ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

FOOTWEAR UNDER THE IMPACT OF DIGITAL TECHNOLOGIES: A REVIEW

TRIPA Florin Marin[1]

[1] Doctoral School of Engineering Sciences, University of Oradea, 1 Universitatii str., 410087 Oradea, Romania, E-Mail: florintripa@yahoo.com

Corresponding author: Tripa, Florin Marin, E-mail: florintripa@yahoo.com

Abstract: *Digital technologies have had a major impact on the footwear industry, transforming both the design and manufacturing processes. The advanced use of 3D scanning and computer modelling allows the creation of customised footwear that is precisely tailored to the specific dimensions, shape and needs of each user. In production, vibration sensors integrated into machines and connected via IoT platforms enable real-time monitoring, enabling rapid detection of problems and predictive maintenance to minimise downtime and repair costs. In addition, analysis of the data collected helps to optimise production parameters, ensuring greater operational efficiency. IoT technologies also play a crucial role in intelligent supply chain management, facilitating real-time tracking of raw materials, inventory and deliveries, leading to reduced losses and improved logistical coordination. Throughout the use of footwear, digital technologies offer significant improvements in comfort, performance and monitoring of the user's health. Sensors integrated into the structure of footwear allow gait analysis, monitoring pressure on the sole and detecting potential postural or medical problems. In addition, digital technologies contribute to user safety by being used to develop smart shoes for people with visual impairments or to prevent accidents in the workplace. By integrating these innovations, the footwear industry is moving towards more sustainable and efficient production, offering more comfortable and safer products that are tailored to the individual needs of each user.*

Key words: *footwear, design, production, innovation, digital technologies*

1. INTRODUCTION

Digital technologies have revolutionised the footwear industry in many ways. The most notable applications include CAD system, 3D printing, process automation and the use of robots, Internet of Things (IoT), the integration of sensors and smart devices, the use of augmented reality (AR) and virtual reality (VR).

Digital technologies have had a profound impact on the industry, changing the way footwear products are designed and manufactured. They have also had a significant impact on the way footwear is used, bringing improvements in comfort, performance and monitoring.

Digital technologies such as 3D scanning and computer modelling make it possible to create customised footwear that perfectly fits the shape and needs of each user. These technologies help to improve comfort and prevent injuries. 3D scanning allows the foot shape to be accurately captured, while computer modelling facilitates pattern adjustments for a perfect fit.

The integration of sensors and smart devices makes it possible to monitor user performance by collecting data on steps, distance travelled, speed and running form. This information is transmitted

to mobile applications, allowing athletes to analyse their performance and adjust their training. Sensors can also detect and analyse foot movements, providing real-time feedback to improve recovery techniques for various conditions.

Digital technologies are used at all stages of the footwear lifecycle, from design to use.

The main objective of this paper is to analyse and highlight the impact of digital technologies on the footwear industry. The study examines how various digital technologies have revolutionised the design, production and use of footwear products.

The methods of scientific research used in the paper are scientific analysis and literature review. The use of digital technologies in the footwear industry is presented separately for each stage that the product goes through, from design to use.

2. USE OF DIGITAL TECHNOLOGIES IN FOOTWEAR

2.1. The use of digital technologies in footwear product design

Computer-aided design (CAD) has transformed the footwear design process by offering advanced tools that enable designers to create, visualize, and perfect their footwear concepts with greater efficiency and precision.

Various researchers have introduced innovative methods and software to improve various aspects of footwear design. For example, Davia-Aracil et al. developed a methodology for the design and validation of shoe soles focusing on structural and functional aspects to meet international safety standards [1]. Luximon and Luximon developed shoe last design software that allows real-time modifications based on foot shape measurements, improving design efficiency and user comfort [2]. Leshchyshyn et al. introduced a method for designing shoe soles with an artistic approach, improving design efficiency and simplifying manufacturing [3] and Luo et al. improved the foot-leg relationship through an integrated design system using database technology for precise fitting [4]. All of these innovations streamline design and manufacturing processes, improve product quality and enhance user comfort and sustainability.

Currently, AI has revolutionised footwear design through automated design assistance. Generative design software enables AI algorithms to rapidly create multiple design prototypes, optimising various parameters of footwear products. This approach simplifies the design phase and ensures that the final products are tailored to the specific needs and preferences of consumers.

An example of this is Adidas, which has applied AI to footwear design by developing the Futurecraft 4D programme. By using Carbon's Digital Light Synthesis (DLS) technology to create high-performance shoe soles, Adidas has created customised soles that are tailored to each athlete's needs in terms of movement, cushioning, stability and comfort. DLS technology enables the production of high-performance footwear at scale and speed, eliminating the need for traditional prototypes or moulds [5].

Another example is Nike, which leverages computer vision, machine learning, data science, and augmented reality to scan customers' feet using a smartphone camera. This process generates a precise 3D model of the foot, enabling accurate shoe size recommendations that enhance customer satisfaction and significantly reduce return rates [6].

Kim et al. have proposed the use of Digital Twins for customized footwear design. Their research shows how Digital Twins can be used to create virtual models of customers' feet, enabling accurate measurements and personalised shoe designs. This approach not only improves fit and comfort, but also reduces the need for physical prototypes, speeding up the design process [7].

3D printing is another example of how digital technologies are being applied to footwear

design. Under Armour has used this technology to create the ArchiTech Futurist, an innovative athletic shoe. This model features a 3D printed midsole that forms a lattice structure to provide optimal cushioning and support [8].

The choice of materials is also crucial in the design phase. Innovations in footwear materials, such as Adidas' Boost technology, offer high-performance cushioning and lightweight, breathable fabrics. These technologies improve the comfort and performance of footwear, making it suitable for a range of sports from running to basketball [9].

In addition, the incorporation of sensors into various parts of the shoe is considered at the design stage. For example, the Nike HyperAdapt 1.0 features pressure sensors embedded in the soles that detect the insertion of the foot and trigger an algorithm to automatically tighten the laces. The shoe also has built-in LEDs that alert the user to low battery levels or a tight fit [10].

New applications of AI will continue to revolutionise the footwear industry by enabling fully customised shoe design through automated assistance. Design software will allow AI algorithms to quickly generate multiple design prototypes, simplifying the design phase and ensuring that the final products are tailored to consumers' specific needs and preferences [11].

2. 2. The use of digital technologies in the footwear production chain

The traditional shoe manufacturing process is labour intensive and involves many manual operations. Therefore, many studies have been conducted on automation in the footwear industry, focusing on robot-based automation. Various methods have been proposed to automate different operations in the shoe manufacturing process. Kim et al. proposed a new robot-based shoe manufacturing system for the upper manufacturing and sole application processes [12]. Oliver et al. propose a robotic cell to automate operations such as sole digitisation, glue application and sole manipulation at different locations in the factory [13]. Molinari-Tosatti and Fassi presented an industrial prototype with roughing and cementing tools [14]. Pedrocchi et al. took a different approach to roughing uppers by designing a fuzzy logic controller [15]. Nemec et al. developed a shoe polishing cell using an industrial robot [16]. Castelli et al. showed how to automate the gluing process and Kim J.Y. proposed an automated glue spraying system [17,18]. Gracia et al. have proposed the automation of the shoe packaging process using a robot [19].

Another directive for using digital technologies in footwear production refers to incorporating vibration sensors into production equipment and interconnecting them through Internet of Things (IoT) platforms, allowing continuous real-time monitoring.

This integration facilitates comprehensive data collection, enhancing predictive maintenance capabilities. IoT platforms enable remote monitoring and data analysis, providing insights into the health and performance of equipment. These platforms are also particularly useful for the optimisation of production activities and efficient supply chain management.

Modern sensors have been developed to be more sensitive and reliable, with the capacity to detect even the most subtle vibrations. These advancements have enhanced the accuracy of the data and the efficiency of fault diagnosis, leading to more effective vibration analysis [20].

Innovations such as wireless sensors have been introduced, eliminating the need for extensive wiring and simplifying installation and maintenance. The utilisation of these sensors within the context of footwear production facilitates enhanced product quality by facilitating the detection of mechanical issues in manufacturing equipment and the resolution of these issues prior to their impact on production. This, in turn, ensures consistent product quality.

Furthermore, the implementation of continuous vibration monitoring has been shown to reduce downtime, thereby ensuring the maintenance of a steady production flow and averting delays

in product delivery [21].

It is widely acknowledged that vibration analysis facilitates the implementation of predictive maintenance, optimising resource utilisation and reducing costs associated with reactive or preventive maintenance. The maintenance of equipment in optimal working condition has also been demonstrated to contribute to a reduction in energy consumption and associated costs.

Furthermore, the identification and resolution of mechanical issues prior to their escalation, as facilitated by vibration analysis, results in the prolongation of production equipment lifespan, thereby diminishing the necessity for recurrent investments in new machinery. The early detection of mechanical failures has been shown to reduce the risk of accidents and to ensure a safer work environment for employees, as properly functioning equipment is less likely to cause hazardous incidents [22].

The employment of sophisticated algorithms facilitates the identification of vibration patterns and trends. Comparisons of this data with established standards can facilitate the identification of anomalies and potential issues. The utilisation of advanced data analytics tools facilitates the rapid processing of substantial data volumes, thereby providing real-time insights into the health status of equipment [23]. AI algorithms can analyse large datasets to identify subtle patterns that indicate potential problems. Machine learning models can predict equipment failures by learning from historical vibration data. This enables more accurate maintenance predictions and recommendations, facilitating proactive interventions. AI-driven analytics can also optimize maintenance schedules, reducing downtime and maintenance costs.

A notable proponent of integrating AI and IoT to enhance various operational facets, including customer experience and supply chain management, is Nike. The integration of IoT sensors and AI algorithms has enabled the company to predict product demand, optimise inventory, and enhance the accuracy of shoe fitting recommendations through AI-powered applications. This holistic approach has resulted in enhanced service quality and operational efficiency [24].

In addition, Nike employs predictive analytics and machine learning algorithms to analyse extensive datasets pertaining to consumer behaviour and market trends. This enables the company to dynamically adjust its supply chain, thereby maintaining optimal stock levels, reducing overproduction, and minimising unsold inventory. This real-time responsiveness facilitates more efficient delivery of products to retailers and consumers [6].

Allbirds, a footwear company, successfully transformed a complex, multi-store, multi-country supply chain into a globally connected supply chain by partnering with ChannelApe. This was achieved by managing the supply chain through a single unified fulfilment platform. This integration enabled Allbirds to manage order fulfilment across multiple facilities more efficiently, saving time and resources that could then be redirected towards brand growth [25].

A study by Casais and Caldas on the digital transformation of the Portuguese footwear industry highlights how small and medium-sized enterprises (SMEs) have adopted the IoT and other digital technologies. These innovations have enabled SMEs to transition from traditional production to a more export-driven and innovative industry. The integration of the IoT has been identified as playing a pivotal role in the enhancement of production processes and supply chain management [26].

Research has also explored how Digital Twins can simulate and optimize manufacturing processes, from material selection to final assembly. By creating virtual replicas of production lines, companies can identify bottlenecks, predict maintenance needs, and improve overall efficiency. The shift from traditional sketches to digital prototypes not only streamlines the design process but also contributes to building a more sustainable fashion ecosystem [27].

The utilisation of Edge computing in the domain of footwear manufacturing has the potential

to enhance the process of production by facilitating real-time monitoring and quality control. Specifically, sensors integrated within manufacturing equipment can collect data on parameters such as temperature, pressure, and vibrations. These data are then processed to detect any anomalies and ensure that the manufacturing process meets the relevant quality standards. A study on edge computing in manufacturing highlights how this approach can reduce latency and improve decision-making on the production line [28].

2. 3. The use of digital technologies during the footwear usage period

The utilisation of digital technologies during the footwear usage period is chiefly concerned with personalised health monitoring and assistive technologies.

Wireless monitoring systems are utilised for data collection, with the capacity to transmit data to central databases for analysis. This facilitates remote monitoring and diagnosis.

Technologies like Bluetooth facilitate wireless data collection and transmission, incorporating features such as GPS tracking, obstacle detection, and physical activity monitoring. For instance, smart shoes can monitor diabetic foot ulcers, assess rehabilitation progress, and detect falls in elderly individuals [29].

Smart shoes embedded with accelerometers, gyroscopes, and pressure sensors allow for precise gait and posture analysis. These data are essential for the correction of posture and the improvement of gait, benefiting both sports performance and medical rehabilitation [30].

Through gait and mobility analysis, smart shoes can aid in the prevention, diagnosis, and treatment decisions for various conditions, or enable individualized disease monitoring [31].

Duan et al. patented an intelligent monitoring and protection system for individuals at risk of diabetic foot ulcers. This system incorporates smart shoes connected to an intelligent terminal device via a wireless connection. The shoes are equipped with a main control module that continuously monitors temperature and pressure to assess ulcer risk. Alerts are generated for both users and healthcare professionals when the risk is high, facilitating early intervention and personalised patient care [32].

Another patent discloses an integrated smart electronic system in footwear, designed to alert workers to nearby objects at night or in dark environments on construction sites. The system incorporates logic circuits that receive signals from a proximity sensor, thereby generating input signals to a wireless transmitter. The system has been developed to prevent accidents by warning workers about nearby obstacles, thereby improving construction site safety [33].

An innovative safety system for visually impaired individuals has been developed, based on the IoT technology. This system integrates smart shoes equipped with three ultrasonic sensors, a microprocessor, water and flame sensors, and GPS technology to detect obstacles and alert users through sound notifications. The system has been developed to assist visually impaired individuals in navigating construction sites safely, without colliding with objects or other people [34].

Sensors embedded in sports shoes record key metrics for runners, including pace, distance, step count, stride length, and cadence. These data can be wirelessly transmitted, facilitating precise performance evaluation and enhancing the efficacy of training sessions [35].

The utilisation of shoe sensors facilitates the provision of personalised feedback on health, fatigue, posture, steps, speed, distance, calories burned, sleep duration, and even weight. By connecting to a device via Bluetooth or through custom applications, real-time personalised coaching becomes possible. Examples of such technology include Digitsole Smart Shoes and Xiaomi MiJia Smart Shoes [10].

The integration of sensors in footwear has also been successfully used for patient monitoring

during rehabilitation treatments. This technology facilitates continuous measurement and recording of ankle movements during physical therapy, thereby enhancing patient care by providing real-time and precise information about foot conditions [36,37].

3. CONCLUSIONS

Digital technologies have had a profound impact on all stages of the footwear industry's product lifecycle, encompassing design, production, usage, and monitoring.

The integration of artificial intelligence, three-dimensional scanning, and three-dimensional printing has profoundly transformed the design process, facilitating the development of personalised and ergonomic products. Technologies such as Digital Twins and augmented reality have optimised shoe fit and comfort, reducing the need for physical prototypes. The integration of innovative materials and sensors within the footwear structure has also been instrumental in enhancing user performance and safety.

Robot-based automation has brought significant improvements to footwear production, reducing intensive manual labour. Various methods have been proposed to automate different operations in the shoe manufacturing process, including packaging.

In the production process, the implementation of IoT sensors and vibration analysis of manufacturing equipment allows for the execution of predictive maintenance. This contributes to cost reduction and enhanced economic efficiency. The application of edge computing and AI has been demonstrated to enhance supply chain management, optimise production processes, and reduce waste.

The integration of embedded sensors into footwear products, along with their wireless connectivity to diverse applications, facilitates the real-time monitoring of user performance and health parameters. Gait analysis applications and parametric monitoring of physical activities provide athletes and patients with real-time feedback, helping to enhance training and rehabilitation processes. Innovations in this field have a significant impact on health, safety and comfort, and are applied in areas such as the prevention of diabetic ulcers and assistance for visually impaired individuals.

Digital technologies are poised to transform the footwear industry, ushering in a new era of sustainable production, enhanced user comfort, and personalised experiences.

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