Design optimisation of TPU modular footwear for sustainable fashion: a South African Fashion Week case study, 2023

Sarel Havenga[1*] and *Philip* van der Walt[2]

1 Idea2Product Skills Development Department, Vaal University of Technology, South Africa
2 Non-department (Bunnycorp-Nexus Advanced Geometries), AM Industry Specialist, South Africa

Abstract. The fashion industry is continuously evolving, and Thermoplastic Polyurethane (TPU) produced modular footwear is emerging as a trend for sustainability. This study aims to optimise the design of TPU modular fashion footwear for the South African fashion sector. The practice-based case study investigated the factors that influence the design and manufacturing of modular footwear using TPU, with a focus on enhancing sustainability. A design framework was developed using CAD software and evaluated the effectiveness of the optimised design in enhancing sustainability through a case study conducted at the SA Fashion Week in 2023. A combination of quantitative and qualitative research methods was employed to collect and analyse data, contributing to the development of sustainable and fashionable modular footwear for the fashion industry. It further provides insights into the challenges associated with the design and manufacturing of TPU modular fashion footwear.

1 Introduction

The fashion industry in South Africa holds a significant position for development within the country's economy and cultural landscape. However, the industry's detrimental impact on the environment has resulted in a growing demand for sustainable alternatives [1]. As a response to these concerns, sustainable fashion needs have emerged as a pivotal concept, emphasising ethical production practices, waste reduction, and the utilisation of environmentally friendly materials. Modular fashion shoes, designed to be disassembled, repaired, and extended in lifespan, have been identified as a potential innovative solution to address these sustainability challenges [2].

TPU stands out as a flexible and durable material, offering unique properties such as water and chemical resistance, as well as increased shear strength and ductility [3, 4]. As a

* Corresponding author: sarelh@vut.ac.za

thermoplastic material, it has proven to be particularly suitable for AM applications in footwear due to these unique properties. TPU exhibits excellent resistance to abrasion, tearing, and chemical degradation, ensuring the longevity and durability of footwear products, even though its use in fashion remains limited [4], [8].

With an increasing focus on innovation and sustainability in footwear design, the application of TPU in the industry has witnessed significant growth, making it a highly relevant subject for investigation [5], [6]. Considering these developments, a real-world case study was conducted during the International South African Fashion Week in April 2023 (Figure 1), aiming to optimise the design of TPU modular fashion footwear for the South African fashion sector.

Fig. 1 Ostrich footwear prototypes used during SAFW23. Courtesy of SAFW and Viviers studios© https://viviersstudio.com/ and Nexus Advanced Geometries© https://bunnycorp.co.za/nexusadvance-dgeometries/

In recent years, additive manufacturing (AM), more specifically, 3D-Printing has gained substantial attention in the footwear industry as a disruptive technology with the potential to revolutionise traditional manufacturing processes. This technology allows for the creation of complex geometries, customisation, and material efficiency, making it an appealing option for sustainable fashion footwear production. Evidently, from Table 1, complex features and geometries are being used, however, the market development persists to be dominated by the sports industry [3, 7].

In 2020, Adidas launched a line of 3D-printed TPU running shoes. The shoes are made from a single piece of TPU, which eliminates the need for stitching and reduces waste Table 1 (A). In 2021, Nike launched a line of 3D-printed TPU sneakers. The shoes are designed to be lightweight and comfortable, and they are also made from recycled materials Table 1 (B). In the same year, New Balance launched a line of 3D-printed TPU running shoes that are made from recycled materials Table 1 (C). In 2022, Puma launched a line of 3D-printed TPU football boots. The boots are designed to provide increased flexibility and control, and they are also made from recycled materials Table 1 (D). Unfortunately, these developments do not include high-fashion modular shoe development to resolve ethical production practices and waste reduction.

TABLE 1 indicate the use of TPU filament in the production of footwear over the last three years.

A	Adidas 3D-printed TPU running shoes: https://newatlas.com/adidas-futurecraft-3d-midsole/39770/	
B	Nike 3D-printed TPU sneakers https://www.popsci.com/nike-3d-printed-sneakers/	
C	New Balance: https://footwearnews.com/2015/focus/athletic-outdoor/new-balance-3d-printed-midsole-running-shoes-sneakers-photos-171347/	
D	Puma 3D-printed TPU football boots: https://www.tradeinn.com/goalinn/en/puma-future-ultimate-mg-football-boots/139553984/p	

In terms of sustainable fashion, TPU presents several advantages. Firstly, its thermoplastic nature allows for the material to be melted and re-moulded, enabling recyclability and an extended life cycle for TPU-based products [9, 10]. This feature aligns with the principles of a circular economy, where materials can be repeatedly utilised, reducing waste and minimising environmental impact [11]. Secondly, TPU demonstrates superior durability, outperforming traditional materials and reducing the need for frequent component replacements. By extending the lifespan of footwear, TPU contributes to waste reduction and sustainability. Thirdly, the traditional manufacturing processes of certain materials, such as leather, often involve significant water consumption and unsustainable practices. However, TPU-based 3D production eliminates these environmentally harmful aspects, offering a more sustainable alternative [1, 4, 12].

The fashion industry's shift towards sustainability has propelled the exploration of TPU in various footwear applications. TPU's versatility enables its use in both inner and outer components of footwear, providing designers with ample opportunities for creative and sustainable designs. However, this versatility should also contribute to the development of modular fashion footwear, which allows for disassembly, repair, and reusability, aligning with the principles of a circular economy [2, 13, 14].

Considering the potential of TPU in sustainable fashion footwear, the current study aims to investigate an optimised design of TPU modular fashion footwear for the South African fashion sector. By leveraging the unique properties of TPU and employing advanced design techniques, the research seeks to enhance sustainability within the fashion industry and address its significant contribution to environmental degradation [15, 16].

2 Methodology

The main research question focused on how TPU modular fashion shoes can be investigated to identify optimisation of the design for local and international fashion designers. The focus was then branched into four sectors that included, what the present literature illuminates, how

the design process will unfold for modular footwear, qualitative data collection during and post the case study and lastly identifying limitations in the design.

The investigation employed a practice-based approach to optimise the design of TPU modular fashion footwear during the case study. In this context, the principles of practice-based research were employed through computer aided design iterations, to explore the research question, which was then followed by the researcher and designer creating physical prototypes together. This supported the stakeholders with sequential parameters for the initial prototype design. Various design iterations were produced (see result section part one) and the final design was then tested on the catwalk at the SAFW23. Due to the highly experimental design of the modular footwear, a small sample size of six sets of shoes was produced for the catwalk models, as a control measure (shown in Figure 1).

The documentation process continued throughout the study and was used to collect visual observations. A combination of qualitative and quantitative research methods was used to collect data for analyses. The qualitative data collection was done through participant interviews, as well as pre- and post-interventions (process flow shown in Figure 2). The visual observations and shoes were used to collect quantitative data through set controls (error indicators- see Figure 12 in results part two) to observe durability, functionality, and sustainability. This allowed the investigators to analyse the thematically data (error indicators) as well as to examine the optimised design suggestions that could be evaluated through user testing.

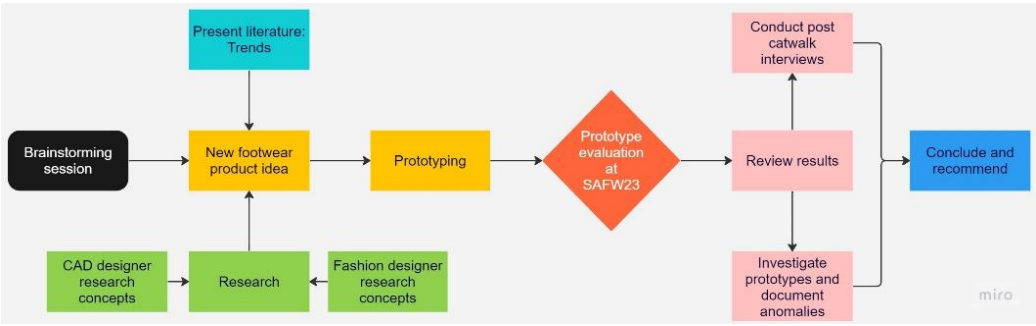


Fig. 2 Overall workflow process for investigating the use of TPU in modular footwear fashion.

In the footwear product ideation stage (yellow in Figure 2) both literature and research methods were used to develop the first phase. The phases were used to develop various emerging concepts during the prototyping phase and is illustrated in the results section. From there the final prototype was tested at the SAFW23 (indicated in orange, Figure 2). From there the participants were interviewed and the physical prototypes investigated for anomalous failures (see the result section part two and three).

Due to the cost savings investigated, it was important that the footwear prototypes were created on an entry-level Material Extrusion (MEX) system and made use of TPU filament from the same manufacturer (Creality). Over a period of one month, during 2022 and 2023 respectively, two versions of the footwear designs were designed and explored consisting of five modular components (see results section part one). The designs became the foundation

to collect the data for an empirically analysable investigation. The final footwear design consisted of six (6) modular components (shown in Figure 3).

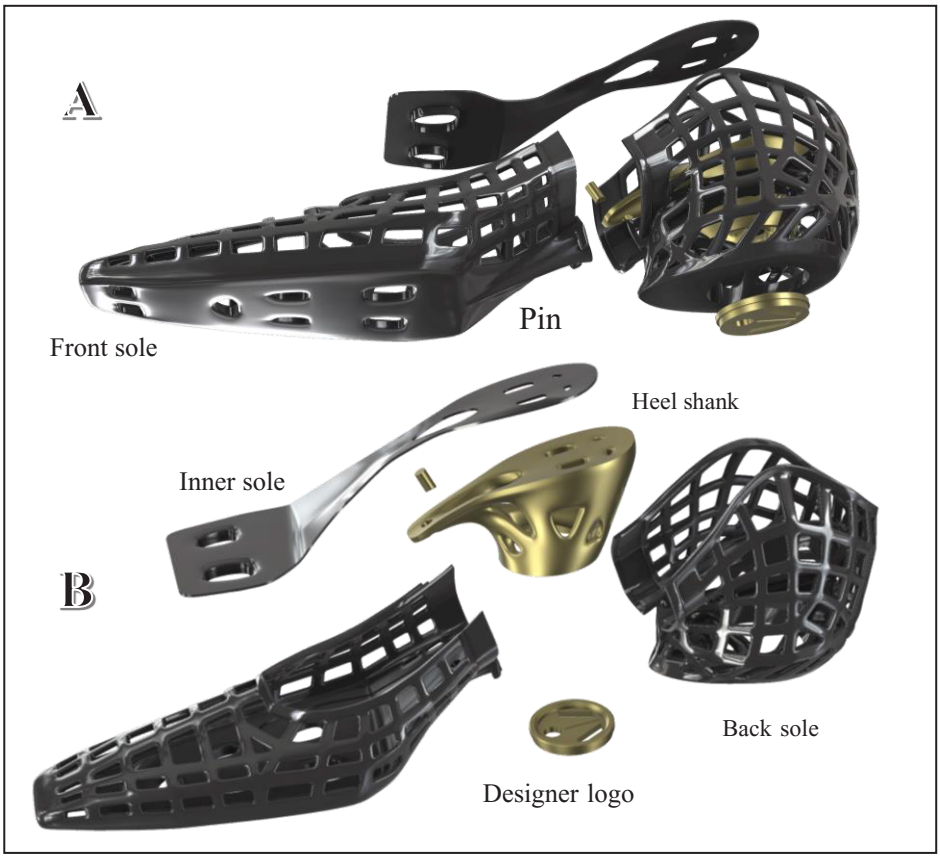


Fig. 3 Modular footwear design for Viviers Studio. (A) Bottom view partially expanded, (B) Top view expanded.

3 Results and Discussion

Due to this investigation focusing on the optimisation of the prototype design, the results are split into three sections. The part one presents the design process results in sequential order leading to the final prototype design. Then the design issues are presented in part two and lastly, the results of the participants are presented in part three.

3.1 Part one: The Design Process:

3.1.1 Phase I | 2019 | Initial Concept

New footwear concept was presented to the design team as a sustainable product for the South African fashion. Reference drawings are supplied, and the model was created with renderings and a turntable video of the design in gold (Figure 4 and 5).

Fig. 4 Conception of the original footwear design

Fig. 5 Original render idea

3.1.2 Phase II | 2022 | Physical Prototype (delayed due to COVID-19)

This phase explored ways to create a physical wearable shoe from the original concept design. After CAD iterations were created in Rhinoceros 3D software, 3D printed samples of the shoe frame were produced to help create the desired shape in leather. Iterations of the heal, shank and base were also produced (Figure 6). Although the study focused on sustainable solutions, a durable control sample needed to be printed that would function similarly to a shoe last. The chosen 3D printing process for the test was Multi Jet Fusion

printing in Nylon to allow a thin light weight frame (Figure 7). The design was completed in multiple parts so that the investigators could test and edit the required sections easily.

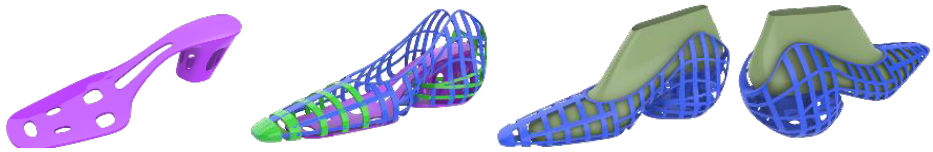


Fig. 6 illustrates the first shoe frame, heal, shank and base designs.

Fig. 7 Sample frame to simulate shoe last and incorporate leather.

3.1.3 Phase III | 2023 | Design Evolution

The client accepted the aesthetic appearance of the prototype based on design considerations. Focus was placed on the inner frame design and it was decided to explore developing the frame version into a wearable shoe with a leather insert, much like a sock. Initial materials and processes were explored based DfAM principles and the only feasible material was indicated as TPU based on the literature and generative design samples. The design team

looked at various 3D printing processes that supported the use of TPU even though the cost and time would seem to play a huge factor. The modular footwear would need to be developed at a very quick pace to reach the expected fashion deadline and required test parts to ensure the designs was feasible Due to these costs and time constraints MEX was used to produce the prototypes. The prototypes were produced in-house to facilitate a faster turnaround time for production and testing. The other options were costly and had to be produced internationally which removed weeks of time to allow for shipping.

To ensure functionality and the original objectives of the study, it was decided to split the footwear into modular components that would allow faster prints as well as produce options for testing and color combinations. Due to using TPU for the first time in a full batch production scenario, further tests needed to be conducted to make sure the final design would not have critical flaws. Another result of interest was that the client also requested elements that would create challenges (move beyond "normal" shoe design). This is indicated in the client's illustration (Figure 8). An initial fluid flow of lattices with curved connections was suggested for increasing overall strength and avoid corner weak spots that could occur with FDM as the direction of the deposition would play a role. Especially the row of openings on the lower part of the front.

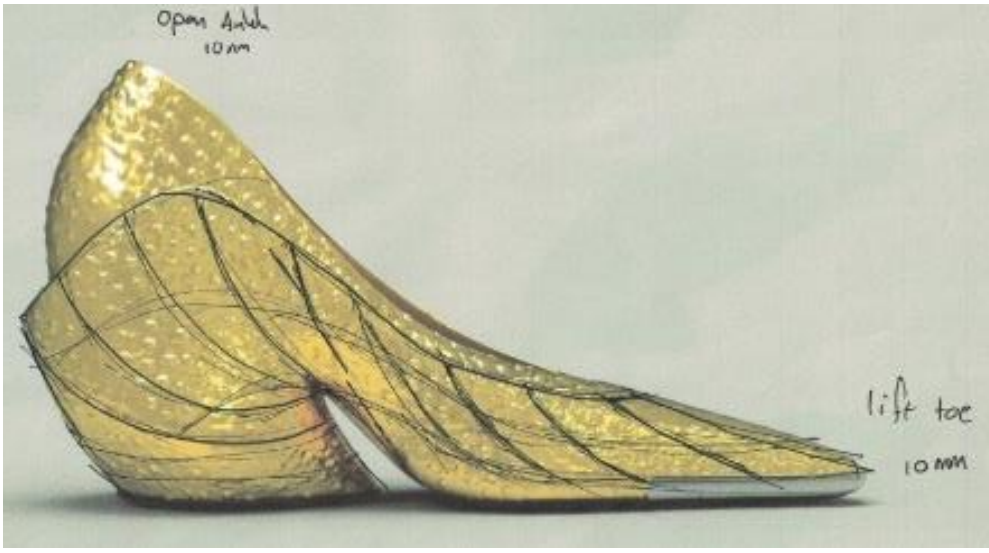


Fig. 8 illustrates the fluid flow of lattices with curved connections.

3.1.4 Phase IV | 2023 | Designing for the AM technology and material.

Based on the suggestion of a fluid flow of lattices with curved connections suggested by the client, the design team proceeded to test the CAD models in Autodesk Fusion 360 for design optimisation. The generative design tool was utilised with set parameters for MEX systems, specific material properties and stress level indicators such as load bearing. Due to the nature of the research for a commercial potential venture, these settings are not disclosed at this stage in the development of the product.

Following the principles of DfAM and the results of the generative design renders, the research team indicated a possible flaw in the angular design of the lattice corners. The

investigators proceeded to design and print lattice corners specimens (Figure 9) and tested various thickness and angle designs.

Fig. 9 Lattice structure test specimen used to determine optimal design.

At this stage in the design process, a small sample size of test specimens were produced for three iterations of the lattice structure and basic qualitative observations were conducted. The lattices were tested for sharp corners and at which point it would impact the design negatively. Print orientation, material extrusion temperature, infill density, melt flow rate and nozzle size were taken into account but not empirically tested.

A redesign of the lattice structure was considered and presented to the client (Figure 10). The stress factor limitations due to the technology (MEX) and material (TPU) was illustrated as possible hindrances to the successful development of the final commercial product. The client proceeded to keep the rectangular shape of the lattice structure. From there an initial shoe was printed to test the heel insert, shank and material performance considering the lattices.

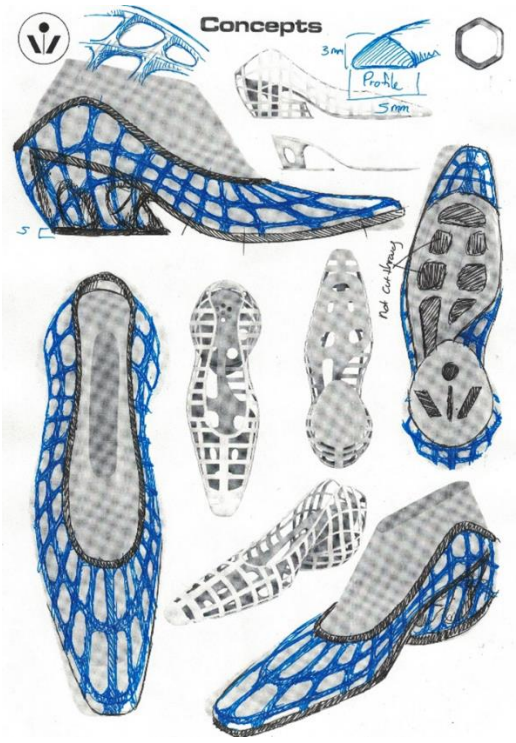
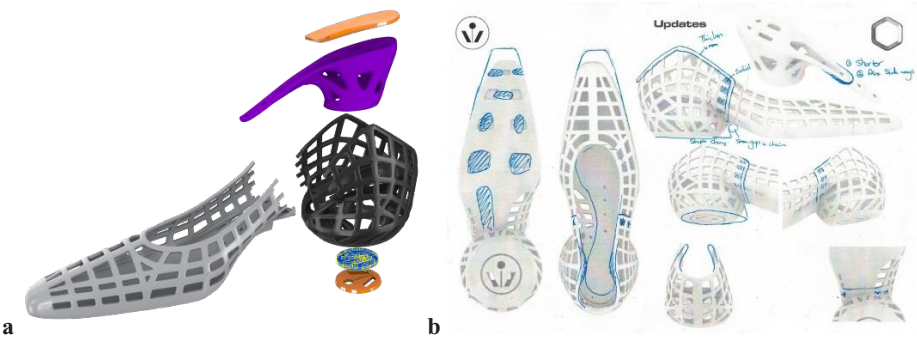


Fig. 10 suggested alternative to lattice structure, that would become crucial in the final prototype.

A final modular footwear design was constructed in CAD to test the heel insert, shank and material performance in consideration of the lattices (Figure 11-a). The modular design was exposed to physical walking tests, which found that although the lattice structure held up there were small shear fractures. It was also observed that a better way to join the modular components needs to be investigated. There were not enough overlapping contact points. The heel shank had to be shortened and an insole that would run from the back to front would be beneficial for function and aesthetics. Final design updates were developed in CAD from the suggested first walking trials (Figure 11-b).



a **b**

Fig. 11 a) first walking test prototype, b) final design suggestions

For the final design the investigators increased the radius of the lattice connections as well as the material thickness to ensure a stronger form (Figure 3). The insole was added with a 1.5mm thickness so that the prototype could print horizontal on the flatbed (stronger and took less time) and it would take the desired shape once fastened. The heel shank was simplified, shortened and printed in PLA. For assembly the shank was slid into the front part of the shoe, a pin locked it into place and the heel section would slide into the heel casing of the shoe. A decent draft angle was present so the process was simplified and the parts could fit snugly. A decent overlap was also present where the parts could be glued together.

3.2 Part two: Design issues.

It is important to note that in part one it was decided to not adjust the lattice structure in the footwear design. This section will present the results of the visual observations recorded after the prototypes were subjected to physical walking during a fashion show. At the point of documentation, the modular footwear was exposed to two fashion shows. During this part of the investigation each pair of footwear was documented through an observation sheet and recording of visual images of the stress fractures (Figure 12). Indicated in red circles clear patterns emerge that illustrate the limitation of the lattice design. This observation will have a catalytic effect on the following results.

The results indicate that two of the four sustainable factors could be highlighted by this case study. Firstly, from the literature review, it seems evident that TPU as a thermoplastic material can be melted and re-moulded, therefore recyclable and extending the life cycle of the material. The prototypes are still in the testing phase and cannot be tested for end-of-life recycling.

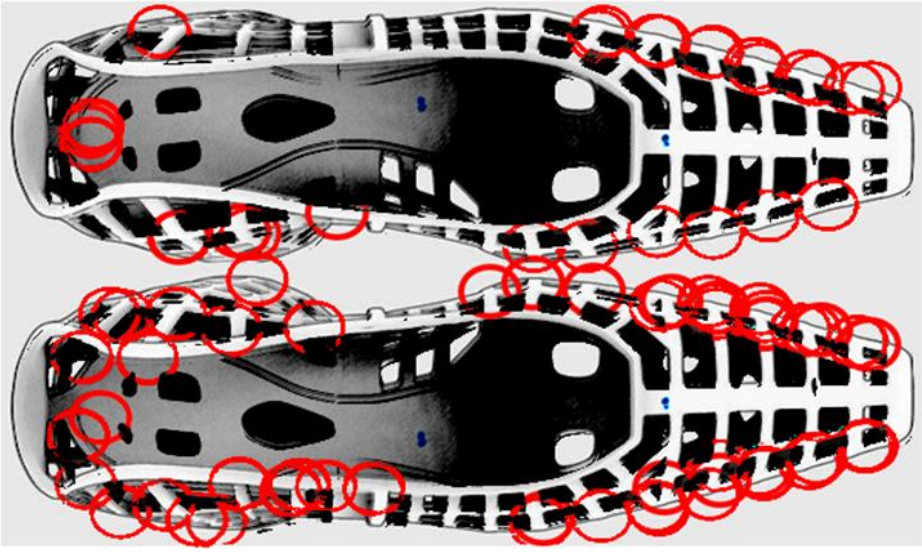


Fig. 12 superimposed stress fractures observed (all prototypes)

Secondly, TPU is durable, with a lower wear and tear ratio than traditional materials, making the replacement of components less frequent. However, this is heavily dependent on the glass transition point and more specifically the melt flow rate. In the initial live experiment fracture points became evident very quickly where retraction speed and melt flow rate were not optimised for each TPU filament (shown in Figure 13).

These delamination or fracture areas indicate that two factors should be considered when developing modular footwear. The first factor is iterative design optimization as well as generative design through software application. The second factor is to benchmark control settings for the MEX technology's filament.

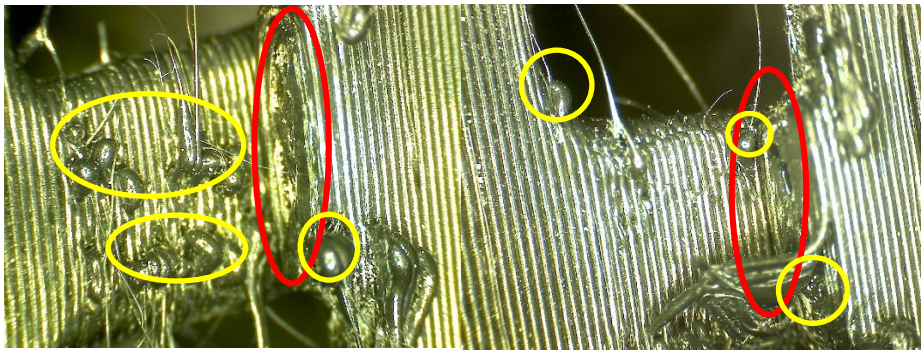


Fig. 13 Delamination fracture from retraction and backflow rate not calculated. Fracture line (RED), over extrusion nodule (YELLOW).

Even though the filaments are from the same manufacturer, the chemical composition is not always the same (colour). This caused deviations in the quality of the modular footwear (see Figure 13).

After various redesigns and specific changes made through generative design to balance the tensile/shear strength properties of the material with the forces used, seventy-five percent

of the prototypes showed evidence of fractures. These fractures are mainly attributed to design restrictions set by the aesthetic visuals chosen for this fashion show (lattice). Voronoi-inspired designs generated through topology optimisation would have produced a stronger prototype with similar aesthetic value.

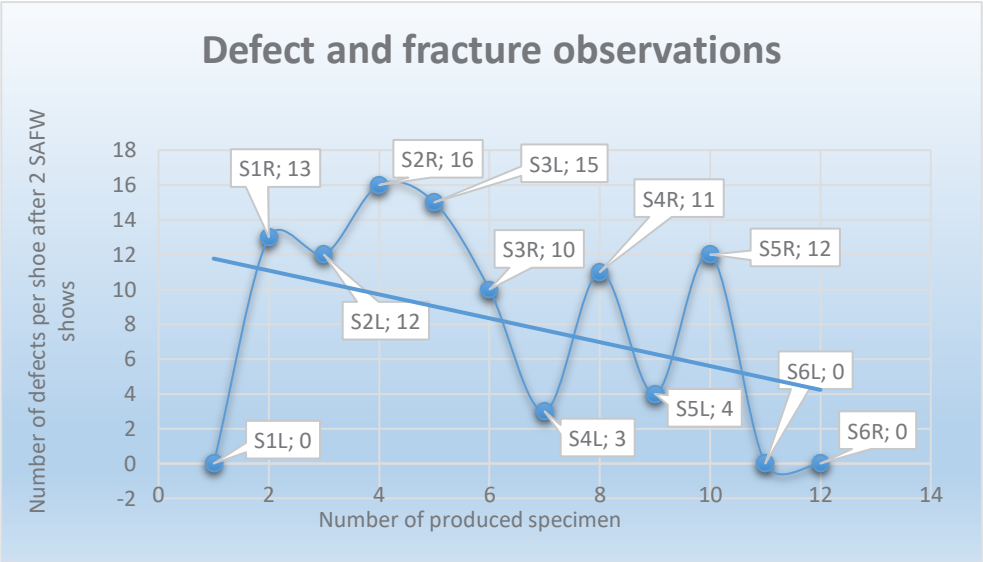


Fig. 14 Deviation and fracture chart for all specimen created in sequence. Legend: S1L= (Shoe, number 1, Left)

3.3 Part three: Qualitative perceptions.

Lastly it was important to gather qualitative observations from end users to validate the successful use of the modular footwear.

TPU is a versatile material that can be used in various footwear fashion applications, including the inner and outer components. This was qualitatively observed through pre- and post-interviews with the models and designers. The overall experience was received positively with a seventy-seven percent marker (see Figure 15).

Participants indicated that they would recommend the use of modular footwear due to feeling it is of high quality, durable, comfortable and easy to use. They furthermore indicated that it is fashionably appealing, with no need for adjustment and enhancing their catwalk performance. The research team feel it is noteworthy that comfort was recurring feedback, even when the components had shear strength failure indications.

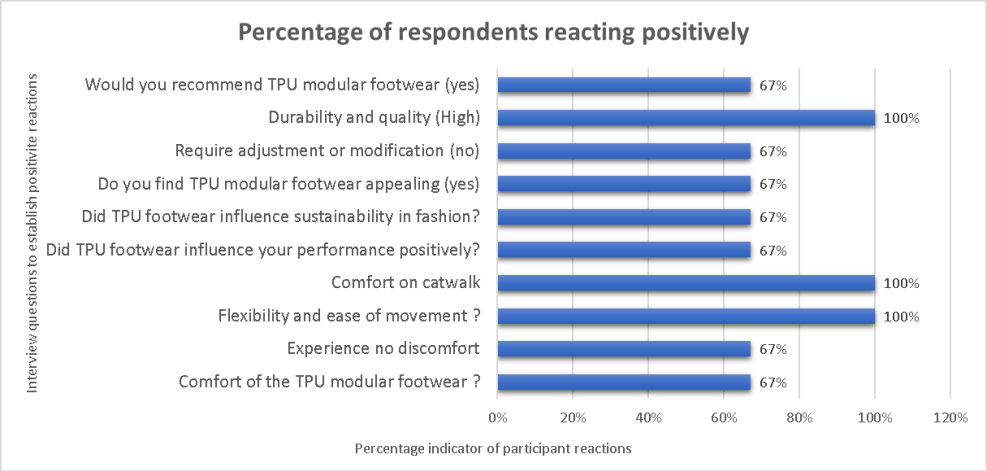


Fig. 15 Interview feedback from participants on their qualitative perception of the modular footwear

4 Conclusion

In conclusion, the fashion industry is facing increasing pressure to adopt sustainable practices to reduce its negative impact on the environment. The concept of sustainable fashion is emerging as a response, with a focus on ethical production practices, waste reduction, and the use of environmentally friendly materials. Modular fashion footwear, designed to be disassembled, repaired, and reused, may offer a sustainable alternative to traditional footwear. The use of thermoplastic polyurethane (TPU) in modular footwear design is increasing due to its durability, flexibility, and sustainability. However, this case study identifies critical development areas that will need to be addressed before MEX TPU modular footwear can be successfully designed for a commercial fashion market. These results could contribute to the development of sustainable and fashionable modular footwear, addressing the fashion industry's significant contribution to environmental degradation. The authors recommend that further research be conducted on the chemistry of the TPU filaments to create production specifications for modular footwear. Standard recorded operating procedures for MEX use of TPU will greatly develop the implementation of modular footwear. Furthermore, a larger study population, in a follow-up study, will corroborate the findings of this investigation.

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