Data acts as the central nervous system for modern footwear supply chains and product development cycles. Industrial production floors are now blanketed with IoT-enabled sensors that continuously collect telemetry data regarding machine temperature, vibration cycles, and throughput speeds. When aggregated into Big Data analytical engines, this massive stream of information shifts factory management from a reactive posture to a proactive model. Supply chain managers utilize these predictive insights to identify impending production bottlenecks, optimize raw material inventories, and seamlessly pivot scheduling in response to global component disruptions²⁵.

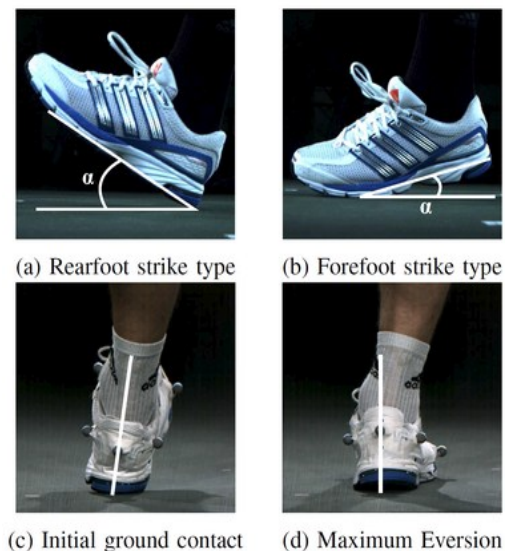


Fig. 22: Shoes with IMU in sole for long-term strike type and pronation analysis⁶.

²⁴ Expo Riva Schuh and Gardabags. (2025, April 15). Artificial intelligence and the shoe business: The next industry revolution has already begun! <https://exporivaschuh.it/en/press-release-detail/artificial-intelligence-and-the-shoe-business-the-next-industry-revolution-has-already-begun>.

²⁵ Arsutoria Studio. (2025, December 15). Footwear 4.0: The platform for smart footwear manufacturing. <https://arsutoriastudio.com/en/footwear-4-0-the-platform-for-smart-footwear-manufacturing/>.

Beyond the factory walls, Big Data directly impacts user-centric product engineering. Modern performance footwear frequently integrates wearable technology, such as Inertial Measurement Units (IMUs) embedded directly into the shoe's sole architecture. Biomechanical research demonstrates that analysing kinematic parameters from these sensor-embedded shoes can successfully drive automated, personalized running shoe recommendations²⁶. Specifically, placing sensors within a precise cavity under the foot's arch yields the cleanest spatial-temporal parameters to reconstruct dynamic foot trajectories during²⁷. The massive datasets collected from these smart-shoe arrays allow biomechanical engineers to model gait degradation patterns over time, providing a quantitative loop that fuels personalized, data-driven footwear design and orthopaedic recommendation engines.

3.4 3D Printing

Additive manufacturing, or 3D printing, has revolutionized footwear production²⁸ by liberating design engineers from the restrictive geometric boundaries imposed by traditional injection and compression moulding. Historically restricted to rapid prototyping, 3D printing is now a viable mass-production methodology for structural end-use components, particularly midsoles. Technologies like Carbon's Digital Light Synthesis (DLS)—which leverages digital light projection, oxygen-permeable membranes, and liquid resins—can generate highly detailed, isotropic polymeric parts faster than conventional 3D printing methods²⁹.

The core technical triumph of additive manufacturing in footwear lies in the production of complex elastomeric lattice structures. Through partnerships like the one between Adidas and Carbon to scale the Futurecraft 4D series, engineers have replaced traditional uniform foam components with a single, monolithic printed lattice³⁰. Software-driven parameters allow the mechanical properties of this lattice to vary across distinct zones of the same midsole. This provides hyper-targeted compression, energy return, and stabilization tailored specifically to an individual athlete's force profile without requiring the labour-intensive assembly of separate components, effectively mitigating mechanical delamination risks.

3.5 Combination of Digitalisation and Sciences

The integration of digitalization with materials science, biochemistry, and life-cycle analytics has enabled the creation of sophisticated "Digital Twins." A digital twin is a dynamic, virtual carbon copy of a physical asset that continuously mirrors its real-world state throughout its lifecycle³¹. In sustainable footwear manufacturing, researchers utilize digital twins coupled with plant simulation software to map, predict, and optimize carbon emissions across material sourcing, active

²⁶ Zrenner, M., Ullrich, M., Zobel, P., Jensen, U., Laser, F., Groh, B. H., ... & Eskofier, B. M. (2018, March). Kinematic parameter evaluation for the purpose of a wearable running shoe recommendation. In 2018 IEEE 15th international conference on wearable and implantable body sensor networks (BSN) (pp. 106-109). IEEE.

²⁷ Machine Learning and Data Analytics Lab. (retrieved 01.06.2026). Personalized running shoe recommendation using different data sources. Friedrich-Alexander-Universität Erlangen-Nürnberg.
<https://www.mad.tf.fau.de/research/projects/personalized-running-shoe-recommendation-using-different-data-sources/>.

²⁸ Roberts-Islam, B. (2026, May 18). Footwear production is broken. So are our feet. Can 3D print fix both? Forbes.
<https://www.forbes.com/sites/brookeroberthislam/2026/05/18/footwear-production-is-broken-so-are-our-feet-can-3d-print-fix-both/>

²⁹ Carbon3D. (2024). Carbon Digital Light Synthesis (DLS) 3D printing technology. Carbon, Inc.
<https://www.carbon3d.com/carbon-dls-technology>

³⁰ Wright, O. (2023, September 21). How do adidas 3D printed midsoles hold up after a year of use? 3DPrint.com.
<https://3dprint.com/303434/how-do-adidas-3d-printed-midsoles-hold-up-after-a-year-of-use/>.

³¹ Transitions Project. (retrieved 2026, June 1). Digital twin <https://transitionsproject.eu/digitalisation-2/digital-twin/>.

production, and final distribution networks³². This allows material scientists to simulate the structural degradation of novel eco-friendly polymers or bio-polyurethanes under high-stress scenarios without executing costly, destructive physical testing.

Furthermore, this intersection has birthed time-based biomimetic design methodologies. Pioneering workflows connect physical footwear embedded with pressure and temperature sensors directly to a cloud-based digital twin³³. As the user wears the shoe, the virtual model is continually nourished with dynamic biological feedback. When the physical shoe approaches its structural end-of-life, the digital twin leverages this cumulative biological data archive to automatically calculate and generate an updated, bespoke geometry for the user's next iteration, representing a complete synthesis of digital computing and biological adaptation.

3.6 Virtual and Augmented Reality

Virtual Reality (VR) and Augmented Reality (AR) have evolved from novel consumer applications³⁴ into indispensable tools spanning the industrial design and retail distribution of footwear. In the design phase, spatial computing environments allow multidisciplinary teams situated globally to collaborate on 3D digital prototypes inside virtual design studios. This high-fidelity visualization entirely replaces the need to manufacture and ship physical style samples across continents, dramatically shortening product development lifecycles and eliminating pre-production material waste.

On the consumer and retail side, AR can bridge the gap between digital product assets and physical product experiences. Research on footwear virtual try-on has demonstrated the use of computer-vision-based foot tracking to align virtual 3D footwear models with moving feet³⁵. For example, Yang et al. developed an AR footwear try-on system using RGB-D data and an Iterative Closest Point (ICP) algorithm to align captured foot data with predefined reference models³⁶. More recent commercial solutions have extended virtual try-on to smartphones and web-based experiences. Platforms such as Fibbl³⁷ and WANNA³⁸ offer footwear VTO that allows consumers to visualize shoes on their feet using mobile devices and AR technologies. By providing realistic visualization of footwear in the user's own context, these systems aim to increase purchase confidence and reduce uncertainty in online shopping. Commercial providers report reductions in return rates, although the magnitude of these effects varies by implementation and should be interpreted as provider-reported evidence. Reducing unnecessary returns can also reduce associated reverse-logistics activities, packaging requirements and transportation impacts.

³² Sattler, B. J., Tundis, A., Friesen, J., & Pelz, P. F. (2024). Modeling water availability during a blackout under consideration of uncertain demand response. *Engineering Proceedings*, 69(1), 130. <https://doi.org/10.3390/engproc2024069130>.

³³ Ashuach, A. (2021). Footwear time based design: Evolve IM biometric evolutionary footwear. Re-FREAM. <https://re-fream.eu/pioneers/footwear-time-based-design/>

³⁴ Zakeke. (2023, May 15). The future of footwear: AR shoes. Abgerufen am 1. Juni 2026, von <https://www.zakeke.com/blog/the-future-of-footwear-ar-shoes/>.

³⁵ Chu, C. H., Chen, Y. A., Huang, Y. Y., & Lee, Y. J. (2022). A comparative study of virtual footwear try-on applications in virtual and augmented reality. *Journal of Computing and Information Science in Engineering*, 22(4), 041004.

³⁶ Yang, Y. I., Yang, C. K., & Chu, C. H. (2014). A virtual try-on system in augmented reality using RGB-D cameras for footwear personalization. *Journal of Manufacturing Systems*, 33(4), 690-698.

³⁷ Fibbl. (Retrieved June 1, 2026). Virtual try-on for footwear brands, <https://fibbl.com/experiences/virtual-try-on-for-footwear-brands/>

³⁸ WANNA. (Retrieved June 1, 2026). Virtual try-on., from <https://wanna.fashion/virtual-try-on/>

4 Globalisation in STEM

The evolution of footwear production has transitioned from a traditional, labour-intensive craft to a sophisticated intersection of STEM disciplines, fundamentally redefined by the principles of Industry 4.0. At the heart of this transformation is material science and biotechnology, which have pivoted toward the development of high-performance, sustainable substrates. Modern midsole architectures, for instance, utilize bio-based thermoplastic polyurethanes (TPU) and high-resilience biodegradable polyester foams to significantly reduce the environmental burden of mass production. These materials are not merely chosen for their sustainability; they are engineered for metabolic efficiency. The rise of Advanced Footwear Technology (AFT), which integrates rigid carbon-fibre plates within energy-return foams, relies heavily on biomechanical modelling to improve a runner's metabolic economy—often quantified by the reduction in oxygen consumption required to maintain a specific velocity.

Digital engineering and parametric design serve as the primary drivers for the industry's globalization. With 3D laser scanning and feature-based algorithms, designers can now capture complex anatomical data to construct customized shoe-last models automatically. This digital-first approach boosts the efficiency of a "distributed manufacturing" model even further, where a design can be conceptualized in one part of the world and executed in another with mathematical precision. Additive manufacturing, or 3D printing, supports this by allowing for the creation of complex lattice structures and uppers, such as the Nike Flyprint³⁹, which optimize breathability and weight in ways traditional weaving cannot. Additionally, prototyping is more flexible, faster and possibly cheaper especially for soles and applications on the upper for more conventional products.

In the context of globalized production, the most critical "appliances" are those that bridge the physical and digital divide. Digital twins⁴⁰ — comprehensive virtual replicas of physical production lines—allow for the real-time monitoring and optimization of factories across disparate geographic locations. By integrating IoT sensors with these virtual models, manufacturers can simulate production bottlenecks and manage carbon footprints across the entire supply chain, from raw material extraction to final logistics.

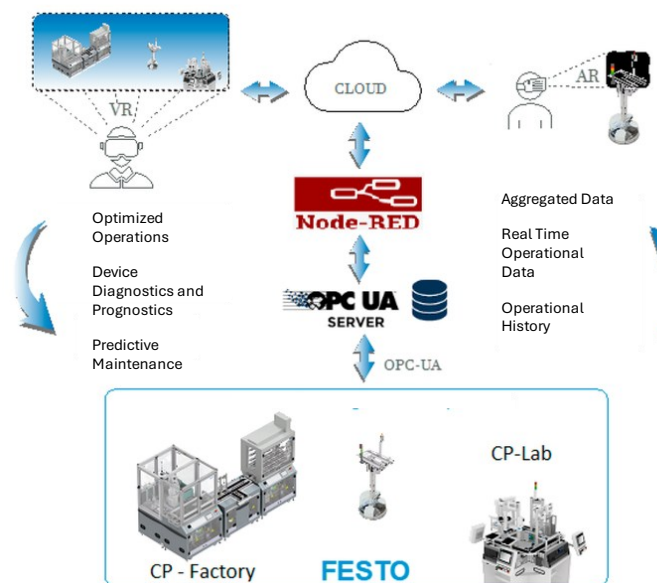


Fig. 23: Immersive DT architecture for the MES¹⁶.

This connectivity is essential for maintaining "innovation readiness" in manufacturing hubs like Bangladesh or Vietnam, where rising labour costs are being offset by the implementation of automated robotic cells.

³⁹ Attard-Manche, A. (2018, November 12). Nike's 3D printing: Just do it. Technology and Operations Management (Harvard Business School / Harvard D^3). <https://d3.harvard.edu/platform-rctom/submission/nikes-3d-printing-just-do-it/>

⁴⁰ Caiza, G., & Sanz, R. (2024). An immersive digital twin applied to a manufacturing execution system for the monitoring and control of industry 4.0 processes. Applied Sciences, 14(10), 4125.

These cells handle high-precision tasks, such as automated glue deposition, using CAD-driven trajectories that ensure identical quality standards regardless of the factory's location.

Finally, the complexity of global sourcing is managed through the "trust appliance" of blockchain technology. By providing an immutable ledger for every component of a shoe, blockchain ensures traceability and ethical compliance, which is increasingly demanded by international regulatory bodies. This synthesis of material science, digital twinning, and automated robotics ensures that modern footwear production is not only a globalized enterprise but one that is increasingly agile, data-driven, and environmentally conscious.

4.1 Demography

The footwear industry represents a highly sophisticated, interdisciplinary convergence of Science, Technology, Engineering, and Mathematics (STEM). From the design of carbon-fiber propulsion plates to the integration of micro-sensors in smart shoes and the algorithmic optimization of automated assembly lines, technical innovations are deeply woven into modern footwear design. However, the human demographic landscapes that drive, participate in, and consume these technological advancements remain characterized by stark structural divisions.

Understanding the demographic distribution across academic research, consumer product adoption, and industrial manufacturing is essential for identifying systemic barriers, optimizing ergonomic design, and forecasting future workforce trends.

While STEM disciplines are extensively integrated into the engineering, testing, and distribution of modern footwear, gender disparities persist within the academic and research systems underpinning these processes. The European Commission's She Figures 2024 report⁴¹ documents the continued underrepresentation of women in science and engineering, particularly at senior research levels. One example can be found in the academic and educational pipelines of biomechanics in Europe. Recent evidence from the United Kingdom illustrates gender differences in participation in sports-related biomechanics education. Hunter et al. (2026)⁴², examining undergraduate biomechanics education at three UK universities, identified substantial differences in male and female participation. At London Metropolitan University, female students accounted for 16.2% of biomechanics enrolments at Level 5 and only 7.1% at Level 6, while women represented 20.5% and 16.9%, respectively, of the overall cohorts. At St Mary's University, London, gender parity was observed among Level 6 biomechanics enrolments, which represented 32% of the overall Level 6 cohort. At Level 5, however, 56% of eligible female students enrolled in biomechanics compared with 71% of eligible male students. The authors discuss these patterns in relation to the broader "leaky pipeline" observed in STEM and biomechanics. These findings highlight the importance of ensuring that footwear biomechanics research and product development incorporate adequately representative female cohorts. Systematic reporting and auditing of participant demographics, together with female-inclusive R&D cohorts, can help identify and address potential sex- and gender-related differences in footwear fit, biomechanics, and performance.

⁴¹ European Commission: Directorate-General for Research and Innovation, She figures 2024 – Gender in research and innovation – Statistics and indicators, Publications Office of the European Union, 2025, <https://data.europa.eu/doi/10.2777/592260>

⁴² Hunter, B., Greenhalgh, A., & Atack, A. C. (2026). Exploring undergraduate students' perceptions of biomechanics curricula: Are there gender differences?. *Journal of sports sciences*, 1-9.

These pipeline dynamics are further constrained by disparities in visibility, professional representation, and recognition within biomechanics. Across major international biomechanics societies, women account for only approximately 32–41% of professional membership, despite substantially higher representation among student members⁴³. Women also remain underrepresented among recipients of prestigious biomechanics awards and in senior leadership positions. For example, women accounted for only 17% of Geoffrey Dyson Award recipients and 16% of ISBS presidents in the periods reported by Janssen (2021)⁴⁴. More broadly, women in biomechanics have been reported to receive approximately 30% fewer scientific citations than men, contributing to disparities in scholarly visibility and recognition⁴⁵.

To systematically analyse and address these equity imbalances, an international cohort of footwear scientists—representing institutions such as the University of Exeter (United Kingdom), Offenburg University (Germany), the University of Malta, and Macquarie University—developed the *Audit protocol for evaluating diversity in sport performance footwear research*⁴⁶. This peer-reviewed framework employs participation-to-prevalence ratios to quantify and track gender representation among both research participants and authors in published athletic footwear literature, establishing a standardized roadmap to enhance diversity across European footwear engineering.

Another can be found in the consumer domain, namely the expansion of smart footwear and customized orthotics which reflect distinct demographic profiles⁴⁷. Men prioritize athletic performance data and athletic running configurations, while women drive rapid growth in general wellness, balance tracking, and therapeutic orthotics. Footwear engineers must synthesize these user segments to design targeted, multi-sensor systems that address clinical and performance needs alike.

Finally, at the industrial level, the transition to capital-intensive automation poses a significant risk of defeminization on global shopfloors (Tejani, S., & Kucera, D., 2024)⁴⁸. Computerized semi-automation has deskilled traditional hand-stitching tasks, lowering entry barriers for male workers and displacing female labour due to deep-seated technological stereotypes and structural caregiving constraints. Mitigating these shifts requires brands and manufacturing suppliers to look beyond basic compliance, actively implementing multi-layered diagnostics, horizontal skill-building pathways, and robust domestic support structures to ensure that technical progress within the footwear industry remains equitable, safe, and empowering.

⁴³ Hunter, B., Greenhalgh, A., & Atack, A. C. (2026). Exploring undergraduate students' perceptions of biomechanics curricula: Are there gender differences?. *Journal of sports sciences*, 1-9.

⁴⁴ Kean, C. O., Burton, S., Janssen, I., Brackley, V., & Atack, A. C. (2026). Empowering women in sports biomechanics: exploring the impact of mentor circles. *Sports Biomechanics*, 25(1), 135-149.

⁴⁵ van Schooten, K. S., David, S., & Diamond, L. E. (2023). Women in Biomechanics and Control of Human Movement: 2022–2023. *Frontiers in Sports and Active Living*, 5, 1337636.

⁴⁶ Mills, K., Mickle, K. J., Dixon, S., Sterzing, T., Denis, Y., Fu, F., ... & Chockalingam, N. (2026). Audit protocol for evaluating diversity in sport performance footwear research: Assessing footwear design, participant representation, and author demographics in published studies. *The Foot*, 66, 102213.

⁴⁷ Fortune Business Insights. (Retrieved June 1, 2026). Smart shoes market, <https://www.fortunebusinessinsights.com/smart-shoes-market-106268>.

⁴⁸ Tejani, S., & Kucera, D. (2024). The Effects of Automation in the Apparel and Footwear Industries and Their Gender Dimensions: Indonesia Case Study. International Labour Organization.

4.2 Economic and Social Factors

While previous advancements focused primarily on the material and digital transformation of production, this shift examines how technology reshapes communication and community engagement, transforming the shoe from a static commodity into a dynamic, traceable, and social asset. Central to this transformation is the Digital Product Passport (DPP), mandated by the EU's Ecodesign for Sustainable Products Regulation (ESPR). By embedding NFC chips or QR codes directly into the footwear's structure—typically within the tongue or midsole—manufacturers provide an immutable "digital birth certificate." This STEM-driven traceability leverages blockchain technology to reveal the entire supply chain, from the specific origin of bio-resins to the exact energy consumption of the final assembly.

Beyond traceability modern brands are hosting community workshops⁴⁹ and "Science Shops"—local hubs where consumers connect to learn about the technical realities of the products they wear. These initiatives promote material literacy through hands-on courses that teach participants how to identify biodegradable polymers versus traditional synthetics, effectively driving market demand for alternative materials through the spread of technical knowledge. For the more technically inclined, customization courses allow community members to attend sessions on parametric design, where they learn to manipulate the of their 3D-printed components to better suit personal aesthetic preferences or specific biomechanical requirements.

4.3 Qualification / Training / Knowledge

More and more production and especially development leans towards CAD, 3D and AI / Agentic software implementation. To keep up to date with all the extremely fast-moving innovations the broad and very traditionally kept curricula of industrial shoemaker apprentices and future developers need to be updated to offer graduates an easier entry into specialist roles and also to open them up for efficient communication practices between departments. After all Footwear production remains highly interdisciplinary.

The developer of today needs to be fit in parametric design, 3D Applications and well versed in the basics on how AI works to be not only flexible in the professional environment but also to be able to trouble shoot and assess automated procedures on their effectiveness.

Basics in programming theory or coding with for example Python can also be very useful as our everyday life and work contains computers on such a high level we mostly don't even think about it anymore. A very bold and challenging task to teach but this is where AI can help quite well.

⁴⁹ FashionUnited. (2024, February 13). Birkenstock opens community studio in London.
<https://fashionunited.uk/news/fashion/birkenstock-opens-community-studio-in-london/2024021374088>.

The "shoemaker" of the future is a technical specialist. The industry is currently facing major talent gap in these specific roles:

Role	Core STEM Skills Required	Typical Responsibilities in the Footwear Industry
Footwear Data Scientist	Python, Machine Learning, Biometric Data Analysis, Statistics	Analyzes biomechanical and consumer data to support footwear personalization, orthotic design, and product optimization.
Computational Designer	Rhino/Grasshopper, Algorithmic Geometry, Generative CAD, Parametric Design	Develops computationally generated footwear geometries, lattice midsoles, and customized products.
Bio-material Engineer	Synthetic Biology, Fermentation Science, Polymer Chemistry, Material Science	Develops sustainable and high-performance materials for footwear applications.
Automation Technician	Robotics Programming (ROS), PLC Programming, Computer Vision, Sensor Integration	Maintains and programs automated manufacturing and quality-control systems.
Biomechanics Engineer	Human Biomechanics, Motion Analysis, Force Measurement, Gait Analysis	Evaluates human movement and translates biomechanical findings into footwear and orthotic designs.

Tab. 4: Example of STEM Skills for positions in the footwear industry.

4.4 Markets and Consumers

The footwear industry relies on a delicate balance of economic constraints and shifting social values. To understand how shoes are created, priced, and sold, one must look at how financial pressures and human behaviours intersect—and how STEM disciplines provide the necessary mechanisms to navigate these dynamics. Fluctuations in raw material prices (such as leather, synthetic rubber, and petroleum-based plastics) directly impact production costs. Global trade disruptions, such as escalating tariff regimes and rising freight costs, create localized price pressures for retailers. To combat those challenges companies had to rely on extensively time-consuming research and predictions based on historical data and experience of specialists. One major progress in that regard is the increasingly broad and reliable utilisation of predictive AI algorithms and stochastic supply chain modelling to mitigate these risks. By analysing vast historical sets of shipping, tariff, and material cost data, logistics engineers can run predictive simulations to optimize procurement timelines. This mathematical hedging allows brands to absorb cost spikes rather than passing them directly to the consumer through aggressive retail price hikes.

These tools enable even small companies to be much more competitive and less vulnerable to volatile markets. This topic is described in more detail within chapter 5.1.

Where the science led approach also shines is the processing of customer data, measurements or pressure maps to offer parametric customisable in- and midsoles (Sneakprint GmbH., 2026)⁵⁰ to incorporate multi zonal hardness for higher comfort and stability. Looking at demographic trends that clearly show a majority of elderly people within our societies this applies to fashionable

⁵⁰ Sneakprint GmbH. (Retrieved June 1, 2026). Sneakprint. <https://sneakprint.me/>

footwear as well as to orthopaedics⁵¹. Arch supports, pressure pads and even the most complex shapes for custom lasts of orthopaedic patients don't need to be handmade anymore. The whole process from measuring to finished footbed can now be fully automated using 3D-Scanners, pressure plates and well-tuned 3D-Printers.

4.5 Compliance

The global footwear industry operates within a highly regulated compliance matrix where advanced analytical chemistry, environmental toxicology, and manufacturing engineering intersect. Placing consumer footwear products on the international market requires strict adherence to legal frameworks designed to mitigate the risks associated with hazardous chemicals used in raw material extraction, leather tanning, fibre processing, and final product assembly. Chief among these regulations is the European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation (EC) No. 1907/2006 (REACH Compliance Data Centre, 2026)⁵². Under REACH, Annex XVII establishes binding limits on specific carcinogenic, mutagenic, or reprotoxic substances (CMRs), endocrine disruptors, and skin sensitizers. Specifically, Entry 72 of Annex XVII enforces strict concentration limits on CMR Category 1A and 1B substances within textiles and footwear in direct contact with human skin, while the REACH Candidate List mandates detailed communications across the supply chain if any Substance of Very High Concern (SVHC) exceeds a concentration of 0.1% by weight.

In the United States, chemical compliance is governed at federal and state levels, creating a complex dual-jurisdictional landscape. The Consumer Product Safety Improvement Act (U.S. Consumer Product Safety Commission, 2026)⁵³ of 2008 regulates children's footwear (intended for ages 12 and younger) by enforcing a strict lead content limit of 100 parts per million (ppm) within any accessible component, alongside restrictions on designated phthalates. State-level regulations further tighten these boundaries; Washington State's Children's Safe Product Act (CSPA) mandates that manufacturers report the presence of 66 separate chemicals of high concern, while California's Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65) requires clear consumer warning labels on products containing chemicals known to cause cancer or reproductive toxicity unless exposure levels fall below established safe harbour limits.

To navigate these overlapping international standards, industry coalitions have developed specialized compliance mechanisms. The Restricted Substances List (RSL), initially established by a dedicated task force of the American Apparel & Footwear Association (AAFA), serves as a compiled index of the most stringent national and international laws governing finished consumer items. The RSL does not regulate factory floor production processes directly; instead, it focuses strictly on whether a substance remains in the finished shoe above detectable thresholds. While some firms limit their RSL parameters to legal compliance, leading global brands expand their corporate RSLs to cover non-regulated emerging chemicals of concern, drawing from nongovernmental organization databases such as the ChemSec⁵⁴ "Substitute It Now" (SIN) list, or developing custom

⁵¹ Sanitätshaus Kocher GmbH. (Retrieved June 1, 2026). 3D-Einlagen. <https://sanitaetshaus-kocher.de/orthopaedie-schuhtechnik/3d-einlagen/>

⁵² REACH Compliance Data Centre. (Retrieved June 1, 2026). Regulation (EC) No 1907/2006 (REACH). <https://reach-compliance.eu/english/legislation/docs/launchers/launch-2006-1907-EC.html>

⁵³ U.S. Consumer Product Safety Commission. (Retrieved June 1, 2026). The Consumer Product Safety Improvement Act. <https://www.cpsc.gov/Regulations-Laws-Standards/Statutes/The-Consumer-Product-Safety-Improvement-Act>.

⁵⁴ ChemSec. (Retrieved June 1, 2026). SIN List. <https://sinlist.chemsec.org/>

protocols like the Apparel and Footwear International RSL Management Group (AFIRM) Packaging RSL.

A critical engineering challenge is that raw material compliance does not automatically guarantee finished shoe compliance. Mechanical, thermal, and chemical changes occurring during final manufacturing—such as adhesive heat activation, physical abrasion, or exposure to curing ovens—can trigger chemical transformations in previously compliant materials. Consequently, brands must utilize an "RSL Matrix"⁵⁵ to map specific materials to high-risk testing parameters, optimizing dynamic testing budgets while conducting random screening of finished inventory via third-party accredited laboratories.

Further information on chemical safety and in chapter 5.5.

⁵⁵ TÜV Rheinland. (Retrieved June 1, 2026). Restricted Substances List Whitepaper. <https://www.tuv.com/content-media-files/master-content/services/products/0211-tuv-rheinland-retail-services/tuv-rheinland-restricted-substances-list-whitepaper-en.pdf>.

5 Sustainability in STEM

5.1 Green Awareness

Unfortunately, green washing and false claims are still a very big problem within the fashion and Footwear industry. This does not only damage trust of customers in brands but also inflicts steady resentment and frustrations towards the general mission of Sustainability by politics and NGOs.

Therefore, the only way to truly achieve robust supply chains is to prove the chemical composition of materials. Through scientific methods like spectroscopy components in manufacturing can be analysed to the smallest molecule and therefore compared to similar probes with the same composition.

After allegations a lot of major fashion brands claimed that none of their products would contain cotton sourced from the notorious region of Xinjiang, China, where forced labour practices⁵⁶ are used in production frequently. These claims could be proven as false by above mentioned scientific method⁵⁷.

5.2 Energy and Process Efficiency

Energy prices can often dictate if a production facility remains profitable or not even if all other costs are well calculated. As markets are volatile due to international crisis or mishaps in fossil energy, such as coal, oil or gas, supply chains, shortcomings in energy efficiency could put companies out of business. The merit order principle⁵⁸ for electricity pricing often gets mentioned in discussions as the most expensive, mostly gas, energy resource pushes prices even when most of the energy mix consists of very cost-effective renewable energies.

To relief the dependency on fluctuating prices of the common industrial energy market companies should invest in local means of production for energy. Especially electricity. Besides machinery and robotics of footwear production facilities one should also keep in mind that offices and temperature regulation also cost a lot of energy, thus money.

In a step towards local self-sufficiency outer production plant surfaces can be fitted with solar panels where applicable. Parking spaces can also be enriched by solar panel roofing. Not only does this protect the cars but it also provides charging capabilities for electric vehicles.

⁵⁶ U.S. Department of Labor, Bureau of International Labor Affairs. (Retrieved June 1, 2026). Against Their Will: The Situation in Xinjiang. <https://www.dol.gov/agencies/ilab/against-their-will-the-situation-in-xinjiang>.

⁵⁷ European Center for Constitutional and Human Rights. (Retrieved June 1, 2026). Baumwolle aus Xinjiang – Textilien Recherche. <https://www.ecchr.eu/pressemitteilung/baumwolle-xinjiang-textilien-recherche/>

⁵⁸ Next Kraftwerke GmbH. (Retrieved June 1, 2026). What does merit order mean? <https://www.next-kraftwerke.com/knowledge/what-does-merit-order-mean/>

An example of this approach is the LOWA factory in Germany and Bošany, Slovakia⁵⁹.

Process optimization in shoe manufacturing often centres on thermal management and operational logistics.

- **Thermal Energy Recovery:** In processes such as the production of Ethylene Vinyl Acetate (EVA) shoe soles, significant energy savings are achieved through heat recovery. Returning hot process condensate to the boiler can result in oil savings of approximately 14.9% and substantially reduce thermal pollution⁶⁰.
- **Digital Twin Simulation:** Digital twin technology is increasingly used to model production lines to identify bottlenecks. By using simulation software (e.g., Siemens Plant Simulation⁶¹), manufacturers can reconfigure layouts—such as parallelizing workstations—to increase throughput without proportional increases in energy usage.

More on the topic on Digital twin Simulation can be read in chapter 3.

5.3 Resource Efficiency & Sustainable Materials

To decouple footwear production from high environmental impacts, engineers are applying circular economy principles to simplify product architectures and close material loops. Standard shoes are highly complex, multi-material systems, often comprising more than 10 distinct components and 70 individual materials bonded with permanent adhesives. This material heterogeneity makes clean mechanical disassembly and recycling technically and economically impractical. In the European Union, approximately 1.2 million tons of post-use shoe waste is generated annually, with only 5% recycled, 15% reused, and 80% sent directly to municipal landfills⁶².

To address this challenge, researchers have integrated Life Cycle Assessment (LCA) with the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation⁶³ to guide the sustainable redesign of complex industrial safety boots⁶⁴. While LCA quantifies environmental impacts, the MCI measures the degree of material loop closure on a scale from 0 (fully linear) to 1 (fully circular). This illustrated that circularity (MCI) and environmental performance (LCA) align at the overall product level but can diverge at the individual component level. For example, thickening a leather upper from 2 mm to 3 mm improves the shoe's physical durability and circular lifetime extension (enhancing the MCI), but also increases the raw leather mass, which substantially raises the carbon and water footprints during the manufacturing phase (negatively impacting the LCA).

⁵⁹ LOWA Sportschuhe GmbH. (Retrieved June 1, 2026). Umwelt & Klima. <https://lowa.com/de/erlebe-lowa/nachhaltigkeit/umwelt-klima>

⁶⁰ Špelić, I., Mihelić-Bogdanić, A., & Budin, R. (Retrieved June 1, 2026). Optimization of energy savings in the shoe sole production process. <https://hdko.hr/optimizacija-energetskih-usteda-u-procesu-proizvodnje-potplata-za-cipele-2/>

⁶¹ Siemens AG. (Retrieved June 1, 2026). Manufacturing process planning. <https://www.siemens.com/en-us/solutions/manufacturing-process-planning/>

⁶² European Commission. (n.d.). LIFE KANNAGreen: Demonstration of a new business and consumption model for the circular economy in the footwear sector (LIFE19 ENV/ES/000118). LIFE Programme. <https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE19-ENV-ES-000118/demonstration-of-a-new-business-and-consumption-model-for-the-circular-economy-in-the-footwear-sector>

⁶³ Ellen MacArthur Foundation & Granta Design. (2015). Circularity indicators: An approach to measuring circularity – Methodology. <https://content.ellenmacarthurfoundation.org/m/77e62bc9924c20d0/original/Circularity-Indicators-Methodology.pdf>

⁶⁴ Ortiz-de-Montellano, C. G. S., Ghannadzadeh, A., & 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. *Journal of Circular Economy*, 3(3).

To navigate these trade-offs, the researchers developed a product-level transition ladder and a prioritization matrix for component redesign. The resulting circular model successfully reduced environmental impacts by 51% (normalized using environmental price indices) through specific engineering interventions:

- Replacing non-recyclable materials such as soft PVC and ethyl vinyl acetate (EVA) with thermoplastic elastomers (TPE).
- Substituting toxic solvent-based adhesives with water-based polyurethane alternatives to facilitate end-of-life disassembly and chemical separation.
- Replacing synthetic toe caps with highly durable, recyclable steel caps to improve durability and ease of recovery.
- Reducing overall product complexity to facilitate mono-material recycling at the end of the shoe's life cycle.

On a larger scale, circular business models like the EU-funded LIFE KANNAGreen project demonstrate the real-world feasibility of closed-loop footwear systems. The KANNAGreen model utilizes a consumer take-back and recycling scheme that processes End-of-Life KANNA shoes (ELKs). Through mechanical separation, thermoforming, and injection moulding, recycled sole materials are directly integrated into new shoe soles, reducing the carbon footprint of each pair of shoes from a 10.6 kg/CO² baseline to 7.22 kg/CO² —a net carbon reduction of 38.3%⁶⁵.

⁶⁵ European Commission, CINEA. (Retrieved June 1, 2026). Demonstration of a new business and consumption model for the circular economy in the footwear sector (LIFE19 ENV/ES/000118). LIFE Programme. <https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE19-ENV-ES-000118/demonstration-of-a-new-business-and-consumption-model-for-the-circular-economy-in-the-footwear-sector>.

For highly mixed, non-separable post-consumer waste streams, researchers are investigating thermochemical treatment options, specifically pyrolysis. Pyrolysis thermally degrades mixed organic polymers, rubbers, and leathers in an oxygen-free reactor. This process converts complex shoe waste into high-value chemical feedstocks and fuel oils, diverting hazardous material mixtures from landfills and driving the industry toward a low-carbon circular economy.

Footwear Design Scenario	Carbon Footprint (kg CO ₂ eq)	Embodied Energy (MJ/kg)	Key Circular Design Strategy	Primary EoL Pathway
Conventional Safety Boot (Bodoga, et al., 2024) ⁶⁶	18.65	~85–110	Linear multi-material construction; solvent-based adhesives	Landfill (~80%)
Gore-Tex Hiking Boot (Bodoga, et al., 2024) ⁶⁷	27.10	~120–145	High-durability laminates and complex multi-material construction	Incineration or Landfill
Circular Redesigned Safety Boot (Ortiz-de-Montellano et al., 2025) ⁶⁸	9.14	~45–60	TPE mono-material design; water-based adhesives; design for recyclability	Mechanical recycling
LIFE KANNAGreen Shoe (European Commission, CINEA, 2026) ⁶⁹	7.22	~35–50	Closed-loop sole regrind; thermoforming	Re-injection moulding

Tab. 5: Environmental Performance and End-of-Life Pathways of Conventional and Circular Footwear Concepts

5.4 Sustainable Design & Circular Economy

True circularity is forged at the drawing board. For a circular economy to be commercially viable, the processes governing product repair, disassembly, and recycling must be fundamentally more cost-effective and less time-consuming than manufacturing a new product from virgin resources. Historically, the labor-intensive friction of separating complex, multi-material components has rendered footwear recycling economically impractical.

To bridge this economic gap, sustainable footwear design increasingly relies on a multidisciplinary framework combining Material Science, Robotics, and Chemical Engineering. This structural transformation is driven by three core STEM strategies:

⁶⁶ Bodoga, A., Nistorac, A., Loghin, M. C., & Isopescu, D. N. (2024). Environmental impact of footwear using life cycle assessment—case study of professional footwear. *Sustainability*, 16(14), 6094.

⁶⁷ Bodoga, A., Nistorac, A., Loghin, M. C., & Isopescu, D. N. (2024). Environmental impact of footwear using life cycle assessment—case study of professional footwear. *Sustainability*, 16(14), 6094.

⁶⁸ Ortiz-de-Montellano, C. G. S., Ghannadzadeh, A., & 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. *Journal of Circular Economy*, 3(3).

⁶⁹ European Commission, CINEA. (Retrieved June 1, 2026). Demonstration of a new business and consumption model for the circular economy in the footwear sector (LIFE19 ENV/ES/000118). LIFE Programme. <https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE19-ENV-ES-000118/demonstration-of-a-new-business-and-consumption-model-for-the-circular-economy-in-the-footwear-sector>.

5.4.1 Advanced Robotics & Automated Disassembly

Traditional footwear construction permanently fuses the upper and the outsole, requiring dangerous and inefficient manual labour to separate them. Modern engineering addresses this bottleneck by integrating automated cybernetics and computer vision into the recycling pipeline. Advanced robotic arms, guided by AI-driven vision systems, can dynamically scan worn, deformed shoes, map their material boundaries, and execute precise mechanical separation using automated cutters or high-pressure water jets without human intervention.

5.4.2 Reversible Bonding & Chemical Engineering

A major frontier in chemical engineering is the development of "smart" adhesives that feature debonding-on-demand capabilities. By replacing permanent, toxic polyurethane glues with stimuli-responsive formulas, engineers can trigger total adhesive failure at the end of a shoe's lifecycle. These specialized bonding agents maintain structural integrity during intense athletic use but completely lose their adhesive strength when exposed to specific, highly targeted thermal shifts, radio frequencies, or mild chemical washes—allowing the sole to cleanly detach from the upper.

5.4.3 Macromolecular Chemistry & Mono-Material Ecosystems

Standard athletic footwear blends up to 40 distinct material fractions (including EVA foams, polyester meshes, nylon threads, and metallic eyelets), which turn into a structurally compromised, contaminated sludge when melted together. To achieve true circularity, material scientists are transitioning toward mono-material architectures, where an entire shoe is engineered from a single polymer family. Prominent industrial milestones that proved the viability of this architecture include the Adidas Futurecraft.Loop⁷⁰, made entirely from TPU, and the Salomon Index.01⁷¹, constructed from cleanly separable polyester and TPU fractions designed for regional recycling loops.

- **The Salomon Index.01** isolates its architecture into exactly two cleanly separable material tracks: a recycled polyester upper and a nitrogen-infused Thermoplastic Polyurethane (TPU) bottom unit (*INFINIRIDE* foam). This isolated matrix yields a 44% reduction⁷² in the product's total carbon footprint, allowing the recovered sole units to be ground down and cleanly re-injected into the supply chain to manufacture alpine ski boots.
- **The Adidas Futurecraft.Loop** was unveiled as a major proof-of-concept in 2019, and saw its commercial public launch (under the "Made to be Remade" banner) in April 2021. It was engineered entirely from a single material—100% reusable TPU (Thermoplastic Polyurethane)—using no glue or solvent adhesives.

⁷⁰ adidas AG. (Retrieved June 1, 2026). adidas schließt den Produktlebenszyklus mit Futurecraft.Loop. <https://www.adidas-group.com/de/media/press-releases/adidas-schliesst-den-produktlebenszyklus-mit-futurecraftloop>

⁷¹ Salomon. (Retrieved June 1, 2026). Introducing the Index.01 recyclable running shoe. <https://www.salomon.com/en-nl/sg/a/introducing-the-index-01-recyclable-running-shoe>

⁷² Salomon. (Retrieved June 1, 2026). Change through innovation. <https://www.salomon.com/en-us/lp/g/sustainability-innovation>

5.4.4 Chemical Recycling and Depolymerization

Mechanical recycling of polymers often leads to degradation of material properties due to chain shortening. An alternative is chemical recycling (depolymerization), where polymers are broken down into their original monomers or intermediate chemical building blocks.

This approach can, in principle, restore near-virgin material quality and remove contaminants such as dyes or additives. However, it remains energy-intensive and not yet widely scaled for footwear materials.

5.5 Chemical Safety

Chemical safety is rapidly transitioning from a localized quality-control check to a primary driver of global footwear innovation, material selection, and manufacturing design. Driven by expanding regulatory frameworks, advanced analytical techniques, and evidence of post-consumer ecological harm, the footwear sector faces a structural shift. Brands must design products that protect both the individual consumer and the broader environment over the item's entire life cycle. Achieving this requires the systematic integration of STEM (Science, Technology, Engineering, and Mathematics) disciplines to pioneer new testing methodologies, enforce end-to-end supply chain traceability, and engineer non-toxic material alternatives.

5.5.1 Paradigm Shift: From Consumer Exposure to Full Life-Cycle Ecotoxicity

Historically, footwear Restricted Substance Lists (RSLs) focused almost exclusively on preventing immediate dermal or systemic harm to the consumer during regular wear. However, foundational environmental chemistry modelling has rewritten this approach.

By subjecting commercially purchased outsole materials to soaking extractions in synthetic brackish water, researchers demonstrated that low water-leaching rates of organic compounds do not guarantee environmental safety⁷³. Instead, the resulting aqueous leachate caused acute ecotoxicological damage—specifically inhibiting larval development in the crustacean *Nitocra spinipes* and limiting growth in the macroalga *Ceramium tenuicorne*. Crucially, this toxicity was traced directly to inorganic zinc, a ubiquitous activator utilized in rubber sulfur vulcanization, rather than the primary polymer matrix itself.

Footwear engineers can no longer look only at Restricted Substance Lists (RSLs) for finished goods. They must use advanced environmental chemistry to predict how a shoe will break down over time. This will drive a shift toward bio-sourced vulcanization activators and non-toxic curing systems to prevent environmental contamination after the shoe is discarded.

⁷³ Ingre-Khans, E., Rudén, C., & Breitholtz, M. (2010). Chemical risks and consumer products: the toxicity of shoe soles. *Ecotoxicology and Environmental Safety*, 73(7), 1633-1640.

5.5.2 Eliminating Targeted High-Risk Compound Classes

This highlights the need for advanced chemical assessments that evaluate both the direct exposure risk to the consumer and the broader environmental toxicity of footwear components as they weather.

- **Toxicological Profiles of Restricted Footwear Compounds**

The specific chemical groups targeted by RSL protocols and regulatory audits are selected based on their toxicological dynamics and their prevalence in footwear processing. These compounds span several functional classes, including dyes, biocides, plasticizers, and heavy metal stabilizers, each posing unique physiological risks:

- **Azo Dyes and Aromatic Amines:** Widely used as colorants in natural leather and synthetic textiles, azo dyes are characterized by at least one azo bond within their molecular structure. Under reductive or basic physiological conditions—such as exposure to human perspiration and skin friction during regular use—these molecules can cleave to release dangerous aromatic amines. Some of these amines, such as 4-toluidine and 4-aminobiphenyl, are classified as Group 1 (known human) carcinogens by the International Agency for Research on Cancer (IARC). While the EU statutory limit is 30 mg/kg, strict industry standards, such as those defined by the German CADS group, lower this threshold to 20 mg/kg to account for stricter standards in other markets.
- **Biocides and Preservatives:** Tanneries rely heavily on biocides to prevent mold, bacterial degradation, and decay during the processing and transport of wet-blue leather intermediates. Typical biocides include chlorinated phenols, such as pentachlorophenol (PCP), and isothiazolinones, such as octylisothiazolinone (OIT). These compounds are highly neurotoxic and act as potent skin sensitizers, capable of causing severe contact dermatitis upon migration to human skin. Manufacturers align their thresholds with eco-certifications like the Blue Angel, enforcing stringent concentration limits to prevent dermal sensitization.
- **Plasticizers and Phthalates:** Synthetic materials, soft PVC, and outsoles rely on phthalate esters (such as DEHP, DBP, BBP, and DIBP) to increase flexibility and mechanical elongation. Because phthalate molecules are not covalently bound to the polymer matrix, they are highly prone to migration, especially under mechanical stress or exposure to lipophilic skin lipids. Phthalates are documented endocrine disruptors linked directly to developmental and reproductive toxicity.
- **Heavy Metals and Stabilizers:** Lead, cadmium, mercury, and hexavalent chromium are utilized as pigment stabilizers, catalysts, and dye-fixing agents. Heavy metals are highly bioaccumulative, resisting metabolic clearance and accumulating in organs over time, which can lead to cognitive, renal, and developmental issues. Hexavalent chromium, a common byproduct of substandard leather tanning, is a known carcinogen and dermal allergen.
- **Bisphenols and Alkylphenols:** Bisphenol A (BPA) and Bisphenol S (BPS) are increasingly detected in polyester, spandex, and recycled synthetics, posing high dermal exposure risks due to their endocrine-disrupting properties. Studies have indicated that non-cotton and recycled synthetics exhibit substantially higher concentrations of bisphenols compared to natural fibres.

5.5.3 Revolutionizing Quality Control with Advanced Analytical Chemistry

As regulatory enforcement intensifies, footwear brands must integrate sophisticated analytical chemistry directly into their supply chains. Traditional testing relies on time-consuming organic solvent extractions followed by Gas Chromatography-Mass Spectrometry (GC-MS) or High-Performance Liquid Chromatography-Tandem Mass Spectrometry (HPLC-MS/MS) to detect parts-per-billion contamination.

To keep up with fast production cycles, the future industry will increasingly adopt ambient ionization techniques like Direct Analysis in Real Time Mass Spectrometry (DART-MS). This allows factories to conduct rapid, non-destructive surface screenings of footwear components in real time, catching restricted substances before products leave the factory floor.

Chemical Compound Class	Primary Application	Regulatory Framework / Agency	Maximum Allowable Limit	Analytical Method
Azo Dyes (releasing aromatic amines)	Textile & leather dyes	EU REACH / CADS	30 mg/kg (REACH), 20 mg/kg (CADS)	GC-MS / HPLC-MS
Phthalate Esters (DEHP, DBP, BBP, DIBP)	Synthetic leather plasticizer	REACH Annex XVII / CPSIA	0.1% by weight (1000 ppm)	GC-MS after solvent extraction
Lead (Pb)	Pigment stabilizer	US CPSIA	100 ppm (footwear components)	ICP-OES / ICP-MS
Bisphenol A / S (BPA, BPS)	Recycled synthetics processing	Proposed REACH Restrictions	Variable; substance-specific	HPLC-MS/MS / GC-MS
Octylisothiazolinone (OIT)	Tannery biocide / preservative	REACH / Skin Sensitization Regs	Proposed sensitization thresholds	HPLC-MS / GC-MS
Heavy Metals (Cadmium, Mercury)	Stabilizers and colorants	EU REACH / US CPSA	100 ppm typical	ICP-MS

Tab. 6: Common Restricted Chemical Substances in Footwear Manufacturing, Their Applications, Regulatory Limits, and Analytical Detection Methods.

5.5.4 Responding to Regulatory Pressures and Market Data

The EU Safety Gate (formerly RAPEX) system continues to identify chemical hazards as a major product safety concern in non-food consumer products. The 2025 Safety Gate Report showed that risks associated with dangerous chemicals accounted for 53% of all notifications, with phthalates, heavy metals, restricted fragrances, and other hazardous substances frequently contributing to enforcement actions and product withdrawals⁷⁴. Furthermore, the European Chemicals Agency (ECHA) REF-10 enforcement project found that 18% of 2,407 inspected consumer products were non-compliant with EU chemical legislation⁷⁵. Common causes of non-compliance included phthalates, lead, cadmium, short-chain chlorinated paraffins (SCCPs), and polycyclic aromatic hydrocarbons (PAHs), particularly in electrical products, toys, sports equipment, and fashion items such as footwear, bags, and clothing. Complementing these enforcement findings, Lavalley et al.

⁷⁴ European Commission. (Retrieved June 1, 2026). Safety Gate 2025 report. Publications Office of the European Union. <https://op.europa.eu/webpub/just/safety-gate-2025-report/en/>.

⁷⁵ European Chemicals Agency (ECHA). (2023). Forum enforcement project on chemicals in consumer products. https://echa.europa.eu/documents/10162/17086/ref-10_project_report_en.pdf/

(2025)⁷⁶ analysed 111 textile, clothing, and footwear products and reported that 63% contained at least one investigated hazardous substance. Among the tested articles, 24% exceeded proposed REACH concentration limits for bisphenols, 19% showed potential non-compliance related to phthalates and PAHs, and 7% exceeded proposed limits for the skin sensitiser octylisothiazolinone (OIT). These findings indicate that hazardous chemicals remain common in consumer textile and footwear products despite existing regulatory controls, highlighting the continuing need for market surveillance, enforcement, and substitution of substances of concern

Ultimately, the future of footwear production belongs to companies that view chemical safety not as a regulatory hurdle, but as a discipline rooted in STEM. By leveraging molecular engineering, toxicology, and advanced data analytics, the next generation of footwear will be high-performing, safe for consumers, and benign to the ecosystems they leave behind.

Current Practice	Future STEM-Driven Footwear Production
Traditionally, chemical compliance in footwear (like restricted substance lists or RSLs) focused heavily on consumer safety—ensuring that toxic chemicals don't leach onto a wearer's skin to cause rashes or toxicity.	Shoes are incredibly difficult to recycle because they are bound complexes of plastics, rubbers, and metals. When they sit in landfills, they weather and breakdown. Heavy rain leaches microplastics and additive chemicals into ground soil and marine ecosystems. Modern "STEM-driven" design looks at the entire life cycle, using predictive modelling to see how a shoe will chemically degrade over 10 to 50 years.
To make rubber durable and bouncy (vulcanization), the industry heavily relies on Zinc Oxide (ZnO) as an activator. When shoe soles wear down on pavement, microscopic rubber particles containing zinc are left behind, which wash into rivers and are highly toxic to aquatic life.	Green chemistry is actively replacing heavy metals with bio-activators (such as amino acid complexes, fatty acid derivatives, or plant-based lipids) to achieve the same structural performance without environmental toxicity.
Currently, factories test materials by sending random sample batches to external labs. This uses traditional methods like gas chromatography (GC-MS), which requires cutting up the shoe, dissolving it in harsh chemical solvents, and waiting days for a report. If a batch fails, entire shipments of shoes are already produced and wasted.	DART-MS (Direct Analysis in Real Time Mass Spectrometry) is a cutting-edge ambient ionization method. It allows technicians to literally point a gas stream at a solid piece of a shoe matrix, instantly vaporizing surface molecules to read their chemical signature in seconds—with zero sample preparation or destructive cutting.
Because footwear supply chains are highly fragmented across multiple tiers of global sub-contractors, polymer non-compliance (using cheaper, unapproved, or contaminated plastics/adhesives) has historically hovered around high margins like the ~18% cited.	Utilizing digital product passports (DPPs), data-driven supply chain transparency, and rigorous molecular tracking ensures that "recycled plastics" entering the factory aren't accidentally cross-contaminated with legacy toxins like phthalates or heavy metals.

Tab. 7: Comparison of Current Chemical Compliance Practices and Emerging STEM-Driven Approaches in Sustainable Footwear Manufacturing.

⁷⁶ Lavallo, R., Agnello, M., Mua, R., Fontana, M., Cravello, B., Piu, M., & Famele, M. (2025). Unveiling the Chemical Safety of Clothing Articles, Textiles and Footwear With Regard to the Presence of Carcinogenic, Mutagenic, or Reprotoxic Substances, Endocrine Disruptors and Skin Sensitizers Under EU Regulatory Restrictions. *Contact Dermatitis*, 93(6), 477-489.

6 Case study and Project Work

6.1 Case Study

6.1.1 Case Study: Development of a Smart Running Shoe

This case study presents a realistic future scenario for the footwear industry. To preserve confidentiality and avoid association with any specific company, the organisation name has been anonymised and used solely for illustrative purposes. It is intended to provide a practical business context from which further learning activities, research questions or assignments can be developed. It does not present a predefined solution or a complete product-development process.

6.1.2 Company Background

InnovStep is a medium-sized footwear company specializing in sports and lifestyle footwear. For many years, the company has successfully served recreational runners by offering affordable and comfortable products. However, increasing competition and changing consumer expectations are putting pressure on the company to explore new forms of innovation. In particular, digital technologies and personalized products are becoming more common in the sports industry.

To strengthen its market position, InnovStep is considering the development of a Smart Running Shoe. The concept involves integrating sensors into a running shoe to collect data about a runner's movement and provide personalized feedback through a mobile application. Potential information could include cadence, stride length, foot-strike patterns, pressure distribution and running speed. Management believes that such a product could create a unique selling proposition and appeal to technology-oriented consumers. At the same time, the company has limited experience with connected products and is uncertain whether the concept can be transformed into a commercially successful business.

6.1.3 Evaluating the Concept

To assess the opportunity, InnovStep has established a project team consisting of specialists from product development, engineering, data analytics, quality management, production and sustainability. The team's objective is to evaluate whether the Smart Running Shoe can provide meaningful customer value while remaining technically feasible and commercially attractive.

Early discussions have highlighted an important challenge: runners primarily buy shoes because of comfort, fit, cushioning and durability. Any digital functionality must therefore deliver clear benefits without compromising the core purpose of the product.

Several technologies are currently being explored. Motion sensors could record acceleration and movement patterns, while pressure sensors might capture information about foot loading during different phases of the running cycle. The collected data could potentially help users better understand their running style and identify opportunities for improvement. However, these data would need to be processed and translated into clear and understandable insights. This would require software development, data analysis capabilities and a reliable digital platform.

Engineers are simultaneously investigating how electronic components could be integrated into the shoe without negatively affecting comfort, weight or durability. Additional questions include power supply, wireless connectivity, data reliability and long-term product performance under real running conditions.

6.1.4 Manufacturing, Sustainability and Business Considerations

The project team is also examining how new technologies could influence future development and production processes. Additive manufacturing and digital prototyping could help reduce development time and decrease the number of physical samples required during product development. Automated quality-control technologies, such as machine vision systems, may further improve manufacturing consistency and product quality.

From a sustainability perspective, however, the picture is less clear. While digital development methods may reduce material waste during prototyping, electronic components can increase product complexity and create challenges regarding reparability, recycling and end-of-life management. New suppliers, additional materials and software-related requirements would also need to be considered.

Financial considerations represent another significant challenge. Developing a Smart Running Shoe would require investments in research, testing, software development, supplier qualification and potential production adjustments. As a result, the retail price would likely be higher than that of a traditional running shoe. Although market research indicates increasing consumer interest in digital products, management remains uncertain whether recreational runners would be willing to pay a sufficient premium to justify the additional investment.

6.1.5 The Decision

After six months of investigation, the project team presents its findings to senior management. The opportunity appears promising, but important questions remain unresolved. The Smart Running Shoe could strengthen InnovStep's position as an innovative footwear company and open new business opportunities. On the other hand, the project involves technical complexity, financial risk and sustainability challenges that cannot yet be fully assessed.

If you were a member of the InnovStep management team, would you proceed with the Smart Running Shoe project? Which factors should have the greatest influence on the final decision, and how would you balance innovation, customer value, sustainability and commercial success?

6.2 Structure of the project work

6.2.1 Innovation, Sustainability & Circularity Analysis in the Footwear Industry

1. Assignment Title

Critical Analysis of Technology-Driven Sustainability and Circular Economy Initiatives in the Footwear Industry Using adidas as a Case Study.

2. Assignment Purpose

This project assesses the understanding of innovative, technology-driven sustainability and circular economy initiatives in the footwear industry. Using adidas as a case study, students will analyse sustainability and circularity programs, technologies, and strategic initiatives implemented across the product lifecycle.

The main objective is to critically evaluate the effectiveness of these initiatives by identifying both successes and failures. Special attention is given to understanding why certain programs perform well, why others face limitations, and how technical, economic, organisational, and consumer-related factors influence outcomes in real industrial contexts.

3. Task Description

Students will analyse sustainability and circular economy initiatives within adidas, focusing on real-world implementation rather than theoretical concepts.

The work must include:

- a) Overview of sustainability and circular strategy
 - Summary of adidas sustainability goals
 - Circular economy pathway and key initiatives
- b) Detailed analysis of selected initiative:
Choose and analyse one of the adidas initiatives in detail, evaluating the following aspects:
 - Intended goals
 - Technologies used
 - Implementation approach
 - Real-world performance
 - Successes and limitations
 - Lessons learned from the initiative for future projects

4. Deliverables

Students must submit:

- Written analytical report/or presentation on adidas sustainability and circularity initiatives
- Case study analysis of selected innovation project
- Evaluation of successes and failures
- Sources and references for the used information
- Final critical reflection

5. Expected Learning Outcomes

Students will be able to:

- Understand how sustainability and circular economy initiatives are implemented in industry
- Critically evaluate the success and failure of innovation-driven programs
- Analyse technical, economic, and organisational constraints
- Interpret sustainability performance data and corporate reporting
- Develop evidence-based conclusions about real-world circular economy systems
- Understand the gap between sustainability ambition and practical implementation

6. Grading Criteria

Basic Assessment (100 Points)

Criterion	Description	Points
Understanding of Sustainability Strategy	Clear analysis of adidas sustainability and circularity approach	15
Initiative Analysis	Depth of analysis of selected programs	15
Success Evaluation	Ability to explain what aspect of the initiative succeeded	15
Failure / Limitation Analysis	Identification and explanation of weaknesses	15
Lessons learned	Ability to evaluate implication for future projects	10
Data Gathering	Providing references and sources of information	10
Clarity & Structure	Logical structure and academic readability	10
Presentation Quality	Visuals, tables, and communication clarity	10

Tab. 8: Grading Criteria

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8 References

- ABB Robotics. (2025, December 3). ABB robots help DESMA pioneer the future of automated footwear manufacturing. ABB News Center. <https://new.abb.com/news/detail/131559/cstmr-abb-robots-help-desma-pioneer-the-future-of-automated-footwear-manufacturing>
- adidas AG. (Retrieved June 1, 2026). adidas schließt den Produktlebenszyklus mit Futurecraft.Looped. <https://www.adidas-group.com/de/media/press-releases/adidas-schliesst-den-produktlebenszyklus-mit-futurecraftloop>
- American National Standards Institute. (n.d.). Industrial robots: Safety and production. ANSI Blog. <https://blog.ansi.org/ansi/industrial-robots-safety-production-ria/>
- Arsutoria Studio. (2025, December 15). Footwear 4.0: The platform for smart footwear manufacturing. <https://arsutoriastudio.com/en/footwear-4-0-the-platform-for-smart-footwear-manufacturing/>.
- Ashuach, A. (2021). Footwear time based design: Evolve IM biometric evolutionary footwear. Re-FREAM. <https://re-fream.eu/pioneers/footwear-time-based-design/>
- Aslam, M., Khan, T. M., Naqvi, S. S., Holmes, G., & Naffa, R. (2019). On the application of automated machine vision for leather defect inspection and grading: a survey. *IEEE Access*, 7, 176065-176086.
- Attard-Manche, A. (2018, November 12). Nike's 3D printing: Just do it. *Technology and Operations Management* (Harvard Business School / Harvard D³). <https://d3.harvard.edu/platform-rctom/submission/nikes-3d-printing-just-do-it/>
- Bai, J., Wu, D., Shelley, T., Schubel, P., Twine, D., Russell, J., ... & Zhang, J. (2025). A comprehensive survey on machine learning driven material defect detection. *ACM Computing Surveys*, 57(11), 1-36.
- Bodoga, A., Nistorac, A., Loghin, M. C., & Isopescu, D. N. (2024). Environmental impact of footwear using life cycle assessment—case study of professional footwear. *Sustainability*, 16(14), 6094.
- Borg, M., Mizzi, S., Farrugia, R., Mifsud, T., Mizzi, A., Bajada, J., & Falzon, O. (2025, July). An Investigation of Foot Temperature Deviations in Individuals with Diabetes: Insights from Wearable In-Shoe Technology. In 2025 47th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) (pp. 1-7). IEEE.
- Caiza, G., & Sanz, R. (2024). An immersive digital twin applied to a manufacturing execution system for the monitoring and control of industry 4.0 processes. *Applied Sciences*, 14(10), 4125.
- Carbon3D. (2024). Carbon Digital Light Synthesis (DLS) 3D printing technology. Carbon, Inc. <https://www.carbon3d.com/carbon-dls-technology>
- Castelli, K., Zaki, A. M. A., Dmytryiev, Y., Carnevale, M., & Giberti, H. (2020). A feasibility study of a robotic approach for the gluing process in the footwear industry. *Robotics*, 10(1), 6.
- ChemSec. (Retrieved June 1, 2026). SIN List. <https://sinlist.chemsec.org/>
- Chu, C. H., Chen, Y. A., Huang, Y. Y., & Lee, Y. J. (2022). A comparative study of virtual footwear try-on applications in virtual and augmented reality. *Journal of Computing and Information Science in Engineering*, 22(4), 041004.

Dias, P. A., Petry, M. R., & Rocha, L. F. (2024, September). The role of robotics: Automation in shoe manufacturing. In 2024 20th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA) (pp. 1-8). IEEE.

Ellen MacArthur Foundation & Granta Design. (2015). Circularity indicators: An approach to measuring circularity – Methodology. <https://content.ellenmacarthurfoundation.org/m/77e62bc9924c20d0/original/Circularity-Indicators-Methodology.pdf>

European Center for Constitutional and Human Rights. (Retrieved June 1, 2026). Baumwolle aus Xinjiang – Textilien Recherche. <https://www.ecchr.eu/pressemitteilung/baumwolle-xinjiang-textilien-recherche/>

European Chemicals Agency (ECHA). (2023). Forum enforcement project on chemicals in consumer products. https://echa.europa.eu/documents/10162/17086/ref-10_project_report_en.pdf/

European Commission, CINEA. (Retrieved June 1, 2026). Demonstration of a new business and consumption model for the circular economy in the footwear sector (LIFE19 ENV/ES/000118). LIFE Programme. <https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE19-ENV-ES-000118/demonstration-of-a-new-business-and-consumption-model-for-the-circular-economy-in-the-footwear-sector>.

European Commission. (n.d.). LIFE KANNAGreen: Demonstration of a new business and consumption model for the circular economy in the footwear sector (LIFE19 ENV/ES/000118). LIFE Programme. <https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE19-ENV-ES-000118/demonstration-of-a-new-business-and-consumption-model-for-the-circular-economy-in-the-footwear-sector>

European Commission. (Retrieved June 1, 2026). Safety Gate 2025 report. Publications Office of the European Union. <https://op.europa.eu/webpub/just/safety-gate-2025-report/en/>.

European Commission: Directorate-General for Research and Innovation, She figures 2024 – Gender in research and innovation – Statistics and indicators, Publications Office of the European Union, 2025, <https://data.europa.eu/doi/10.2777/592260>

Expo Riva Schuh and Gardabags. (2025, April 15). Artificial intelligence and the shoe business: The next industry revolution has already begun! <https://exporivaschuh.it/en/press-release-detail/artificial-intelligence-and-the-shoe-business-the-next-industry-revolution-has-already-begun>.

FashionUnited. (2024, February 13). Birkenstock opens community studio in London. <https://fashionunited.uk/news/fashion/birkenstock-opens-community-studio-in-london/2024021374088>.

Fibbl. (Retrieved June 1, 2026). Virtual try-on for footwear brands, <https://fibbl.com/experiences/virtual-try-on-for-footwear-brands/>

Fortune Business Insights. (Retrieved June 1, 2026). Smart shoes market, <https://www.fortunebusinessinsights.com/smart-shoes-market-106268>.

Huang, Y.-Y., Lai, J.-T., & Wu, H.-H. (2025). Real-time 3D vision-based robotic path planning for automated adhesive spraying on lasted uppers in footwear manufacturing. *Applied Sciences*, 15(11), 6365. <https://doi.org/10.3390/app15116365>.

Hunter, B., Greenhalgh, A., & Atack, A. C. (2026). Exploring undergraduate students' perceptions of biomechanics curricula: Are there gender differences?. *Journal of sports sciences*, 1-9.

Ingre-Khans, E., Rudén, C., & Breitholtz, M. (2010). Chemical risks and consumer products: the toxicity of shoe soles. *Ecotoxicology and Environmental Safety*, 73(7), 1633-1640.

Intech Vietnam. (n.d.). Automation in footwear production: The key to improving production capacity. <https://intechvietnam.com/news/tech-news/automation-in-footwear-production-the-key-to-improving-production-capacity-1455/>

International Federation of Robotics. (2026, April 8). Robot density surges in Europe, Asia, and Americas. <https://ifr.org/ifr-press-releases/news/robot-density-surges-in-europe-asia-and-americas>

International Organization for Standardization. (2021). Robotics — Vocabulary (ISO Standard No. 8373:2021). <https://www.iso.org/standard/75539.html>

Kean, C. O., Burton, S., Janssen, I., Brackley, V., & Atack, A. C. (2026). Empowering women in sports biomechanics: exploring the impact of mentor circles. *Sports Biomechanics*, 25(1), 135-149.

Kim, M. G., Kim, J., Chung, S. Y., Jin, M., & Hwang, M. J. (2022). Robot-based automation for upper and sole manufacturing in shoe production. *Machines*, 10(4), 255.

Kochan, Anna. "Actis and the shoe industry." *Assembly automation* 16.3 (1996): 30-31.

Lavalle, R., Agnello, M., Mua, R., Fontana, M., Cravello, B., Piu, M., & Famele, M. (2025). Unveiling the Chemical Safety of Clothing Articles, Textiles and Footwear With Regard to the Presence of Carcinogenic, Mutagenic, or Reprotoxic Substances, Endocrine Disruptors and Skin Sensitizers Under EU Regulatory Restrictions. *Contact Dermatitis*, 93(6), 477-489.

Lewin, M., Price, C., & Nester, C. (2023). Can a shoe-mounted IMU identify the effects of orthotics in ways comparable to gait laboratory measurements?. *Journal of Foot and Ankle Research*, 16(1), 54.

LOWA Sportschuhe GmbH. (Retrieved June 1, 2026). Umwelt & Klima. <https://lowa.com/de/erlebe-lowa/nachhaltigkeit/umwelt-klima>

Machine Learning and Data Analytics Lab. (retrieved 01.06.2026). Personalized running shoe recommendation using different data sources. Friedrich-Alexander-Universität Erlangen-Nürnberg. <https://www.mad.tf.fau.de/research/projects/personalized-running-shoe-recommendation-using-different-data-sources/>.

Mills, K., Mickle, K. J., Dixon, S., Sterzing, T., Denis, Y., Fu, F., ... & Chockalingam, N. (2026). Audit protocol for evaluating diversity in sport performance footwear research: Assessing footwear design, participant representation, and author demographics in published studies. *The Foot*, 66, 102213.

Minaoglou, P., Tzotzis, A., Efklidis, N., & Kyratsis, P. (2024). Integrating artificial intelligence into the shoe design process. *Engineering Proceedings*, 72(1), 7. <https://doi.org/10.3390/engproc2024072007>.

Next Kraftwerke GmbH. (Retrieved June 1, 2026). What does merit order mean? <https://www.next-kraftwerke.com/knowledge/what-does-merit-order-mean/>

Nof, S. Y. (Ed.). (1999). *Handbook of industrial robotics*. John Wiley & Sons.

- Oh, J. (2025). Towards cognitive collaborative robots: Semantic-level integration and explainable control for human-centric cooperation. arXiv preprint arXiv:2505.03815.
- Oliver, G., Gil, P., Gomez, J. F., & Torres, F. (2021). Towards footwear manufacturing 4.0: shoe sole robotic grasping in assembling operations. *The International Journal of Advanced Manufacturing Technology*, 114(3), 811-827.
- On. (2026, April 20). On brings its LightSpray™ technology to London with an immersive public experience at the height of running season. On Pressroom. <https://press.on-running.com/-1wgx4h>.
- Ortiz-de-Montellano, C. G. S., Ghannadzadeh, A., & 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. *Journal of Circular Economy*, 3(3).
- REACH Compliance Data Centre. (Retrieved June 1, 2026). Regulation (EC) No 1907/2006 (REACH). <https://reach-compliance.eu/english/legislation/docs/launchers/launch-2006-1907-EC.html>
- Reeman Robot. (15. June 2026). How much does an industrial robotic arm cost? Complete pricing guide. <https://reemanbot.com/posts/how-much-does-an-industrial-robotic-arm-cost-complete-pricing-guide>
- Richter, F. (2026, September 24). Rise of the robots [Infographic]. Statista. <https://www.statista.com/chart/26210/operational-stock-of-industrial-robots/International>
- Federation of Robotics. (2026). Industrial robots. <https://ifr.org/industrial-robots>
- Roberts-Islam, B. (2026, May 18). Footwear production is broken. So are our feet. Can 3D print fix both? *Forbes*. <https://www.forbes.com/sites/brookerobertsislam/2026/05/18/footwear-production-is-broken-so-are-our-feet-can-3d-print-fix-both/>
- Salomon. (Retrieved June 1, 2026). Change through innovation. <https://www.salomon.com/en-us/lp/g/sustainability-innovation>
- Salomon. (Retrieved June 1, 2026). Introducing the Index.01 recyclable running shoe. <https://www.salomon.com/en-nl/sg/a/introducing-the-index-01-recyclable-running-shoe>
- Sanitätshaus Kocher GmbH. (Retrieved June 1, 2026). 3D-Einlagen. <https://sanitaetshaus-kocher.de/orthopaedie-schuhtechnik/3d-einlagen/>
- Sattler, B. J., Tundis, A., Friesen, J., & Pelz, P. F. (2024). Modeling water availability during a blackout under consideration of uncertain demand response. *Engineering Proceedings*, 69(1), 130. <https://doi.org/10.3390/engproc2024069130>.
- Siemens AG. (Retrieved June 1, 2026). Manufacturing process planning. <https://www.siemens.com/en-us/solutions/manufacturing-process-planning/>
- Sneakprint GmbH. (Retrieved June 1, 2026). Sneakprint. <https://sneakprint.me/>
- Špelić, I., Mihelić-Bogdanić, A., & Budin, R. (Retrieved June 1, 2026). Optimization of energy savings in the shoe sole production process. <https://hdko.hr/optimizacija-energetskih-usteda-u-procesu-proizvodnje-potplata-za-cipele-2/>
- Tejani, S., & Kucera, D. (2024). The Effects of Automation in the Apparel and Footwear Industries and Their Gender Dimensions: Indonesia Case Study. International Labour Organization.

Transitions Project. (retrieved 2026, June 1). Digital twin <https://transitionsproject.eu/digitalisation-2/digital-twin/>.

TÜV Rheinland. (Retrieved June 1, 2026). Restricted Substances List Whitepaper. <https://www.tuv.com/content-media-files/master-content/services/products/0211-tuv-rheinland-retail-services/tuv-rheinland-restricted-substances-list-whitepaper-en.pdf>.

U.S. Consumer Product Safety Commission. (Retrieved June 1, 2026). The Consumer Product Safety Improvement Act. <https://www.cpsc.gov/Regulations-Laws--Standards/Statutes/The-Consumer-Product-Safety-Improvement-Act>.

U.S. Department of Labor, Bureau of International Labor Affairs. (Retrieved June 1, 2026). Against Their Will: The Situation in Xinjiang. <https://www.dol.gov/agencies/ilab/against-their-will-the-situation-in-xinjiang>.

van Schooten, K. S., David, S., & Diamond, L. E. (2023). Women in Biomechanics and Control of Human Movement: 2022–2023. *Frontiers in Sports and Active Living*, 5, 1337636.

VDI 2860:1990–05, Montage- und Handhabungstechnik; Handhabungsfunktionen, Handhabungseinrichtungen; Begriffe, Definitionen, Symbole

Vogel Communications Group GmbH & Co. KG/ ABB Press Release. (2026, February 2). ABB robots and DESMA are shaping the future of automated shoe production. <https://www.all-about-industries.com/abb-robots-shape-the-future-of-automated-shoe-production-a-c3c4ede7486dfaf08900ecaa49b12b52//>

WANNA. (Retrieved June 1, 2026). Virtual try-on., from <https://wanna.fashion/virtual-try-on/>

Wright, O. (2023, September 21). How do adidas 3D printed midsoles hold up after a year of use? 3DPrint.com. <https://3dprint.com/303434/how-do-adidas-3d-printed-midsoles-hold-up-after-a-year-of-use/>.

Yang, Y. I., Yang, C. K., & Chu, C. H. (2014). A virtual try-on system in augmented reality using RGB-D cameras for footwear personalization. *Journal of Manufacturing Systems*, 33(4), 690-698.

Young, F., Mason, R., Wall, C., Morris, R., Stuart, S., & Godfrey, A. (2022). Examination of a foot mounted IMU-based methodology for a running gait assessment. *Frontiers in Sports and Active Living*, 4, 956889.

Zakeke. (2023, May 15). The future of footwear: AR shoes. Abgerufen am 1. Juni 2026, von <https://www.zakeke.com/blog/the-future-of-footwear-ar-shoes/>.

Zetamotion. (n.d.). Automated visual inspection for shoes and footwear. Retrieved September 29, 2026, from <https://zetamotion.com/product/shoes-and-footwear/>

Zrenner, M., Ullrich, M., Zobel, P., Jensen, U., Laser, F., Groh, B. H., ... & Eskofier, B. M. (2018, March). Kinematic parameter evaluation for the purpose of a wearable running shoe recommendation. In 2018 IEEE 15th international conference on wearable and implantable body sensor networks (BSN) (pp. 106-109). IEEE.