INTEGRATION OF INNOVATIVE TECHNOLOGIES IN VARIOUS STAGES OF FOOTWEAR DESIGN AND MANUFACTURING

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ABSTRACT. The article analyzes process innovation in the footwear industry through the integration of digital technologies and additive manufacturing, with the aim of streamlining production and promoting sustainability. The paper documents the transition from traditional methods to an innovative workflow, which begins with concept sketches and continues with parametric design in Rhinoceros software. A central aspect is the ecological approach, through the proposal of biocomposites based on thermoplastic polymers and natural fiber waste, compatible with FDM 3D printing technology. The practical results of the research include the development of 10 concept sketches and the digital design of 17 component elements, including six sole models, six heel models, and five complete shoe models (upper and sole assembly). It is concluded that this synergy between 3D scanning, computational design, and sustainable materials enables enhanced customization and a significant reduction in production time, offering advanced solutions for the niche industry and the circular economy. The objectives of this paper are to document and clarify aspects of footwear design and manufacturing through the use of new technologies.

KEYWORDS: footwear, concept sketches, design, 3D printing

INTEGRAREA TEHNOLOGIILOR INOVATOARE ÎN DIVERSE ETAPE ALE PROIECTĂRII ȘI FABRICAȚIEI DE ÎNCĂLȚĂMINTE

REZUMAT. Articolul analizează inovarea proceselor din industria de încălțăminte prin integrarea tehnologiilor digitale și a fabricării aditive, vizând eficientizarea producției și promovarea sustenabilității. Lucrarea documentează trecerea de la metodele tradiționale la un flux de lucru inovator, ce pornește de la schițe de concept și continuă cu proiectarea parametrică în software-ul Rhinoceros. Un aspect central îl reprezintă abordarea ecologică, prin propunerea unor biocompozite pe bază de polimeri termoplastici și deșeuri de fibre naturale, compatibile cu tehnologia de imprimare 3D prin metoda FDM. Rezultatele practice ale cercetării includ elaborarea a 10 schițe concept și proiectarea digitală a 17 elemente componente, printre care se numără șase modele de tălpi, șase modele de tocuri și cinci modele complete de încălțăminte (ansamblu față și talpă). Se concluzionează că această sinergie între scanare 3D, design computațional și materiale sustenabile permite o personalizare accentuată și o reducere semnificativă a timpului de execuție, oferind soluții avansate pentru industria de nișă și economia circulară. Obiectivele lucrării sunt documentarea și clarificarea aspectelor privind proiectarea și fabricarea încălțămintei prin utilizarea noilor tehnologii.

CUVINTE CHEIE: incaltaminte, schite de idee, proiectare, imprimare 3D

INTÉGRATION DE TECHNOLOGIES INNOVANTES AUX DIFFÉRENTES ÉTAPES DE LA CONCEPTION ET DE LA FABRICATION DE CHAUSSURES

RÉSUMÉ. Cet article analyse l'innovation des processus dans l'industrie de la chaussure grâce à l'intégration des technologies numériques et de la fabrication additive, dans le but d'optimiser la production et de promouvoir la durabilité. Il documente la transition des méthodes traditionnelles vers un flux de travail innovant, qui commence par des esquisses conceptuelles et se poursuit par la conception paramétrique dans le logiciel Rhinoceros. Un aspect central est l'approche écologique, à travers la proposition de biocomposites à base de polymères thermoplastiques et de déchets de fibres naturelles, compatibles avec la technologie d'impression 3D par la méthode FDM. Les résultats concrets de la recherche comprennent l'élaboration de 10 esquisses conceptuelles et la conception numérique de 17 éléments composants, parmi lesquels figurent six modèles de semelles, six modèles de talons et cinq modèles complets de chaussures (ensemble tige et semelle). Il est conclu que cette synergie entre la numérisation 3D, la conception assistée par ordinateur et les matériaux durables permet une personnalisation accrue et une réduction significative des délais de fabrication, offrant des solutions avancées pour l'industrie de niche et l'économie circulaire. Les objectifs de ce travail sont de documenter et de clarifier les aspects liés à la conception et à la fabrication de chaussures grâce à l'utilisation des nouvelles technologies.

MOTS-CLÉS : chaussures, esquisses conceptuelles, conception, impression 3D

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INTRODUCTION

The current landscape of the footwear industry is marked by an accelerated transition toward digitalization, where the integration of innovative technologies is becoming the cornerstone of footwear manufacturing. The use of parametric design and emerging technologies opens new horizons in the optimization of complex geometries, enabling the development of products that meet consumers' individual needs. The need to reduce production times, operational costs, and raw material consumption, alongside sustainable waste management, necessitates moving away from conventional methods in favor of modern, digitized manufacturing processes.

The evolution of consumer preferences, with a desire for greater customization and active involvement in product configuration, has led to a profound shift in design practices. While traditional methodologies have long ensured production stability, their limitations in terms of adaptability are giving way to algorithmic design [1]. This new paradigm not only overcomes the geometric barriers of classic forms but also maximizes the potential of cutting-edge technologies, offering solutions tailored to the user's physical and morphological characteristics (precise dimensions, ergonomics, aesthetic options).

3D scanning plays a significant role in customizing footwear by accurately capturing the anthropometric characteristics of the user's foot. The data obtained allows the product's geometry to be adapted to the individual dimensions and characteristics of the foot, reducing pressure points and improving load distribution during walking. Compared to systems based on standardized sizes, this approach leads to a better fit, increased comfort, and improved ergonomics, reducing the risk of discomfort or deformities caused by ill-fitting footwear. Integrating 3D scanning data into the digital design process thus enables the development of customized products tailored to the functional and anatomical needs of each user.

The future of footwear development is defined by the synergy between 3D scanning, digital knitting, sensor technology, and 3D printing [2–8]. 3D printing, in particular, facilitates the production of highly complex structures that are impossible to create using traditional methods such as casting, while also ensuring greater automation and increased cost-effectiveness [2–5]. Complementarily, 3D scanning enables the precise digitization of anthropometric data, which is essential for customized design, reducing human error and providing virtual models that can be validated through durability simulations as early as the design phase [8].

In footwear production, the traditional manufacturing process consists mainly of design, pattern making, cutting, sewing, and sole attachment and finishing. The entire production process is time-consuming and highly complex. Combining 3D modeling technology with 3D printing technology can rapidly produce footwear, thereby reducing time and enhancing the competitiveness of footwear companies [9–11].

The use of 3D software and technology for footwear modeling allows for the creation and modification of footwear shapes in accordance with design requirements. Some products have complex shapes, and 3D modeling technology can be used to improve their design. 3D modeling technology is necessary to integrate fashion elements more quickly and effectively [12, 13].

Thus, processing technology appears to play a significant role in footwear production in modern society and is a realistic and important driving force in its development and advancement, capable of effectively propelling the footwear industry forward.

The main objectives of this scientific paper are to document and clarify aspects related to the design and manufacture of footwear using new technologies.

EXPERIMENTAL

Materials and Methods

Product design methodology is defined as the steps followed by a designer or design team to create a new product [14]. Aesthetics and ergonomics begin to take shape during these stages and continue through the end of the process [15].

Proper management and execution of the initial stages play a crucial role, as they save time and resources and yield improved solutions without having to restart the process.

We start with concept sketches; then, in the subsequent stages of the process, the design is carried out using a CAD (Computer-Aided Design) system; finally, a prototype will be created using 3D printing.

Environmental concerns and cost reduction, as well as the implementation of circular economy and bioeconomy principles, etc., for the sustainable use of natural resources, have led to the need to develop new generations of materials. Manufacturers of polymer composites are seeking alternatives to optimize and replace traditional products with new ones containing a high proportion of bio-based, recyclable, or compostable materials, in the interest of sustainability and responsible practices.

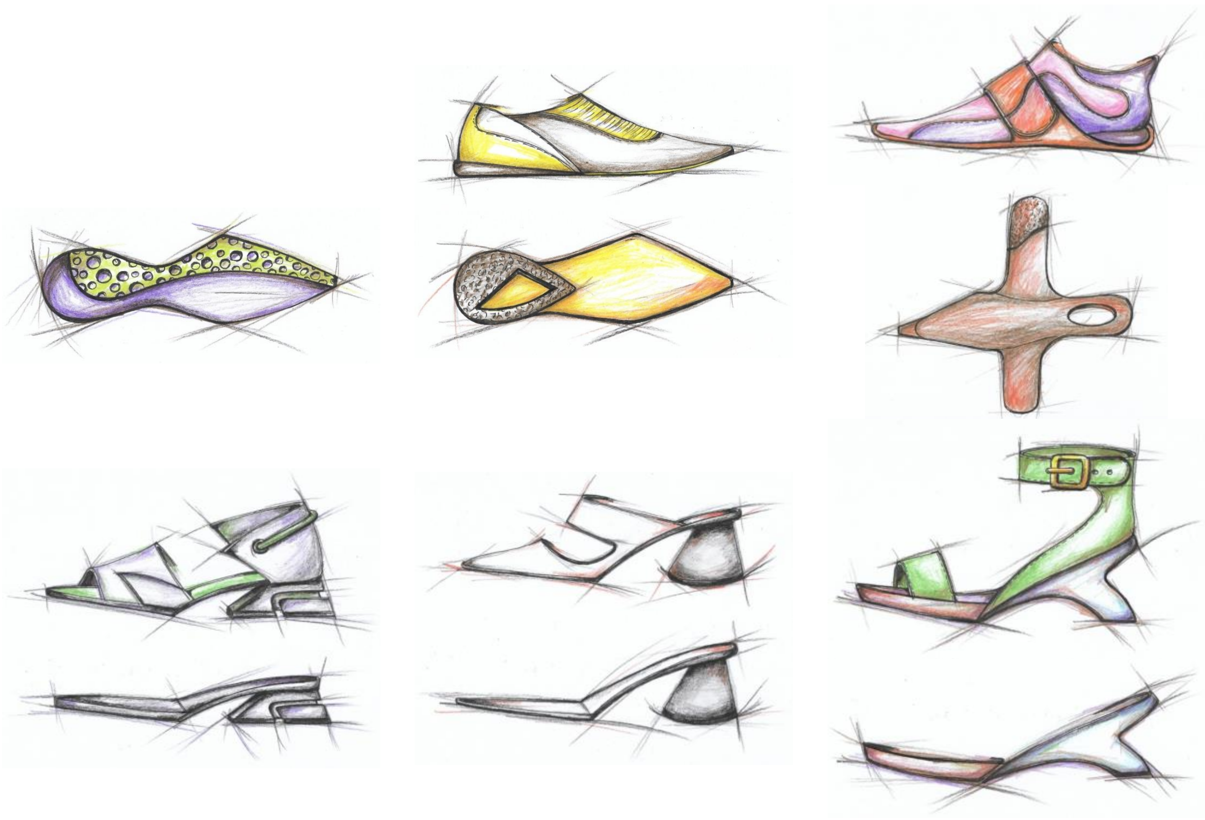
The materials to be used in 3D printing via the FDM (Fused Deposition Modeling) method are biocomposites based on thermoplastic polymers (such as TR-SBS, TPU, PLA) and natural fiber waste functionalized through melt blending. The TPU-, PLA-, and TR-SBS-based biocomposites used for FDM printing provide a balance between flexibility, mechanical strength, and low weight. TPU provides elasticity and shock absorption, PLA offers rigidity and dimensional stability, and TR-SBS provides wear resistance and flexibility. The addition of natural fibers helps increase stiffness and reduce material density, resulting in lighter and more sustainable footwear components without compromising functional performance.

RESULTS AND DISCUSSIONS

Concept Sketches

Concept sketches are a graphical representation of the product and an essential tool in all phases of the design process and in all its forms.

Ten concept sketches of footwear products were developed (Fig. 1), whose components (soles, heels) can be produced using 3D printing.



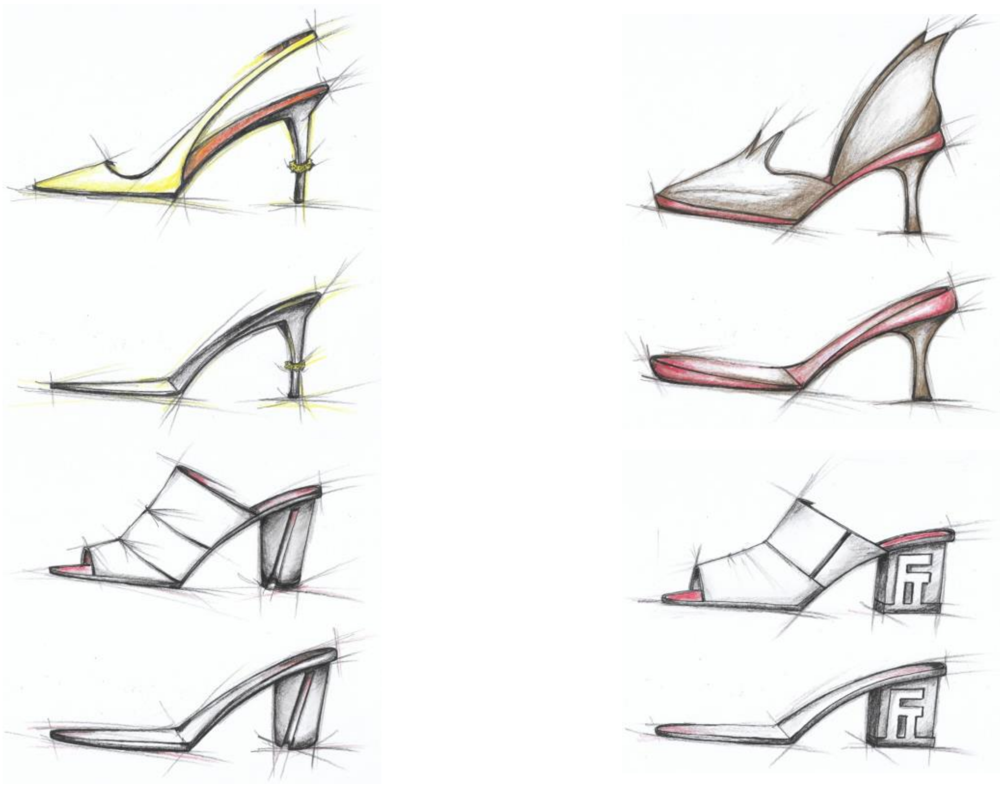


Figure 1. Concept sketches of footwear (*Dsg. Traian Foiasi*)

3D Design

CAD/CAM systems represent the new generation of computer-aided design and engineering solutions in the footwear industry. Starting from a last model, a complete footwear model can be quickly created in any combination of colors or textures. The result is a realistic 3D visualization of the product, ideal for presentations to buyers and manufacturers.

Computational design uses algorithms and computational tools to optimize design processes, facilitating rapid prototyping and iteration. By harnessing the power of computation, designers can explore complex design spaces, leading to innovative solutions that might not be feasible using traditional methods alone. Computational design plays a significant role in footwear design, revolutionizing the way shoes are created and manufactured.

Compared to traditional CAD workflows, where modifying geometric parameters typically requires repeated manual interventions on the model, computational design algorithms allow for the automatic updating of the entire geometry by modifying a small number of variables. This parametric approach significantly reduces the time required for product development and optimization, as the designer can quickly generate and evaluate multiple design variants without having to completely remodel the components. In the case of footwear, algorithms enable the instant adjustment of dimensions, thicknesses, lattice structures, and ergonomic features based on user requirements or data from 3D scans. Furthermore, integrating algorithmic design with digital simulation and 3D printing reduces the number of physical prototypes needed for validation, thereby lowering material consumption and the costs associated with the development process. As a result, efficiency is improved both by shortening design and testing cycles and by increasing flexibility in product customization.

The design of the component elements of the footwear models was carried out using Rhinoceros, a computer graphics and computer-aided design (CAD) software. The software is based on a mathematical model that focuses on producing an accurate representation of the curves and surfaces of free-form shapes in computer graphics. Rhinoceros can be used for computer-aided design (CAD), computer-aided manufacturing (CAM), rapid prototyping, 3D printing, industrial design (e.g., automotive design, boat design), product design (e.g., footwear design, jewelry design), as well as multimedia and graphic design [16]. Rhinoceros offers compatibility with other software, as it supports over 30 CAD file formats for import and export [17].

Thus, 17 components of footwear products were designed:

- ✓ six models of flat soles, based on the concept sketches of footwear previously presented (Fig. 2–4);

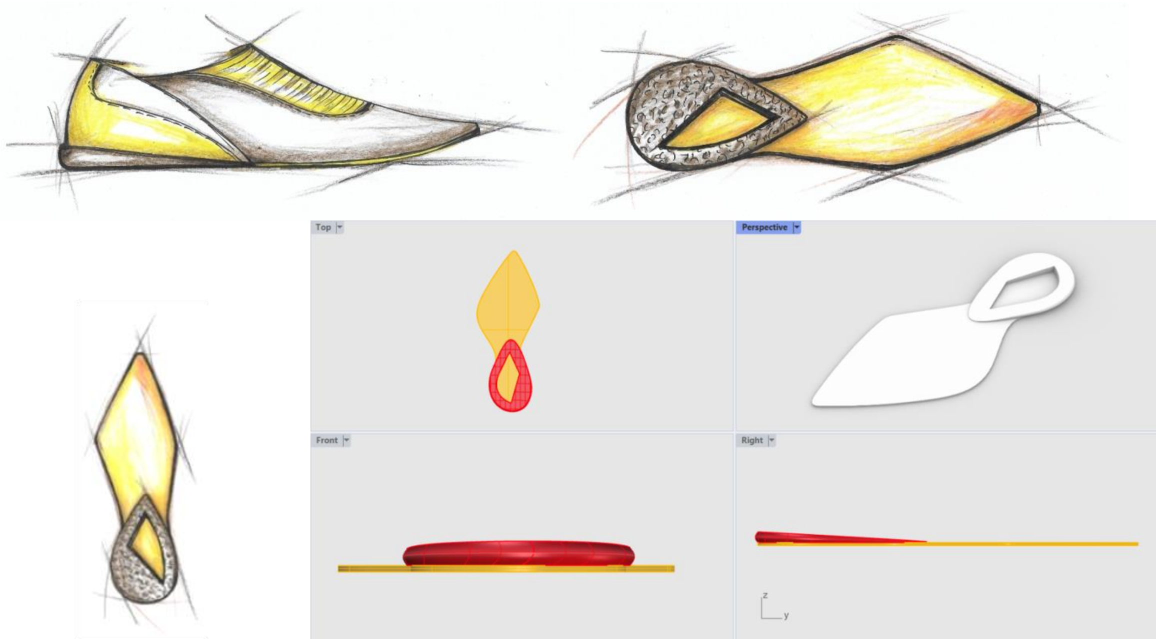


Figure 2. Sole model 1

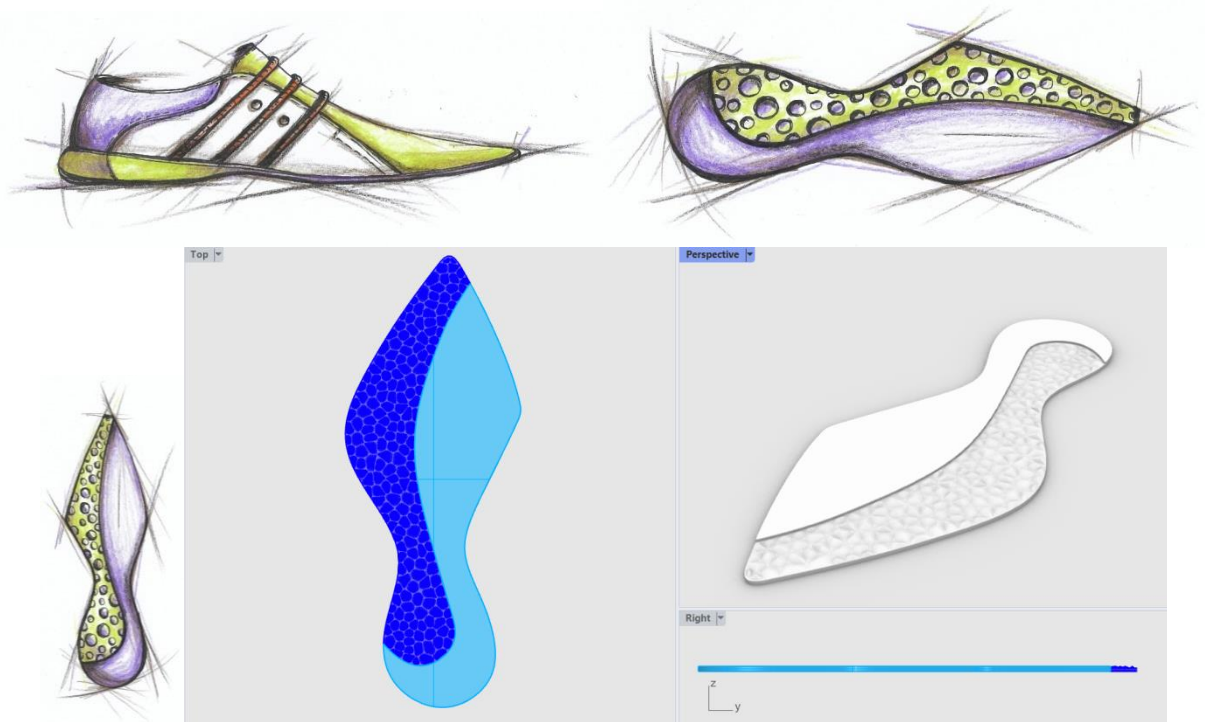


Figure 3. Sole model 2

✓ 6 heel models for the designed soles (Fig. 4-5);

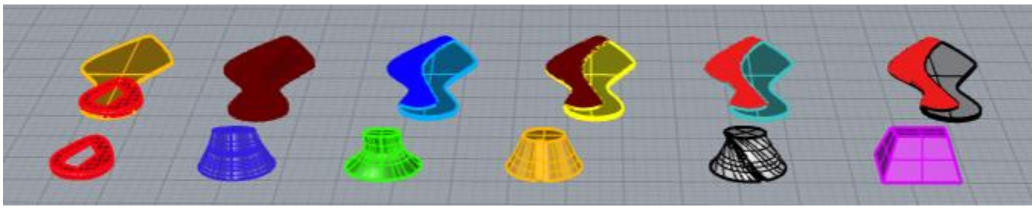


Figure 4. Heel models for the designed soles

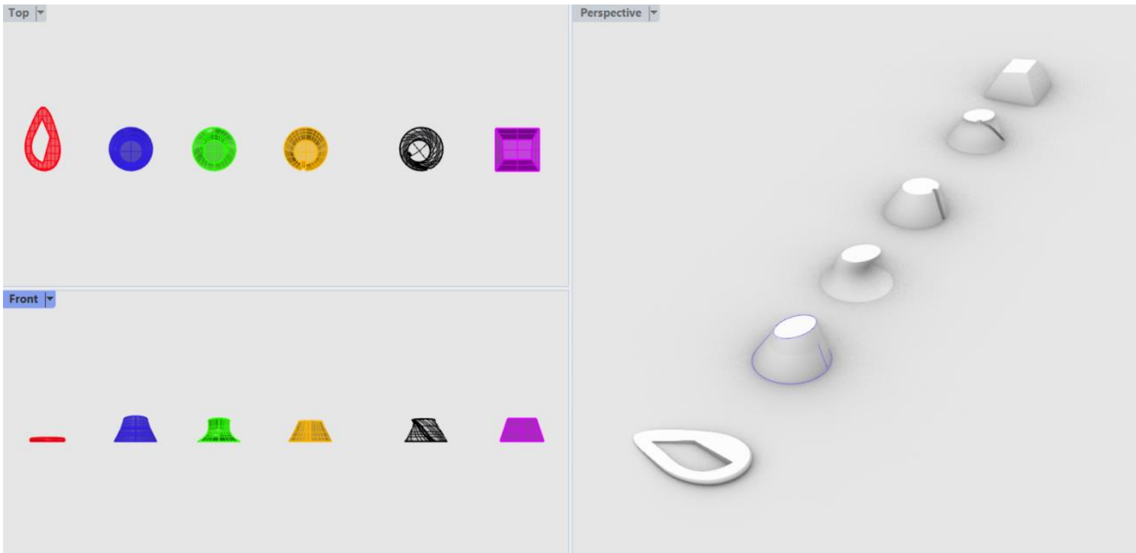


Figure 5. Heel models

✓ 5 complete footwear models – upper and sole (two elements) (Fig. 6).

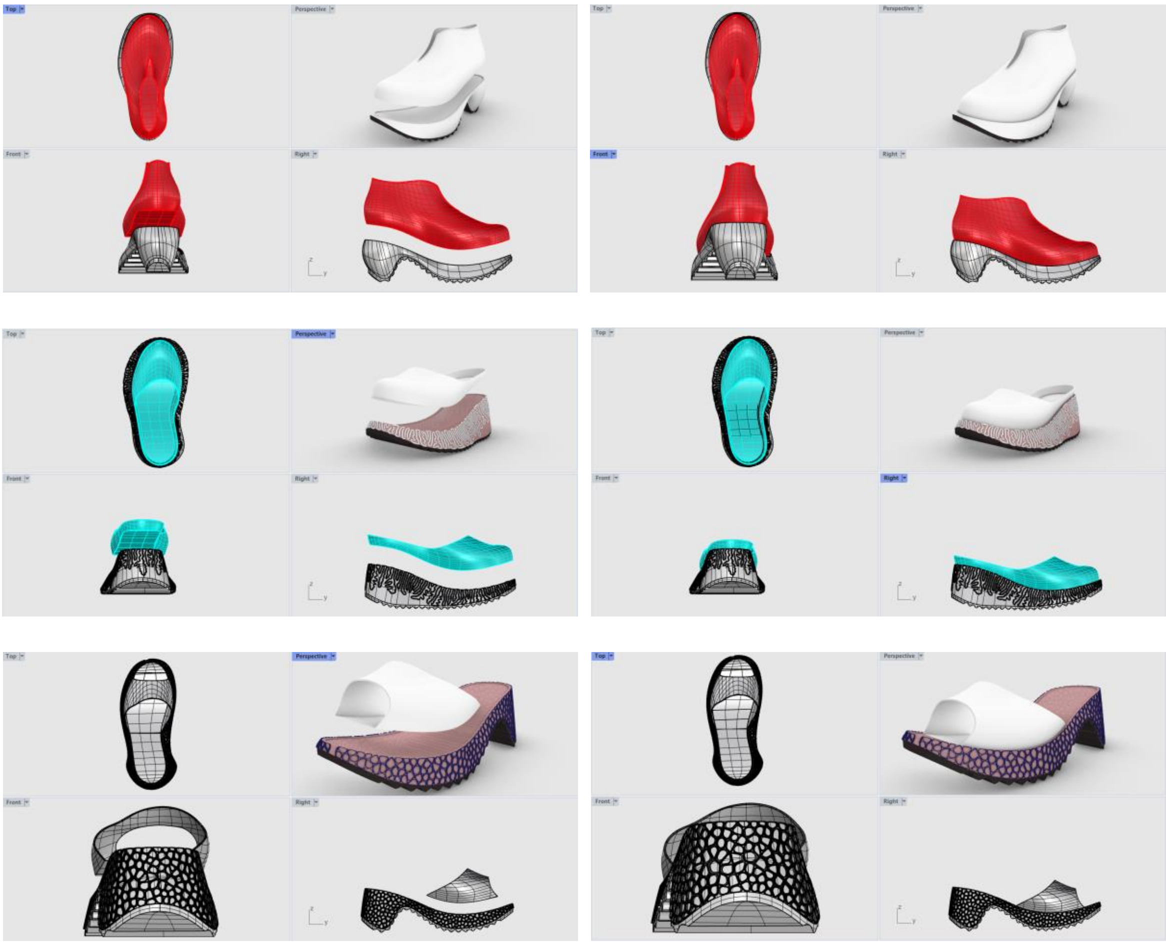


Figure 6. Complete footwear models

3D Printing

3D rapid prototyping systems are a revolutionary solution that allows for the creation, within a few hours, of physical three-dimensional objects or models of designed objects directly from 3D CAD/CAM electronic files [18].

Rapid prototyping equipment enables the creation of highly complex samples for verification and validation purposes before a new product is launched into production. Computer-aided 3D printing falls under the category of rapid prototyping technologies and enables the creation of physical prototypes by solidifying successive layers of multi-component powder and bonding them using a liquid binder.

3D printing of footwear using the FDM (Fused Deposition Modeling) method, also known as FFF (Fused Filament Fabrication), is an additive manufacturing process that builds objects layer by layer by extruding a molten thermoplastic filament. This technology is popular in the industry due to its low costs and the possibility of rapid customization.

Creating a pair of shoes using FDM involves several essential steps [19]:

- Digital Design: Creating a 3D model (CAD file) that may include complex lattice structures to optimize weight and cushioning.
- Slicing: Preparing the model for the printer by converting it into instructions (G-code) that define the print head’s path.
- Printing: The filament is heated to a semi-liquid state and deposited in layers onto the print bed.
- Post-processing: Removal of support structures (if necessary), sanding or varnishing of surfaces to achieve a finished appearance.

Fig. 7 shows examples of footwear that can be produced using 3D printing.

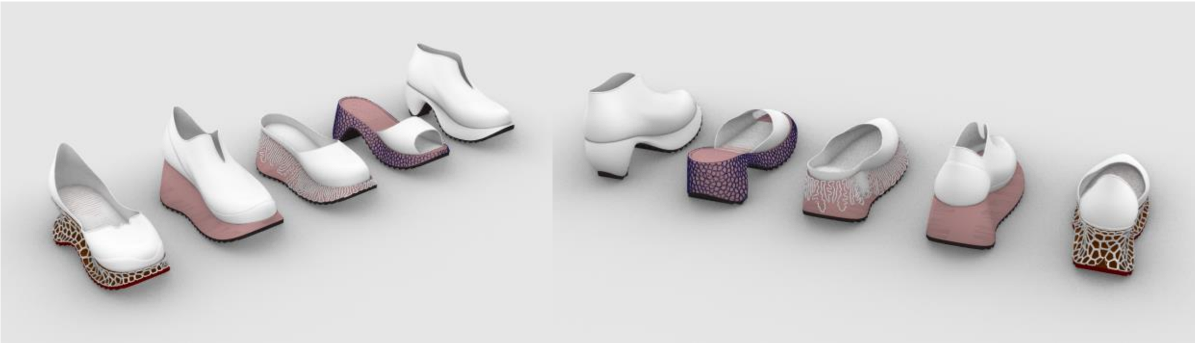


Figure 7. Models that can be produced using 3D printing

Industrial Scalability and Economic Feasibility

The results obtained in this research demonstrate the potential of integrating digital technologies into a modern workflow for the footwear industry. The development of the 10 concept sketches and the digital design of the 17 components (six sole models, six heel models, and five complete footwear models) highlight the ability of CAD tools to rapidly generate design variants and support iterative product development processes. Compared to conventional methods, where every change requires manual adjustments to drawings and prototypes, using Rhinoceros software allows for rapid model updates and the exploration of a greater number of design solutions in a shorter amount of time.

A key advantage of the proposed workflow is the integration of 3D scanning into the initial design stages. By digitizing the user's anthropometric characteristics, the data obtained can be transferred directly to the CAD environment, facilitating the development of products tailored to the individual characteristics of the foot. In an industrial context, this approach lays the groundwork for implementing production systems geared toward mass customization, in which each product can be adapted to customer requirements without significant changes to the manufacturing infrastructure. Thus, companies can more effectively meet the growing demand for customized products, while maintaining control over costs and delivery times.

Using the Rhinoceros platform also helps increase interoperability between the various stages of the development process. Compatibility with numerous CAD formats facilitates integration with other software systems used in the industry, reducing the risk of information loss and optimizing data transfer between design, simulation, and manufacturing. This feature is essential for industrial-scale implementation, where collaboration between design, engineering, and manufacturing departments directly influences the efficiency of the product development process.

FDM 3D printing complements this digital workflow by enabling the rapid transformation of virtual models into functional prototypes. Eliminating the need for molds in the early stages of development significantly reduces costs and the time to market for new products. In addition, the technology enables the manufacture of complex geometric structures, including lattice structures designed to optimize weight and comfort, which are difficult or impossible to produce using conventional methods. From an industrial perspective, this flexibility favors small- and medium-scale production, where the high costs of dedicated equipment and manufacturing tools often represent an economic barrier.

The economic feasibility of the workflow is also supported by the use of biocomposites based on thermoplastic polymers and natural fibers. These materials offer the possibility of reducing the consumption of non-renewable resources and recycling waste streams, contributing to the development of production models compatible with the principles of the circular economy. At the same time, additive manufacturing uses material only in the areas necessary for the product's construction, which leads to a reduction in material waste compared to subtractive processes or traditional manufacturing methods.

Although large-scale implementation requires initial investments in 3D scanning equipment, specialized software, and 3D printing systems, the benefits generated by reduced development time, optimized material consumption, and increased customization can offset these costs in the medium and long term. Consequently, the proposed workflow proves particularly attractive to niche footwear manufacturers, medical and orthopedic applications, as well as companies focused on high-value-added products, where flexibility and adaptability are key competitive advantages.

CONCLUSIONS

This paper highlights the advantages of integrating innovative digital technologies into the various stages of footwear design and manufacturing, from concept development to prototyping. The proposed workflow, based on concept sketches, 3D scanning, computational design, CAD modeling, and 3D printing, demonstrates the potential for transforming traditional processes into a modern, flexible, and efficient system.

Ten concept sketches were developed, and 17 footwear components were designed, including six sole designs, six heel designs, and five complete footwear designs. The use of Rhinoceros software enabled the rapid development of design variants and the optimization of complex geometries, reducing the time required for design and facilitating product customization according to user requirements. The use of computational design algorithms has made it possible to reduce the number of manual modeling operations and accelerate the iterative product development process, offering a significant advantage over conventional CAD methods based on successive modifications to the geometry.

3D printing using FDM technology enables the rapid production of prototypes and components with complex structures that are difficult to achieve using conventional methods, reducing the costs and development time associated with new products.

An important aspect of the research is the use of biocomposites based on thermoplastic polymers and natural fibers, which support sustainability goals and the circular economy by utilizing renewable resources and reducing waste. This approach contributes to the development of innovative products with a low environmental impact and performance levels that meet the demands of modern industry.

In conclusion, the synergy between 3D scanning, digital design, and additive manufacturing represents a promising direction for the footwear industry, offering extensive opportunities for customization, process efficiency, and sustainable development. The implementation of these technologies can provide a significant competitive advantage for manufacturers focused on niche products, orthopedic applications, and high-value-added products.

Future research will focus on the construction and experimental testing of the developed prototypes, as well as the evaluation of their mechanical, functional, and ergonomic performance.

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