

Design, research and development of a collection of women's high-heeled shoes using polylactide 3D printing

Part 2: Development and production of a prototype of women's shoes

Dizajn, istraživanje i razvoj kolekcije ženskih cipela visokih potpetica primjenom 3D ispisa od polilaktida

2. dio: Razvoj i izrada prototipa ženskih cipela

Scientific paper / Znanstveni rad

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Abstract

The first part of the paper Design, research and development of a collection of women's high-heeled shoes using polylactide 3D printing presents the design research of the author's collection, and this second part describes and visually documents the process of developing and producing prototypes of women's high-heeled shoes. The introductory part of the paper briefly describes the process of fused deposition modelling (FDM), the characteristics of desktop 3D printers and the application of additive manufacturing (AM) in shoe design. The experimental part of the paper describes the process of designing CAD models of heels and their production on a desktop 3D printer made of polylactide (PLA) using the example of two realised prototypes of women's shoes as well as the construction of shoe uppers using traditional techniques and processes in shoe production. By using 3D printing, the author's idea should be quickly and easily translated into the production of more complex shapes of heels. The paper also aims to show how modern technologies are impacting all areas of human endeavour, including the footwear industry. The need for fast and innovative solutions on the market is emphasised by the constantly growing number of fashion models and the shortened product life cycle. In this context, additive manufacturing (3D printing) enables the production of products in a short time directly from a computer model (e.g. Computer Aided Design - CAD) without additional tools, as the results of the work on examples of prototypes of women's high heels show.

Keywords: fused deposition modeling; CAD model construction of heels; 3D printing; polylactide, high heels prototypes

Sažetak

U prvom djelu rada prikazano je dizajnersko istraživanje autorske kolekcije, a u drugom djelu opisan je i vizualno dokumentiran proces razvoja i izrade prototipova ženskih cipela visokih potpetica. Uvodni dio rada sažeto opisuje postupak taložnog očvršćivanja (engl. *Fused Deposition Modeling* – FDM), karakteristike stolnih 3D pisača te primjenu postupaka aditivne proizvodnje (engl. *Additive Manufacturing* - AM) u dizajnu obuće. Eksperimentalni dio rada, na primjeru dva realizirana prototipa ženskih salonki, opisuje proces konstrukcije CAD modela potpetica, njihovu izradu na stolnom 3D pisaču od polilaktida (PLA) i konstrukciju gornjišta salonki tradicionalnim tehnikama i postupcima u proizvodnji obuće. Primjenom 3D ispisa želi se na brz i jednostavan način interpretirati autorska ideja u izradi složenijih oblika potpetica. Rad također teži prikazati kako suvremene tehnologije utječu na sve grane ljudske djelatnosti, uključujući i obućarsku industriju. Naglašava se potreba za brzim i inovativnim rješenjima na tržištu zbog stalnog porasta broja raznih modela obuće i skraćenog vijeka trajanja proizvoda. U tom kontekstu, aditivna proizvodnja (3D ispis) omogućuje izradu tvorevina u kratkom vremenskom roku izravno iz računalnog modela (engl. *Computer Aided Design* - CAD) bez dodatnih alata, što je i prikazano u rezultatima rada na primjerima realiziranih prototipa ženskih cipela visokih potpetica.

Ključne riječi: taložno očvršćivanje; konstrukcija CAD modela potpetica; 3D ispis; polilaktid; konstrukcija gornjišta; salonka; prototipovi visokih potpetica

1. Introduction

The footwear industry is constantly evolving, with sustainability and the integration of digital technologies recognised as the most important trends [1]. In response to these demands and the market's need for rapid, innovative solutions due to the continual shortening of product lifecycles, additive manufacturing (AM) has emerged as a key technology. AM, also known as 3D printing, is an advanced technology that is significantly transforming footwear design and manufacturing processes. These processes have been developed and applied since the second half of the 1980s. Although initially focused on rapid prototyping (RP), tools, and lasts, advances in material development have enabled AM to be used today for producing finished products in small batches or as personalised, individual items. The basic principle of additive manufacturing is to build an object by adding material layer by layer. This method offers a significant advantage in creating products quickly, directly from a computer model (Computer Aided Design – CAD), without the need for additional tools. Additive processes provide great flexibility in shaping, enabling the creation of complex geometric forms that would be extremely difficult or impossible to achieve with traditional manufacturing techniques [2]. In the fashion sector, including footwear, AM significantly reduces the time and cost of developing new models, especially when producing prototypes and small series, including personalised pieces [3].

One of the most widely used additive manufacturing processes is Fused Deposition Modelling (FDM), also known as Fused Filament Fabrication (FFF). FDM is popular due to its affordability, ease of use, and the wide range of commercially available materials. In this process, a polymer material in the form of a wire (filament) is fed through a nozzle, where it is heated to its melting temperature. The softened material is then deposited layer by layer onto the 3D printer platform, where it solidifies. The most commonly used materials for FDM are polymers, including polylactide (PLA), a biodegradable thermoplastic derived from renewable resources, and acrylonitrile butadiene styrene (ABS), an amorphous copolymer known for its dimensional stability [2, 3]. Many 3D printers are available on the market today with different characteristics and purposes; one of these is the BCN3D Sigmax R19 model, which was used in this work for 3D printing high heels made of polylactide (PLA). This printer features an independent dual extrusion system (IDEX), allowing it to print duplicate and mirrored objects, making it suitable for larger production runs. Before 3D printing, CAD models are converted into STL files, which are processed in appropriate software (e.g. BCN3D Cura or MakerWare) to generate G-code for the printer [4, 5]. Key printing parameters that must be defined include layer thickness (0.1–0.3 mm), infill density (10–100%), print speed, and nozzle and extrusion temperatures (e.g. 200 °C for PLA). Print orientation is also important and is determined by the desired mechanical properties, model geometry, and the need for support structures [6, 7].

In this paper, the application of the FDM process was investigated for creating original prototype models of women's high-heeled shoes made of PLA, enabling the realisation of complex and unconventional design ideas.

2. Experimental part

The experimental section presents the stages involved in constructing and producing an original mini collection of women's avant-garde shoes using digital tools and technologies. It describes the process of constructing the upper, creating a CAD model of the heels in a three-dimensional modelling programme, and preparing and 3D printing the heels from PLA. Two prototype models of women's pumps were produced in collaboration with a team of experts from the Ivancića Shoe Factory d.d. Ivanec.

2.1. Upper Construction of Women's Pumps

Footwear construction begins with the selection of a last, which determines the appropriate parts of the shoe bottom (heel, sole, insole),

the built-in components (mounting lug, toe cap), and the cut parts of the upper. A last is a stylised representation of the foot's shape, serving as the basis for making footwear. It is produced according to standard measurements prescribed by a particular measurement system or based on individual foot measurements. The last is designed to fit inside the shoe as a foot would, allowing space for movement and accommodating the heel and sole. The last varies with the type of footwear and also with the shape of, for example, the front part, or the size or width of the foot. The shape of the last determines the appearance, form, and type of footwear, as well as the heel height.

Understanding footwear construction requires knowledge of human foot anatomy. The feet are among the most sensitive and complex parts of the body. They occupy a small area, yet bear the weight of the entire body and help maintain balance. They are under constant strain and stress. Well-designed shoes must be not only aesthetically appealing but also comfortable and supportive of efficient mobility. For these reasons, it is always necessary to consider the following basic principles in footwear construction [8, 9]:

- The space in the front part, from the top of the shaft (end of the shoe) to the tip of the toes, should be about 10–15 mm, allowing room for the foot and movement of the toes inside the shoe when walking.
- The shape of the heel is important for proper adjustment to the ankle when moving; if it is too loose or too tight, it can cause discomfort.
- When wearing high heels, the centre of gravity shifts to the toes, so an insole with an anatomical cushion in the front part is important.
- The heel must be of optimal height and increase proportionally with the sole in the front part, providing greater comfort and ease of movement.
- A raised front part in footwear is a basic addition between the bottom of the toes of the shoe and the ground (the front part is raised upwards instead of descending flat to the ground) and is used to adjust the gait.

The last selected for the prototype of women's flat shoes "*Garbody 4.0*" is an uncast California-type last made of plastic polymers, with a metal insert for opening and a wedge for removing the last. It was produced based on an individual scan of the author's foot using a 3D foot scanning device. As this is a custom last, the shape and height of the heel are determined according to personal requirements. The heel height of 8 cm represents the optimal height that does not cause deformations and keeps the foot in a healthy position. The second parameter in the appearance of the shoe is the front shape of the last, for which a pointed appearance was selected (Figure 1a). When choosing a pointed shape for the toe cap, it is important to leave enough space for a healthy position of the toes. The last size is: f.u 36, e.u 3.5, and cm 24 (f.u - Paris point, e.u - English point, and cm - centimetre system). A copy of the last was made by applying paper tape to the surface of the last (Figure 1b). Copying the last is a manual process that reduces all uneven surfaces to a single flat surface, allowing for a precise and controlled start to the model construction process. This method is characteristic of artisanal footwear production and of industrial production that still uses the manual method of making last copies or personalised lasts. With the development of specialised computer systems, 2D last measurements can now be easily and precisely obtained from 3D scanned lasts. By copying the last, the last profile measurement is obtained, on which the upper parts of the footwear are drawn. Errors in making a copy of the last are reflected in the aesthetic appearance of the model, such as the upper of the shoe not adhering well to the last when assembled. Figure 1c shows the inner and outer copies of the mould, with markings for the last number, size, model name, and last side. Differences between the inner and outer sides of the foot result in differences in the last copy, which are equalised by making an average last copy (Figure 1d) that provides the basis for the model, with differences in the lower part if present. The differences that are equalised arise due to foot asymmetry, differences between the inner and outer sides of the foot, or an incorrectly determined centreline along which the middle is cut [10].

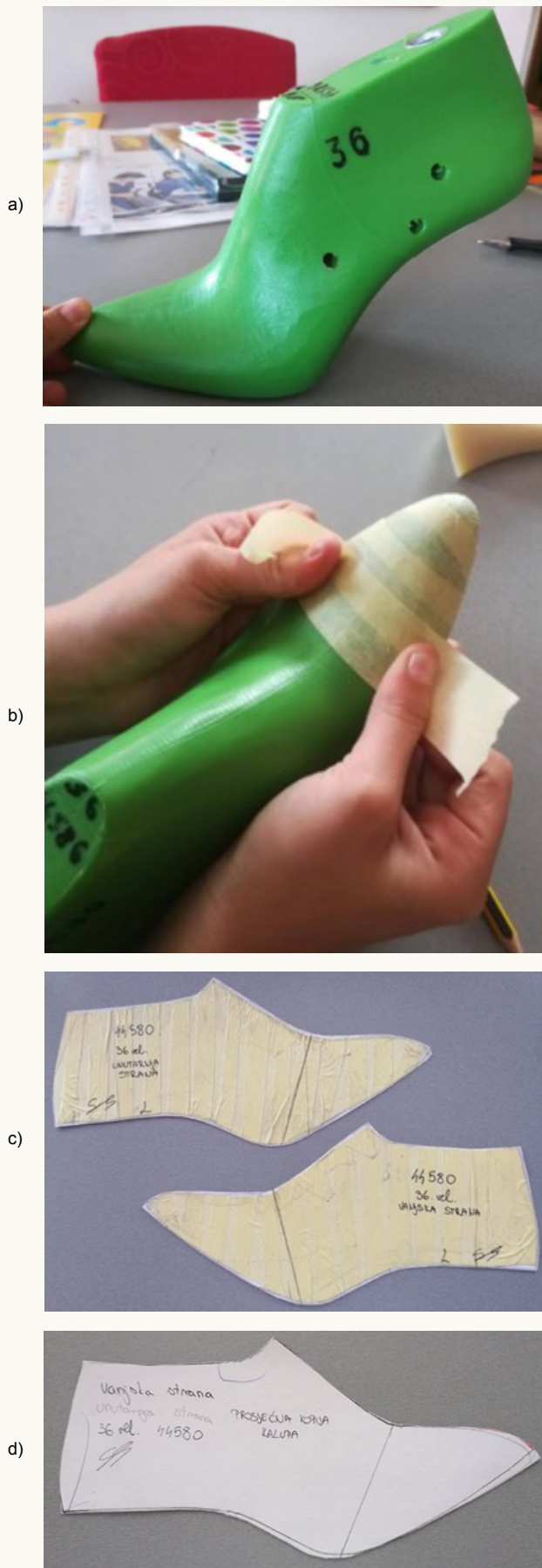


Figure 1. The process of making a copy of a last: a) the last; b) covering the last with self-adhesive tape; c) the inside and outside of the last copy; d) the average last copy

Although shoe modelling is an individual process and each cut part varies according to the last and shoe model, there are standard starting points from which the design process begins. A set of measurements that depend on the length of the last is called the model base (Figure 2). The model base is drawn on paper with a right angle on the x-axis, where the heel of the average copy of the last is placed at the heel height appropriate for the last, in this case 8 cm, while the front part is lowered on the y-axis. In this position, the average copy of the last is drawn, marking the fold of the toes and heel, which is obtained by constructing the golden ratio. The centre line of the shaft is drawn according to the fold of the toes, and on the heel part, the height of the shaft and a 3 mm allowance for the built-in shaft are determined, depending on the length of the last. Before designing the cut parts, it is necessary to mark the recess (allowance) in the lower part, the values of which depend on the thickness of the material and the technological production process. A slip-on groove is an addition to the last copy that allows the upper part of the shoe to be slipped onto the last, or allows the upper parts of the shoe to be joined to the lower parts. For the prototype of the pumps, these were added in accordance with the technological manufacturing process and practice at the Shoe factory Ivančica d.d. Ivanec, where the prototypes were made [10].

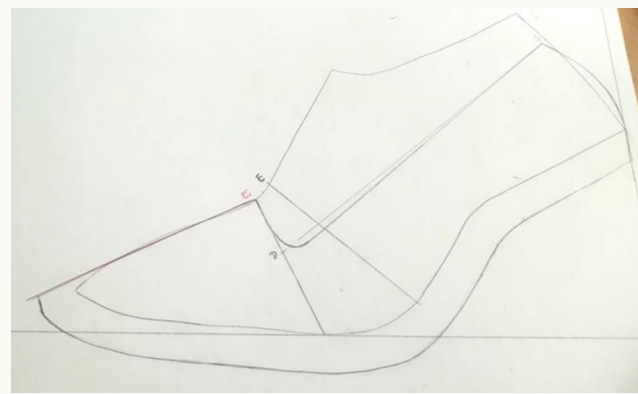


Figure 2. Basis of the model

2.1.1. Computer Aided modelling of women's pumps

Computer-aided footwear production is used at all stages, from development to manufacturing, with footwear modelling in the Procam Dimension computer programme as one example. The main advantages of this method are greater precision, reduced production time, and the ability to make rapid changes.

The hand-made model base is imported into the computer programme using a digitising device or a graphics tablet, which consists of a tablet board and a drawing device (mouse or pen), for further processing (Figure 3a).

The model base is placed on the tablet board, and the position points that project the base lines onto the screen are determined using the mouse. The model base lines are outlined, particularly the fold lines of the toes and foot, as well as the drawn cut parts of the pump.

The marked points create lines that are transferred to the computer programme for further editing (Figure 3b). The process of designing footwear in the computer programme begins with drawing additional lines that define the cut parts. Drawing these lines is simple and quick, and it is important that each line closes a surface with other lines so that a new cutting part can be created. The "new cutting part" command marks all lines that form the desired cutting part and creates it in a separate window for further editing (Figure 3c). According to the technological instructions and processing requirements, appropriate technological marks are added for the positions of parts or seams, and the grooves are drawn.

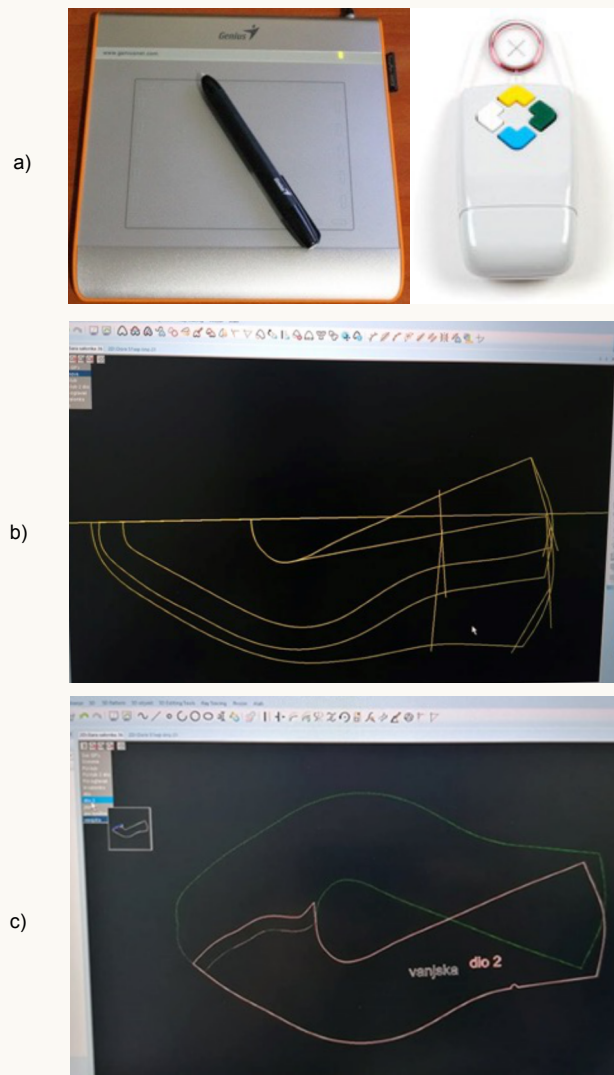


Figure 3. Computer modelling in the CAD programme Procam Dimension: a) digitiser – tablet panel and mouse for drawing lines; b) base of the model and c) cutting parts of the upper section of the prototype "Garbody 4.0 – heart"

After processing all the upper cutting parts, the lines for the lining, interlining, and sponges are drawn, and the cutting parts for these are prepared in the same way. The cut parts for the top of the "Garbody 4.0 - srce" salon consist of two sarees joined face to face at the front and at the heel. At the front, a tongue made of two parts (upper and lower) is added, with a sponge inserted. The top of the "Garbody 4.0 - mozak" lounge is made using the classic lounge procedure, from two parts cut for the inner part and the heel, joined face to face. The upper part is decorated with additional decorative elements, whose positions must be marked for easier and more accurate navigation during production. The lining and interlining are constructed identically on both models. The lining consists of two parts, while the interlining consists of two parts and reinforcement for tucking.

2.1.2. Pattern-Making for Cutting Parts

After all the cutting parts have been modelled, templates for the face, lining, intermediate lining, and sponge cutting parts are produced using the automatic cutting machine. The prepared templates, used to cut the parts for the prototype, are shown in Figure 4. They also serve as a reference for the modeller and assist in model creation. Figure 4a shows the prepared templates for cutting the face parts of prototype 1, "Garbody 4.0 - heart"; Figure 4b shows the face cutting parts of prototype 2, "Garbody 4.0 - brain"; and Figure 4c shows the cutting

parts of the lining. The lining cutting parts are identical for both prototypes.

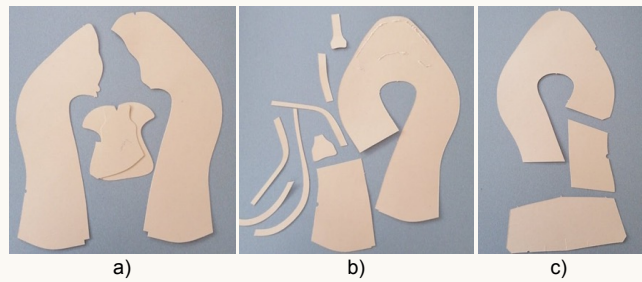


Figure 4. Pattern parts: a) faces of prototype 1, b) faces of prototype 2 and c) lining

2.2. Computer Aided design of heel prototypes

The heel construction for the prototype models "Garbody 4.0 - heart" and "Garbody 4.0 - brain" was carried out using the Solid Edge CAD programme for 3D modelling. The sketching, solid body creation, and surface tools from the programme toolbar were used to construct the heels.

Although the heel would ideally be modelled according to the imported 3D scan of the mould, in this case, as it is a prototype model, the heel was constructed based on manual measurements (Figure 5). Creating a model in Solid Edge begins with a 2D sketch consisting of geometric shapes defined by points, lines, arcs, and ellipses. The upper part of the heel, or the attachment that connects to the upper part of the mould, is constructed according to a copy of the sole part of the mould imported into the programme. During construction, it is necessary to consider the thickness of the material in the area of the recess and the part of the sole that fits into the heel section. To achieve the desired circular appearance of the heel tapering towards the bottom, several parallel planes were created above the upper plane, on which circles were sketched and then connected (Figure 5a). Using surface tools (e.g. Surfaces), a solid heel shape was created, serving as the basis for both prototypes (Figure 5b). For heel stability, after 3D printing, it was planned to press in a metal reinforcement with threads to accept the central screw (for attachment to the upper) and the heel counter. The heel was therefore designed with a central space of 2.5 mm to accommodate this reinforcement.

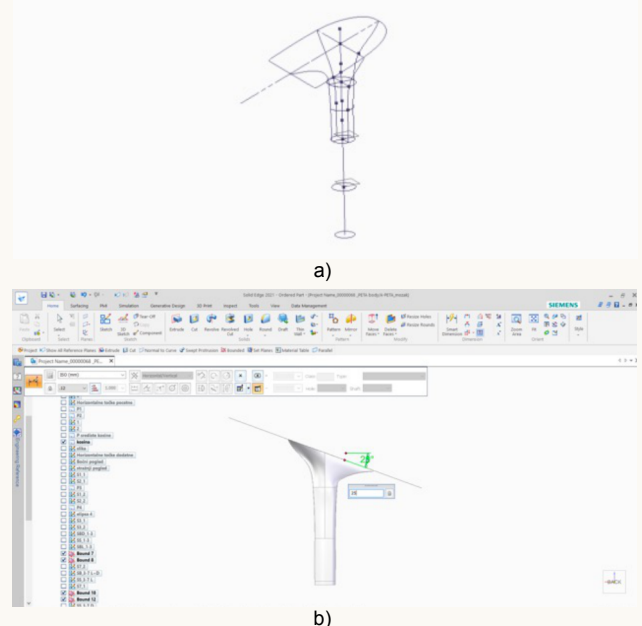


Figure 5. Heel construction in the Solid Edge computer programme: a) modelling and b) CAD model

The prototype high heel “Garbody 4.0 - heart” (prototype 1) was further developed with 3 to 5 mm thick curves extending along the entire heel, constructed on separate planes to allow printing in a different colour (Figure 6). A recess is also created on the outer part of the heel to accommodate an insert that extends to the heel section of the upper. The insert is a separate component attached after the heel assembly and is constructed using inset images of the mould from different positions (Figure 6a). The final appearance of the CAD model of the heel and the prototype insert is shown in Figure 6b.

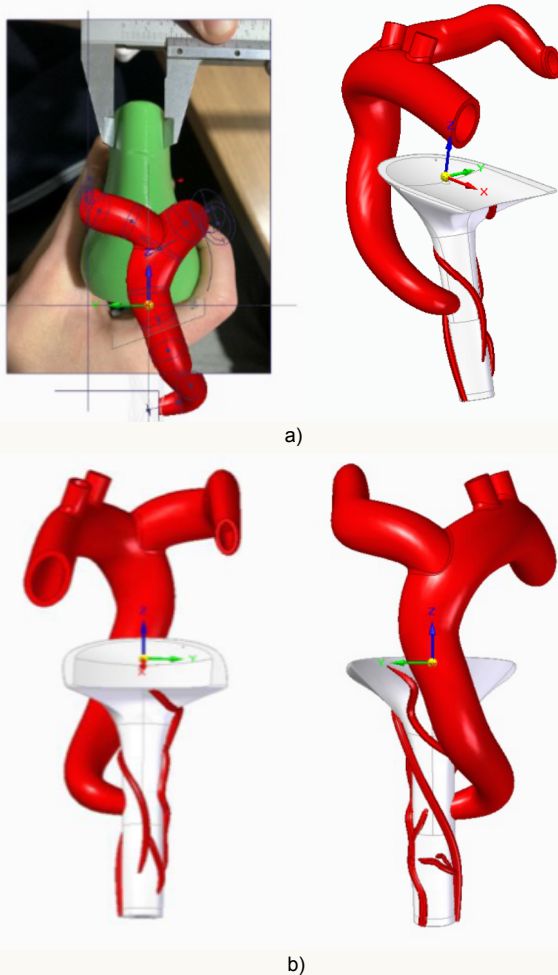


Figure 6. View of the CAD model of the heel for prototype 1: a) heel insert and b) final CAD model of the heel and insert prepared for two-colour printing

The prototype of the “Garbody 4.0 - brain” model was created by adding an object to the base of the heel to form a relief surface (Figure 7a). Irregular, organically shaped lines resembling brain convolutions were drawn on the heel surface and formed into relief structures with a thickness of 1 to 3 mm using the extrude command. The final CAD model of the heel for the “Garbody 4.0 - brain” prototype is shown in Figure 7b.

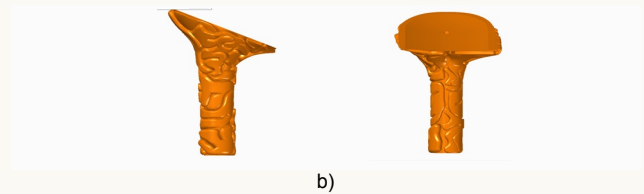
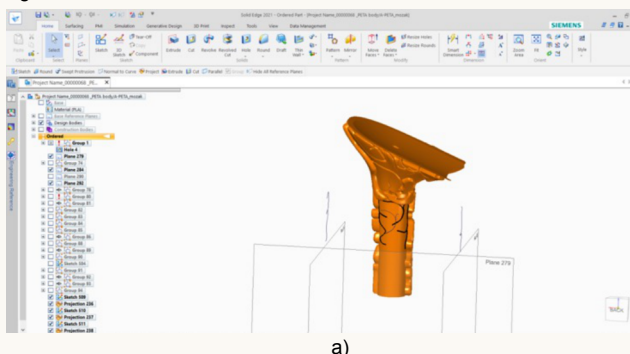


Figure 7. View of the CAD model of the heel for prototype 2: a) design in the Solid Edge computer program and b) final CAD model of the heel

2.3. Preparing CAD models of heel prototypes for 3D printing

Preparing the completed CAD models of high heels for 3D printing begins by saving the model as an STL file, which is then processed in the G-code generation programme, BCN3D Cura. This software prepares the model for 3D printing by loading it and generating the G-code required for the manufacturing process on the 3D printer. During preparation in BCN3D Cura, it is necessary to define the 3D printing parameters, including print position and orientation, as well as settings such as layer thickness, nozzle temperature, platform temperature, print speed, infill density, and fan speed (material cooling). The choice of 3D printing orientation is an important parameter that depends on the shape and geometric complexity of the model and affects its mechanical properties, manufacturing time, and the amount of support structure that must be removed later.

Since the support structure in the FDM process is removed by fracturing, an orientation that increases 3D printing time is sometimes chosen to avoid support structures that are difficult to remove. For the prototypes of the “Garbody 4.0 - Heart” (Figure 8a) and “Garbody 4.0 - Brain” models, a vertical orientation was chosen. This orientation is inverted relative to the actual position of the heel, with the aim of avoiding support structures and possible visible traces of their removal. The prototype of the “Garbody 4.0 - Heart” heel is planned for two-colour printing using two extruders. For multi-colour printing, a prime tower is used. Nozzle and filament adjustment on this tower is carried out before 3D printing, with a primer layer printed for each colour or extruder change (Figure 8b). This helps to avoid errors that could occur due to an insufficiently heated nozzle.

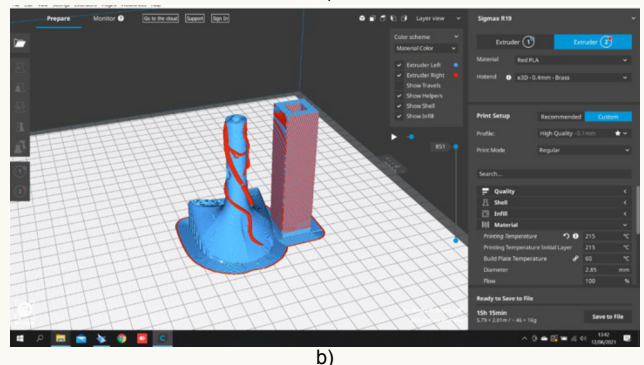
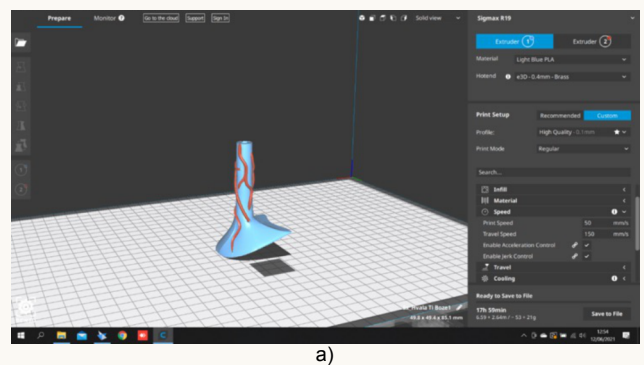


Figure 8. Preparing the first model for 3D printing in BCN3D Cura: a) vertical orientation and b) two-colour 3D printing with support

Table 1 shows the specified 3D printing parameters for heel prototypes.

Table 1. The 3D printing parameters of the heel prototypes

Print Parameter	Value
Layer thickness	0.1 mm
Infill density	100 %
Infill build speed	50 mm/s
Extrusion temperature	200 °C
Platform temperature	60 °C

The BCN3D Cura programme also allows estimation of material consumption and 3D printing time. These parameters depend on the settings listed in Table 1. Material consumption varies significantly with changes in layer thickness and infill density, while printing time is also affected by the selected printing speed. Table 2 presents the predicted 3D printing time and material consumption for both heel prototypes.

Table 2. Estimated material consumption and 3D printing time

	Estimated material	Printing time
Heel of the model "Garbody 4.0 - heart"	52 g	16 h i 50 min
Heel attachment "Garbody 4.0 - heart"	56 g	14 h i 24 min
Heel of the model "Garbody 4.0 - brain"	42 g	12 h i 20 min

2.3.1. 3D Printing of Polylactide (PLA) Heel Prototypes

The 3D printing process for polylactide (PLA) heels began with test prints to verify the CAD model and identify any errors. During one test print, an error occurred in which the extruder moved incorrectly relative to the coordinate system generated by the G-code, resulting in a deformed heel (Figure 9a). The first 3D print of the prototype heel model "Garbody 4.0 - brain" was produced in a neutral colour (Figure 9b). Inspection of this prototype revealed that the height of the heel formed an incorrect angle in relation to the bottom of the mould, causing the centre of gravity of the body to be directed towards the toes, which could lead to discomfort and foot deformation. Figure 9c shows the errors and test 3D prints of individual parts of both heel prototypes.

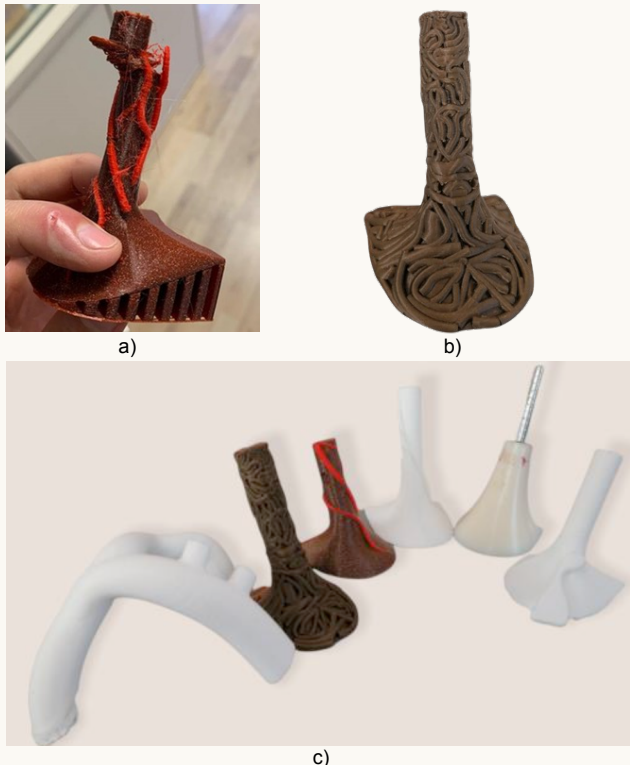


Figure 9. Test 3D printing: a) deformed heel appearance, b) incorrectly constructed heel and c) examples with errors

The prototyping process on a 3D printer begins by transferring the G-code to the device using an SD memory card. The material, a plastic wire with a diameter of 2.85 mm, is slowly unwound from the reel and fed into the material delivery mechanism. The material is then heated until it melts and exits through a nozzle, with the heater temperature set to 200 °C. The molten material is deposited and bonded to the work surface or to a previously printed layer, where it cools and hardens. After one layer is completed, the platform shifts vertically in the z-direction. This process of applying material layer by layer is repeated until printing is complete (Figure 10). After the printed objects are removed from the 3D printer work surface, the support structures must be separated. Any remaining unnecessary residues and impurities are carefully removed using sandpaper.

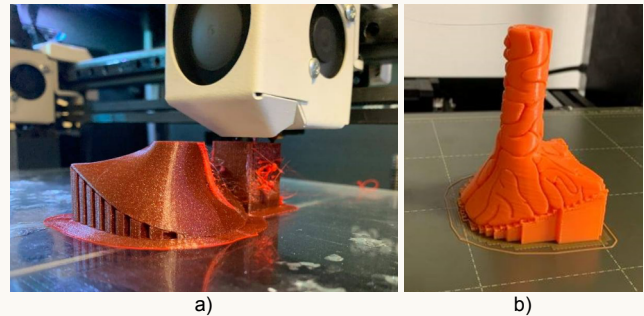


Figure 10. 3D printing of heel prototypes: a) prototype 1 and b) prototype 2

3. Results

The results include photographic records of the completed shoe uppers and the corresponding 3D-printed prototypes of heels made from polylactide (PLA) "Garbody 4.0 - heart" and "Garbody 4.0 - brain". The construction of the cutting parts, production of the uppers, and assembly of the 3D-printed heels were carried out at Ivančica d.d. Ivanec with the assistance of a professional team. The shoe upper consists of the upper parts, lining, midsole, reinforcement, and sponge, with an integrated stiffener in the front section. The industrial stages of upper production included cutting, preparation of parts for assembly (such as technological marking, hemming, and stabilisation of parts with the midsole), hemming of the edges, assembly of the uppers, gluing the lining, and assembly of the upper and lining. Figure 11 shows the completed uppers of the women's shoe prototypes.



Figure 11. Realised tops of the women's salon model: a) prototype 1 and b) prototype 2

The heel prototypes were constructed using CAD models created in the Solid Edge computer program and 3D printed on a BCN3D Sigmax R19 desktop 3D printer with PLA (Figure 11). For the prototype heel "Garbody 4.0 - heart", material consumption was 52 g, and printing took 17 hours and 8 minutes. The addition to the heel part of the same model

required 56 g of material and 14 hours and 49 minutes of printing. The prototype heel "Garbody 4.0 - brain" was printed in 12 hours and 43 minutes, with material consumption of 42 g. Comparison with the predicted estimates in Table 1 shows that actual material consumption and 3D printing times are slightly higher than estimated.

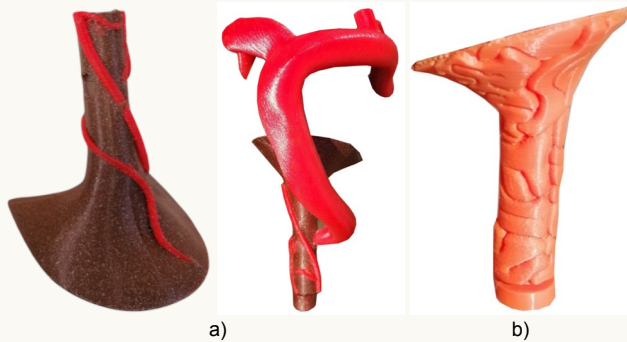


Figure 12. Realized prototypes of the heels of the models: a) prototype 1 "Garbody 4.0 - heart" and b) prototype 2 "Garbody 4.0 - brain"

The assembly of the upper and lower parts of women's pumps began with the installation of the assembly hub. The technological assembly processes included several steps: attaching the sole to the mould, machine stitching the front and heel parts onto the mould, attaching the sides of the upper, sanding the grooves, coating the grooves and sole with glue, gluing and pressing the sole, drying, and attaching 3D-printed heel prototypes. After the sole is attached, the mould is removed, the insole is inserted, and finishing follows, including cleaning the upper of glue and pencil residues, final polishing, and dressing. Figure 13 shows the completed prototype of the "Garbody 4.0 - heart" model, and Figure 14 shows the prototype of the "Garbody 4.0 - brain" model.



Figure 13. Completed prototype of the "Garbody 4.0 - heart" model



Figure 14. Completed prototype of the "Garbody 4.0 - brain" model

4. Conclusion

The use of modern technologies has significantly enhanced the precise visualisation of the author's concept and shoe design described and presented in the first part of the paper, "Design, research and development of a collection of women's high-heeled shoes using 3D printing from polylactide" (K&O vol. 73 no. 3/2024). The process of developing heel prototypes, from concept to realisation, has demonstrated that a range of skills is required for the successful production of the designed product, including knowledge of computer-aided design (CAD) modelling, experience with desktop 3D printers, and the selection of suitable polymers for the intended application.

A key advantage of 3D printing is the ability to rapidly materialise complex design solutions through prototyping. However, if the aim is to create unconventional heel shapes for small-scale production, it is necessary to conduct thorough research into the cost-effectiveness of production and the compatibility of materials for the intended application.

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