Mix Sustentável

Distributed Manufacturing via Digital Fabrication: A Strategy for Sustainable Local Production of Footwear Components

Manufatura Distribuída via Fabricação Digital: Uma Estratégia para Produção Local Sustentável de Componentes de Calçados

Fabricación Distribuida a través de Fabricación Digital: Una Estrategia para la Producción Local Sostenible de Componentes de Calzado

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Abstract: This research raises questions regarding a systemic change in the current footwear production and consumption model, through the use of strategies oriented towards Distributed Manufacturing and Digital Fabrication of shoes components. It aims to validate such strategies for a sustainable local production, providing small companies of the sector more autonomy and involvement in the processes, towards a more distributed and hybrid (digital and artisanal) manufac-

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turing process. It emphasizes the development of Distributed Economy solutions through the creation of value for actors in small local businesses in the sector. Through a single case study with a participatory observation, the process of redesigning a shoe was conducted in 4 main phases with a small local company in the sector in partnership with a makerspace. The project was carried out with the support of design tools to develop solutions, and as a result, a prototype of a shoe was obtained, made in collaboration between the actors, showing that the local-global capacity of the Distributed Manufacturing via Digital Fabrication strategy has the potential to provide sustainable alternatives to the complex global supply chains for footwear and a possible solution to the excessive consumption of resources in this sector.

Keywords: Distributed Manufacturing; Digital Fabrication; Design for Sustainability; Footwear.

Resumo: Esta pesquisa levanta questões sobre uma mudança sistêmica no atual modelo de produção e consumo de calçados, através do uso de estratégias orientadas para a Manufatura Distribuída e Fabricação Digital de componentes de calçados. Objetiva validar tais estratégias para uma produção local sustentável, proporcionando às pequenas empresas do setor mais autonomia e envolvimento nos processos, rumo a um processo de manufatura mais distribuído e híbrido (digital e artesanal). Enfatiza o desenvolvimento de soluções de Economia Distribuída através da criação de valor para atores em pequenos negócios locais do setor. Através de um estudo de caso único com observação participativa, o processo de redesign de um calçado foi conduzido em 4 fases principais com uma pequena empresa local do setor em parceria com um makerspace. O projeto foi realizado com o apoio de ferramentas de design para desenvolver soluções e, como resultado, obteve-se um protótipo de calçado, feito em colaboração entre os atores, mostrando que a capacidade local-global da estratégia de Manufatura Distribuída via Fabricação Digital tem o potencial de fornecer alternativas sustentáveis às complexas cadeias de suprimentos globais de calçados e uma possível solução para o consumo excessivo de recursos neste setor.

Palavras-chave: Manufatura Distribuída; Fabricação Digital; Design para Sustentabilidade; Calçados.

Resumen: Esta investigación plantea cuestiones sobre un cambio sistémico en el modelo actual de producción y consumo de calzado, mediante el uso de estrategias orientadas hacia la Fabricación Distribuida y la Fabricación Digital de

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Conflict of Interest

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componentes de calzado. Su objetivo es validar tales estrategias para una producción local sostenible, proporcionando a las pequeñas empresas del sector más autonomía e implicación en los procesos, hacia un proceso de fabricación más distribuido e híbrido (digital y artesanal). Hace hincapié en el desarrollo de soluciones de Economía Distribuida mediante la creación de valor para los actores en pequeñas empresas locales del sector. A través de un estudio de caso único con observación participativa, el proceso de rediseño de un calzado se llevó a cabo en 4 fases principales con una pequeña empresa local del sector en asociación con un makerspace. El proyecto se realizó con el apoyo de herramientas de diseño para desarrollar soluciones y, como resultado, se obtuvo un prototipo de calzado, realizado en colaboración entre los actores, demostrando que la capacidad local-global de la estrategia de Fabricación Distribuida a través de Fabricación Digital tiene el potencial de proporcionar alternativas sostenibles a las complejas cadenas de suministro globales de calzado y una posible solución al consumo excesivo de recursos en este sector.

Palabras clave: Fabricación Distribuida; Fabricación Digital; Diseño para la Sostenibilidad; Calzado.

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1 INTRODUCTION

This study is aimed to professionals and researchers in the field of design working in the footwear sector. This sector is also the professional field of activity of the main author of this article, who works as a designer, pattern maker and manufacturer at a small and locally based brand of shoes, partner of this research. The study also had the support and partnership of a makerspace that enabled the development and production of one component for one of the company's shoe models through Digital Manufacturing (DM), which is the focus of this paper. It brings a reflection on promoting more distributed production and consumption systems; developing designers' skills and competencies for sustainability and systemic innovations for value generation for local actors in small businesses, thus enabling a greater distribution of assets, with a view to social and economic equity.

Given this context, it is important to highlight some aspects of the footwear industry that encourage a reflection on the current production and consumption model of this sector. The footwear value chain is very complex, centralized, and globalized. Most manufacturers outsource services or parts of their production due to the wide variety of products and the high competition on prices. The complexity of this context is exacerbated given the lack of support and encouragement for micro and small companies to use new technologies (Hines; Bruce, 2012). For KONGPRASERT e BUTDEE (2017), achieving sustainability in the footwear production and consumption system implies increasing the value in the sector's products and services, by making a transition to slower production cycles and locally based production systems. Also, the dominant economic model of the sector, based on large-scale centralized production, establishes dynamics that also distance consumers from the production process and reduce opportunities for local actors to appropriate and control their economic environment. Consequently, according to VEZZOLI *et al.* (2018), this model mischaracterizes cultural identities and limits the diversity of local economic activities. Therefore, the network connections proposed by the Distributed Economy (DE), if properly designed, and considering the principles of sustainability, has the potential to promote the sustainable development of a given sector. Local actors can share their resources in different ways, including skills, knowledge, and their production or service capabilities (Santos *et al.*, 2021).

Hence, this paper describes the developing process of a sole for a shoe through the use of Distributed Manufacturing (DM) via Digital Fabrication (DF) as a result of a redesign project of a shoe model designed by the research partner. The main objective established by the designers and leaders of the company for the shoe redesign was to implement the greatest number of strategies oriented towards the Distributed Economy (DE) in the short term. In order to achieve this, the strategy selected was DM via DF, given the difficulty presented by the company in acquiring inputs and components for the footwear production locally, as the region where the company is located (Curitiba, Brazil) does not have manufacturing industries of the sector. The redesign project focused on the Pre-Development phase of products, and it was made based on the model proposed by ROZENFELD *et al.* (2006), where the main objectives are to guide the best decision about a company's product portfolio and the definition of the project's final objective.

Also, according to VEZZOLI *et al.* (2018), the initial phases of the product development process are the

most efficient for implementing sustainable design strategies. Thus, through the research process a partnership with a local DF laboratory (makerspace) were sought to assist in solving the problem reported by the company related to the lack of access to local inputs (such as soles and insoles for the shoes) and also, to add value to the company product through the use of DM via DF, ensuring the valorization of local resources and skills, an important principle for the Distributed Economy concept. Given the above, the main goal of this **paper is to validate distributed manufacturing via digital fabrication as a strategy for a sustainable local production of footwear components for small companies of the sector,** providing them more autonomy and involvement in the processes, towards a more distributed and hybrid (digital and artisanal) manufacturing process.

2 THE UNSUSTAINABILITY OF THE FOOTWEAR SECTOR

The fashion world, considered a great expression of human creativity and artisanal expertise, is responsible for unsustainable practices that lead to environmental, social, and economic impacts (Vezzoli *et al.*, 2022). Sustainability initiatives in the footwear industry are being implemented, but they still have little impact. The high volume of solid waste generated throughout the production chain, the waste of resources, the productive or unsold surplus, and the footwear itself at the end of its life cycle are typically discarded in landfills due to a lack of management systems in the sector and in cities (Ashton, 2018; Rathinamoorthy; Kiruba, 2020; Sharma *et al.*, 2021; Vier *et al.*, 2021).

The footwear industry depends on a wide range of components made from different materials, including leather, rubber, synthetic or plastic materials, canvas, rope, and wood, among others (Muller; Paluszek, 2017). Given the huge variety of shoe models and styles, there are also hundreds of different production processes and designs, which makes footwear a complex and delicate crafted product (Rathinamoorthy; Kiruba, 2020). Hence, the footwear sector's value chain determines the relationship between stakeholders, connects suppliers, manufacturers, distributors, wholesalers, retailers, customers, and organizes the flow in channels between them for the acquisition of raw materials, processing into finished products, and distribution to the final consumer (BoËr; Dulio, 2007).

This industry has been experiencing accelerated growth, which, combined with the rising of input prices, triggers a strong competition between brands and manufacturers, resulting in significant impacts on the economic dimension of sustainability (BoËr; Dulio, 2007; WORLD FOOTWEAR, 2022). Also, the annual report of the United Nations Economic Commission (UNECE, 2018) points to the footwear sector as responsible for environmental impacts that contribute to health risks for humanity and the environment. Even though there have been efforts to use durable, biodegradable, sustainable, or low-emission materials, quantitative information on the long-term environmental implications of recently created smart materials is still scarce. The footwear industry also depends heavily on chemical products, which are the main causes of pollution and environmental degradation (Rathinamoorthy; Kiruba, 2020).

Despite the existence of new technologies, the vast majority of manufacturers still rely on artisanal practices as their main resource (ABICALÇADOS, 2022; Passos, 2014). The lack of transparency and trace-

ability of the footwear value chain, also generates impacts on the social dimension of sustainability (Hines; Bruce, 2012). Given these facts, the role of Design for Sustainability (DfS) and innovation in the production processes and the sector's value chain, proves to be fundamental to rethink the initial design phase of shoes by implementing more sustainable strategies within the sector, which can be also considered a central technical challenge for small businesses (Rinaldi; Bandinelli, 2021).

However, the vast majority of footwear industries and brands adopt a production model called fast-fashion, characterized by efficient and fast production, where items are consumed and discarded within a short period of use (Tapia *et al.*, 2021). This production model is characterized by low worker pay and reduced raw material quality, often adopted to reduce the cost of items for consumers, which consequently leads to increased consumption and waste (Vezzoli *et al.*, 2022). This is also a direct effect of centralized, high-capacity mass production. The linear, centralized production model typically restricts design, production, and innovation through patents and intellectual property rights, becoming barriers for small producers seeking to contribute to locally based economic activity (Santos *et al.*, 2021).

In this sense, the concept of the Distributed Economy (DE), where circular flows of resources, connections, and collaboration between actors, emerge as activities that run counter to centralized, linear production (Johansson; Kisch; Mirata, 2005). If this model is properly designed with sustainability principles in mind, it has the potential to promote the sustainable development of a given sector. Local actors can share their resources in various ways, including skills, knowledge, and their productive or service capabilities (Santos *et al.*, 2021).

2.1 Distributed Manufacturing and Digital Fabrication

The Distributed Economy (DE) involves small-scale production units, located close to or in the same location as end users, who in turn can also become producers and have control over activities, assuming the role of manufacturer or service provider. They can be standalone or connected to share various forms of goods and services. DE's local units are capable of meeting nearby local needs, including artifact production and service demands throughout the product lifecycle (Santos *et al.*, 2021). The International Institute of Environmental Industrial Economics (IIIEE, 2009) defines DE as an alternative structure for society and the economy, based on small-scale businesses in a local economic context, potentially leading to a more sustainable social and economic structure. It also lists some of the key elements that can be attributed to the concept of DE: (i) expanding the use of local renewable resources; (ii) generating wealth for a greater number of people; (iii) reducing pollutant and waste emissions at the local and regional levels; (iv) locally maintained value-added benefits; (v) greater sharing of skills and knowledge; (vi) higher value-added material resources; (vii) diversity and flexibility of economic activities; (viii) increasing the diversity and intensity of communication; (ix) collaboration between local activities.

Hence, DE is a concept developed given the current industrial production systems, which promotes innovative regional development strategies, where production units can be much more flexible and resilient to

respond to changes (Johansson; Kisch; Mirata, 2005). Thus, Distributed Manufacturing (DM) is the small-scale production unit's system, where individuals, small businesses, and a local community can become producers. The proximity between production units promotes interaction with end customers and production facilities, such as factories, workshops, personal fabrication labs or makerspaces (Caccere; Santos, 2017).

The topic of DE is relevant to the footwear sector as the centralized current model has demonstrated a comparatively high level of impacts. Communities and the environment, in both developing and developed countries, suffer at the expense of companies that are not based in communities and seek low-cost labor and resources in other countries, adopting production and distribution practices with high impacts (IIIEE, 2009). CLARK (2008) introduces the concept in the fashion industry as a tool to promote sustainability, strengthening the local economy, allowing personalization, and diversification of products, providing direct interaction between producer and user, implying greater transparency in the consumption and production system. The implications of DE for the footwear sector are highlighted in ANDRADE (2024)'s research, which demonstrates how the concept can mitigate the impacts caused by the sector in the environmental, social, and economic dimensions.

In the environmental dimension for example, it can support the transition of companies in the sector to the Circular Economy; reduce the demand for inputs from the globalized value chain, reducing environmental impacts. In the social dimension, DE promotes a culture of mutual aid; promotes greater socioeconomic equity and social cohesion; reducing problems of human and labor rights violations caused by a lack of traceability and transparency, and social, racial, and gender inequalities. While in the economic dimension, it enables on-demand and customized production; fosters new business models creation; monitoring of product performance and implementation of changes more quickly and effectively due to the advantages of local production control; facilitates negotiations with suppliers and promotes the growth of local skills and the development of the local economy (Andrade, 2024).

The implications of DE also highlighted the generation of new use of the potential emerging digital technologies in the footwear sector, such as IoT (Internet of Things), AI (Artificial Intelligence), and DF (such as Additive Manufacturing technologies). This phenomenon enables mixing digital and physical technologies, greater flexibility in manufacturing and service provision, and knowledge-sharing among local actors (Vezzoli *et al.*, 2018). DF is associated with new manufacturing skills through the use of technologies and digital control systems, and it can bring the designer closer to the manufacturing process of their creations and has the potential to reduce the impacts caused by the fashion sector by involving, respectively, distributed design and distributed manufacturing (DM) (Caccere; Santos, 2017; Pasetti, 2021; Perez; Santos, 2017). It also has the potential to enable customizations and manufacturing closer to or carried out by the end user (prosumer), potentially reducing the resources required for transportation and packaging. FabLabs, which are workshops for sharing equipment, production, and digital resources, encourage the spread of the Maker Culture and Self-production, these approaches imply the propagation of the DE concept (Santos *et al.*, 2018).

An example is the shoe "microfactories" presented by MONTES e OLLEROS (2020). In their study, the authors describe the processes of two innovative shoe factories, significantly smaller and highly digital and automated. These factories enable the production of personalized shoes in small batches. This, in turn,

enables designers to involve groups of users and isolated suppliers to develop solutions and collaboratively configure a new product, service, or Product-Service System. This collaboration network includes laypeople, prosumers, producers, creative communities, specialists from different areas, and the role of the Designer becomes the articulation of this network (Santos *et al.*, 2021). On-demand production also allows for small batch manufacturing or even custom fits, while also adapting product design and lifecycle management. It makes it possible to directly connect producers to consumers, or even other actors involved throughout the product life cycle (BoËr; Dulio, 2007; Montes; Olleros, 2020; Morlet *et al.*, 2019).

Another relevant example to mitigate the impact on the footwear sector through DM and DF is the 'ShoeLab.' This project originates from a feasibility study on DM and the Circular Economy. MORENO *et al.* (2017) analyze this project, examining how the use of DM, combined with a product-service system (PSS) approach and emerging technologies, can enable a new strategy for the footwear industry. The project proposes on-demand footwear production for consumers, integrated with digital manufacturing to facilitate reverse logistics and the recycling of shoes at the end of their life cycle. According to the authors, the project demonstrates the validation of a business model concept with significant potential in the footwear industry, combining circular and distributed strategies.

Thus, small-scale production units can be supplied with local resources or via DF, reducing the impacts arising from the transport of raw materials and products (IIIEE, 2009). Given the arguments presented so far, it is clear that there is a possibility of a new relationship between companies in the footwear sector and their resource flows. With a more democratic management of its activities, it implies a systemic change for the footwear sector.

3 METHODOLOGICAL PROCEDURES

This study aims to solve a practical problem by presenting a real solution and knowledge applied to a specific situation. Thus, the nature of the research is applied and the approach is qualitative (GIL (2017)). The objective is exploratory in order to understand the research problem and research concepts (Prodanov; Freitas, 2013). Therefore, the method used to conduct the research was a **case study** with **participatory observation**, and it was carried out in 4 main phases as described below:

Phase 1: A **systematic literature review** was conducted to define the main constructs regarding the three areas of the research: Footwear Industry, Distributed Manufacturing, and Digital Fabrication.

Phase 2: The **case study** was carried out through a **participatory observation** of a shoe redesign project in a small company of the footwear sector in partnership with a makerspace, both located in the city of Curitiba-Brazil. This phase took place on the premises of the research partners, and had the participation of the designers and leaders of the organizations. Within the context of developing the redesign of a product, a **workshop** was organized with the designers and leaders of the company, based on the Pre-Development phase of the Product Development Process model proposed by ROZENFELD *et al.* (2006).

The process involved the use of several design tools based on PAZMINO (2015), to support the creation

process and decision-making, such as the **analysis of the company's product portfolio**; a **polarity matrix**, used to establish **priorities and requirements** for the project based on DE principles; a **brainstorming session** with the application of a **morphological matrix** tool to develop alternatives for the project; followed by a **decision matrix** to support the selection of the alternative to be developed integrating as many ED solutions as possible in the short term.

Phase 3: Consisted of the realization of the project in a real situation. After selecting the alternative to be developed for the footwear redesign project, a prototype was made in **co-design** between the footwear company and the makerspace. The co-design process means the active involvement of the stakeholders throughout product development, and value creation is collaborative, with the exchange of experiences among those involved, who are encouraged to have autonomy in their decisions to solve the problem. It refers to the collective creativity of partners, designers, and the future user (Leite, 2021; Santos *et al.*, 2021).

The project and the shoe prototype production made it possible to understand the viability of the shoe component production and the shoe as a whole using the DM strategy via DF in practice. In order to validate it, a **semi-structured** interview was conducted to the company's designers and leaders, which sought to assess their perceptions regarding the use of the design tools used in the project; understand how the project helped in the reflection on the concepts of DE; the degree of perceived learning resulting from its application; the effectiveness in identifying opportunities for short-term improvements for the development of DE-oriented solutions in the initial phases of footwear development; and also, whether the resulting solution was aligned with the strategic planning, enabling the DM strategy via DF in the business.

Phase 4: Finally, a critical reflection is made on the possible advances in knowledge resulting from the developed project and, also, the viability of its integration into the practice of small companies in the footwear sector. Further analysis, for an in-depth discussion is made based on the results obtained, and supported by the theoretical basis presented, both within the scope of the constructs presented, as well as the principles and heuristics aimed at implementing ED.

4 RESULTS

The main activity of the footwear company partner of the research is the creation, development, production, and sales of shoes. The business model emphasizes the recovery and appreciation of the classic and traditional shoemaking process, where artisanal techniques guide the production model. The brand has been serving the local market for over 10 years with a small-scale production, reusing leather and textile leftovers from other local industries as a source of raw materials for the uppers (the superior part of the shoe). But most of the other inputs are provided by several partners from different regions of the country (such as rubber, ready-made soles, laces, eyelets and buckles). These components from different suppliers are prepared, cut and/or sewn in the brand's workshop, that is, they are handcrafted, resulting in the finished products locally.

Nevertheless, the dependence on these inputs, that comes from external locations, reduces autonomy and possibilities in product design, and generates negative impacts caused by transportation. Despite the local

production model, all the creation and production process are centralized, since the shoes production method consists of 3 main parts, that are produced separately and then glued and sewn together (sole, insole and upper).

As proposed in the Product Pre-Development phase by ROZENFELD *et al.* (2006), the **analysis of the product portfolio** must be the first activity carried out on a redesign project or a new product development. It aims to ensure that the company has a set of projects that meet the needs of its target audience and are aligned with the business's strategic planning. The portfolio analysis is a process of deciding which projects should or should not be developed. This process involves evaluating existing projects and products, identifying new ideas, prioritizing, and selecting products.

This stage took place through a workshop planned and carried out by researchers on the premises of the company, with the participation of the designers and leaders from the organization. In this very first step, the designers and leaders from the organization discussed all the products from their portfolio. The team analyzed 20 different footwear models and their variations already developed by the company, in order to define the product to be developed, so that it contemplates short-term changes oriented towards ED.

The products in the company's portfolio have already defined and established technical, modeling, and production process aspects. Not all models are currently in production and commercialization, but with each decision to produce a new batch, some technical aspects undergo necessary adaptations, and materials are modified based on availability in the company's inventory. Considering the wide variety of models already developed by the company, the team opted to redesign one of the models in the portfolio, with the support of a **decision matrix**.

Some criteria were established considering environmental aspects of the products, customer acceptance and time of year for launch (summer or winter). The shoe selected for the redesign project was one of the brand's first successful creations and represents several of the company's concepts, such as quality and durability, and appreciation of the shoe craft. The shoe model is called Derby, and its production was discontinued in 2019 when the supplier of natural latex plates for the soles closed its activities. The designers tried to replace the artisanal production of soles from plates with ready-made soles to optimize the production process and reduce waste, but the cost of developing ready-made soles for this model with external suppliers became unfeasible for the business. Figure 1 presents the Derby shoe model before the redesign project.

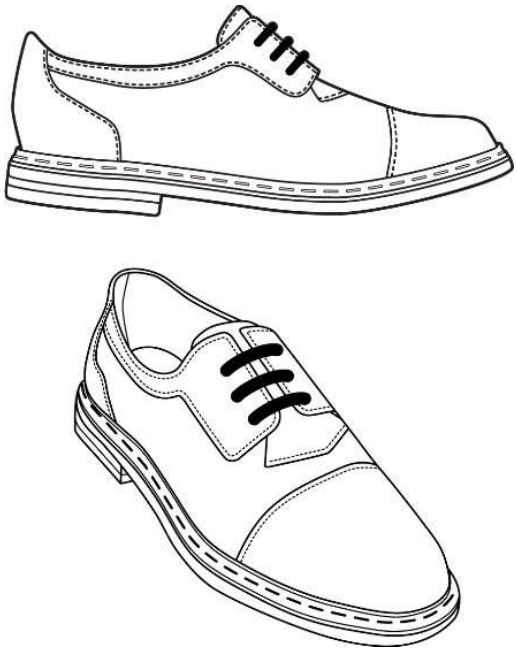

Figure 1 – The Derby Shoe Model Before the Redesign Project

Source: Authors (2024).

Once the product to be redesigned from their portfolio was selected, the group established **priorities and requirements** for the project that could be achieved in the **short-term**, based on DE principles and locally available resources for its production with the support of a **polarity matrix**. The priorities and requirements were: i) the shoe must guarantee easy repair and maintenance, extending its life cycle; (ii) the insole must be replaceable; (iii) the product design must maintain the elements that identify the brand, (iv) it must allow better use of leftovers from the business own production and/or enable the reuse or incorporation of leftover materials from other companies; (v) the project must meet the desires and needs of the local public by promoting better approximation and also prioritize partnerships with local suppliers or service providers.

Therefore, to assist the development of the next redesign phase, a **brainstorming** session was conducted to generate new ideas for the project and the group designed alternatives using a **morphological matrix**, as shown in Figure 2.

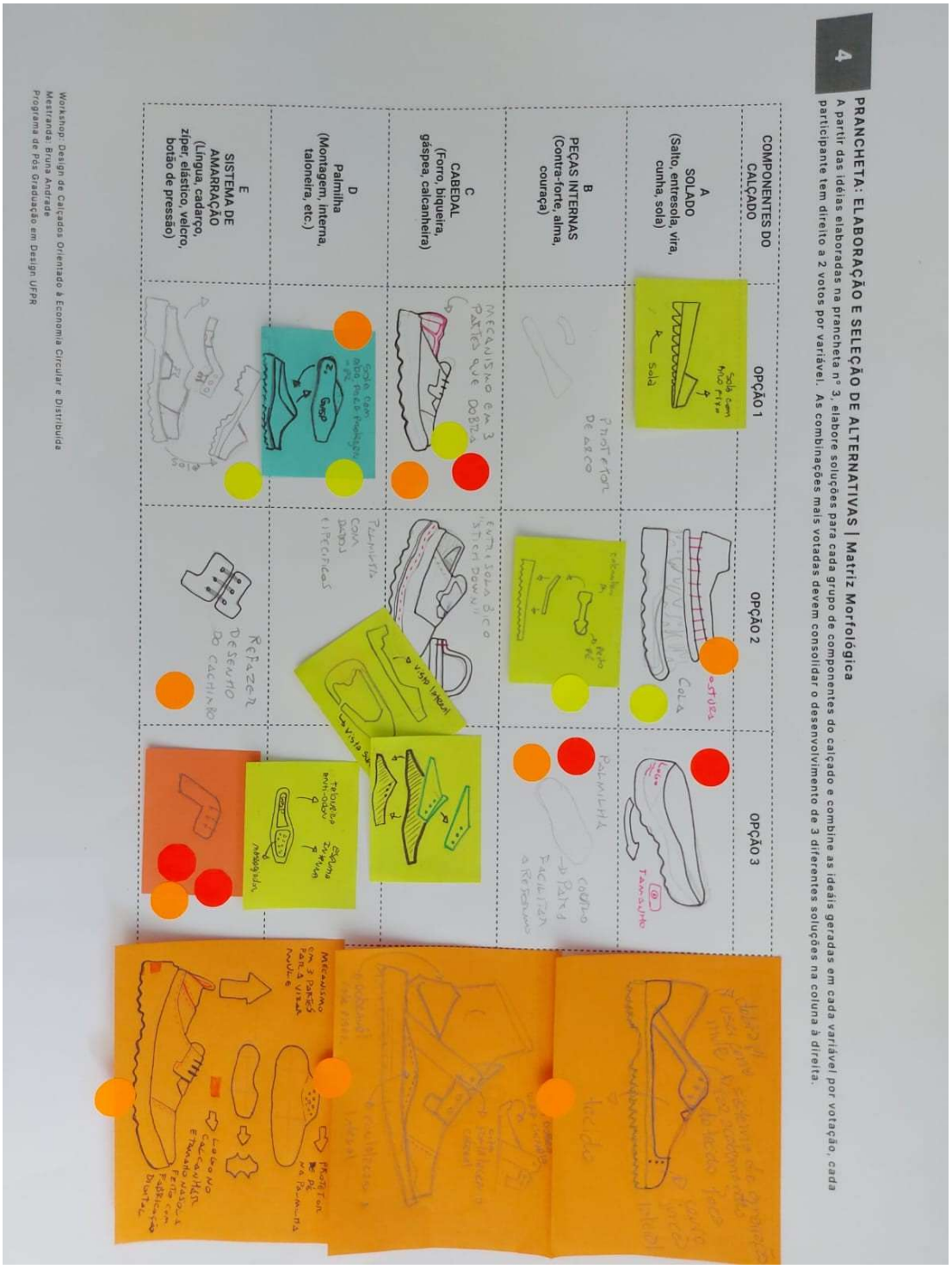

Figure 2 – Morphological Matrix for the Derby Shoe Model Redesign

Source: Authors (2024).

Through the creation process, it was decided that the sole of the shoe (one of the three main components) could be created in partnership with a local makerspace, using DF tools. This decision was taken due to the lack of suppliers of this component locally, and as a way of taking a first step in decentralizing the footwear

production, by integrating a local partner in this process. Another important decision made during this phase, was that customers would become the suppliers for some of the shoe inputs for the uppers, by providing disused textile or leather materials. which would be only produced on-demand. According to the designers, this is important in order to optimize the use of disused local materials, and also to bring the customer closer to the brand and meet their desires and needs in a co-design process.

The workshop resulted in the development of ED-driven solutions for the redesign of the research partner company's Derby shoe model. The company's designers and leaders opted to develop a prototype of the selected alternative in partnership with the Makerspace to test the solutions.

The final concept for the Derby redesign seeks to optimize the lifespan of the product and materials, value local resources, skills, and culture, and strengthen and value local resources and skills through a campaign to encourage customers to send in disused textile materials for reuse in the shoe upper, ensuring that the shoe will be made exclusively on demand. Figure 3 represents the alternative designed and selected during this process, ensuring a product customization.

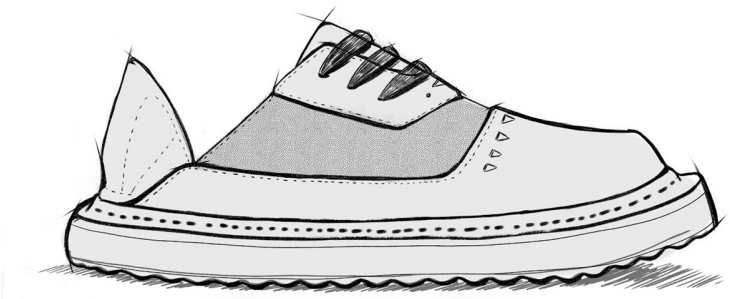

Figure 3 – Alternative Selected for the Derby Shoe Model Redesigned

Source: Authors (2024).

The **local makerspace** selected to support the project provides services such as product sprints, courses and workshops, 3D scanning, 3D printing, CNC milling, laser cutting, electronics and IoT development, molding and casting services. A meeting between the designers and leaders of both organizations was held, to understand what could be accomplished in terms of developing a sole for the shoe. The decision-making during the project was a collaborative process, where the makerspace offered their services and resources, and the company's designers shared their knowledge about the product, the materials, and the production processes.

The details of sole development using DM via DF were not part of this article's text production scope, although they were part of the broader research scope. For more information on the development and formulation of the sole using DF technologies, refer to ANDRADE (2024)'s research, which describes in detail the

processes, steps, and results of the prototype development that occurred during this research.

As a result, a prototype of the Derby shoe was developed, in which the sole was designed and produced within a makerspace. The prototype sole was created via DF through the use of additive manufacturing by printing with TPU material (Thermoplastic Polyurethane - a flexible and resistant elastomer). The shoe's upper was made from materials provided by the customer. The digital optimization process with the brand's elements can be seen in Figure 4.

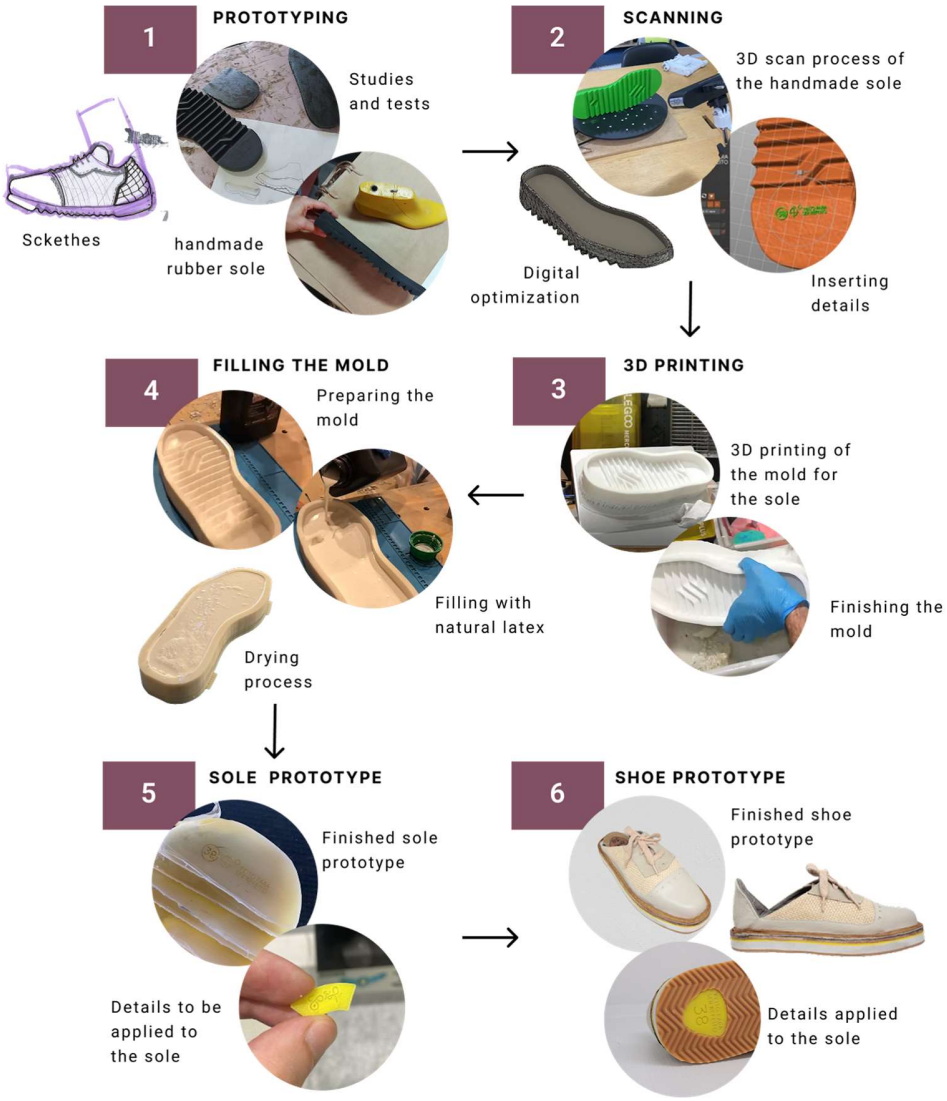

Figure 4 – Digital Optimization with the Brand's Elements

Source: Authors (2024).

The sole design process and prototyping development using digital fabrication technologies is shown in Figure 5.

Figure 5 – Sole Design Process and Prototype for the Derby Shoe Model Redesign

Source: Authors (2024).

The insole was produced by the company itself, using leftover materials from its own production. The complete shoe sole development process via digital fabrication, from design to final prototype assembly is shown in Figure 6.

Figure 6 – Shoe Sole Development Process Via Digital Fabrication

Source: Authors (2024).

The semi-structured interview with the designers and leaders of the company revealed that integrating DM and DF strategies in their business was considered feasible. According to them, having local partner was essential to ensure autonomy in product development and customization for the company's brand, in addition to agility in prototyping and optimization of transportation costs and lead times for production, and also for enabling the production of small batches on demand. They also highlighted some of the advantages and potential benefits that could be obtained from the integration of DM and DF in their business model, such as: greater product diversity, production of unique and customized pieces, greater customer involvement, strengthening

local partnerships, local economic development, reduced environmental impact through reduced transportation and material waste, and the possibility of expansion to other product lines.

5 DISCUSSION

The adoption of DM via DF strategies proved to be an effective way to increase the autonomy of small companies in the footwear sector. The partnership between the research partner and the local makerspace enabled the production of customized components (the shoe sole), which would not be possible through traditional supply chains, given the high costs and minimum order quantities typically required by large suppliers. This result corroborates the findings of JOHANSSON, KISCH e MIRATA (2005) and SANTOS *et al.* (2021), who argue that distributed production units can be more flexible and resilient, capable of meeting specific local demands.

The project demonstrated that the use of design tools adapted for implementing ED principles can facilitate decision-making in small businesses. The morphological matrix, polarity matrix, and other tools helped structure the creative process and ensure that sustainability criteria and ED were considered from the beginning of the redesign. This approach aligns with the recommendations of VEZZOLI *et al.* (2018) regarding the importance of integrating sustainability strategies in the initial phases of product development.

Regarding the environmental dimension, the project contributed to waste reduction in several ways: (i) use of customer-provided disused materials for the shoe upper; (ii) use of production leftovers for the insole; (iii) local production of the sole, reducing transportation impacts; (iv) on-demand production model, eliminating unsold inventory. These results support the arguments of GWILT (2020) about the potential of distributed and circular strategies to mitigate environmental impacts in the fashion sector.

In the social dimension, the project promoted greater interaction between different actors: company, makerspace, and customers. This collaboration strengthened local ties and enabled knowledge sharing between the partners. Customers became active participants in the production process (prosumers), which can increase emotional attachment to the product and extend its useful life. These findings are consistent with the principles of co-design and participatory production advocated by Leite (2021) and ARMSTRONG *et al.* (2021).

From an economic perspective, although the unit cost of producing a sole via DF is higher than mass-produced soles, the total cost considering transportation, minimum order quantities, and storage becomes competitive for small batches. Furthermore, the possibility of customization and the use of local resources add perceived value to the product, which can justify a price premium. These results align with the discussions of MONTES e OLLEROS (2020) about the new economies of scale enabled by digital microfactories.

However, it is important to highlight some limitations and challenges identified in the project. First, the production capacity of a makerspace is limited compared to industrial facilities, which means that the DM via DF model is more suitable for small batches and customized production. Second, the technical knowledge required to operate DF equipment represents a barrier for some small companies, requiring training or specialized partnerships. Third, the durability and performance of digitally fabricated components need to be

validated through long-term use tests.

Moreover, RODRIGUES (2025)'s research discusses the future of work in fashion from the perspective of emerging technologies and investigates principles and strategies that integrate DF technologies via DM. Based on a study of multiple cases of small businesses in the fashion sector that already employ the strategies discussed in this article, Rodrigues's research resulted in guidelines to guide small entrepreneurs on how to lead their fashion brands toward a more sustainable and distributed context, also leveraging remote work and the hybrid use of technology (digital and artisanal), which allows greater autonomy for designers and producers as demonstrated in the shoe prototype development process in this article.

According to the results of her research, the author also highlights the advantages of DM and the use of emerging technologies, such as making the industrial production more efficient; facilitating the use of upcycling techniques; robotics and blockchain used to track raw materials, as well as certify their origin and products and control supply chains; increased transparency in production chains; reduce steps between design and prototype, eliminating potential errors, among others (Rodrigues, 2025).

The development of the prototype in this project proved that shoe production is feasible with the support of a local makerspace with DF resources. The process used to develop the sole carried out in this research, also raises reflections about carrying out future studies that incorporate the use of local materials in the sole production (such as leftovers from local rubber industries or even the use of different natural fibers), expanding also the use of circular economy strategies.

Other advantages identified, deals especially the reduction of dependence that small local brands have on large inputs and components suppliers for footwear production. By developing the soles locally via DM and DF they can increase their autonomy in the design and production processes, increasing the diversity of their local economic activities, as proposed by Santos *et al.*, (2021). Likewise, as previously mentioned, the DM via DF strategy applied in the project has the potential to increase the perceived value through the quality and design capital inserted into the shoe, including the exclusivity of on-demand production and the consumer's emotional involvement with the shoe and the brand itself.

Using DF in design, modeling, prototyping, or part-production (components) not only promotes innovation but also optimizes processes and uses fewer financial resources, as it operates through the use of digital technologies and systems. DF allows designers to become more involved in the manufacturing process of their creations and has the potential to reduce the impacts of the fashion industry, as it involves distributed design and distributed manufacturing, respectively (CACCERE e SANTOS (2017); Santos *et al*., 2021).

In addition to the theoretical implications, this study has practical implications for small companies in the footwear sector and for public policies aimed at promoting sustainable production. The validation of the DM via DF model in a real case provides evidence that these strategies are not just theoretical concepts, but viable alternatives that can be implemented by small businesses with adequate support. This includes access to makerspaces or fab labs, training in design tools and digital fabrication technologies, and incentive programs for local partnerships.

The results also suggest that educational institutions, especially design and engineering schools, have an important role in preparing future professionals to work with these new production paradigms. Curricula should

include not only technical skills related to DF, but also knowledge about sustainability, distributed economy, and co-design methodologies.

It is important to note that the transition from a centralized production model to a distributed one is not a binary process, but rather a spectrum of possibilities. Companies can adopt hybrid approaches, combining mass production for certain components with local and customized production for others, depending on technical and economic feasibility. This flexibility is one of the advantages of the DE concept, which recognizes the diversity of contexts and allows for adapted solutions.

Finally, it is crucial to emphasize that the environmental benefits of DM via DF are not automatic. As pointed out by several authors, digital technologies also have environmental impacts, including energy consumption, electronic waste, and the use of virgin materials in some printing processes. Therefore, the implementation of these strategies must be accompanied by a careful analysis of the entire lifecycle and the adoption of complementary practices, such as the use of renewable energy, recycling of materials, and design for disassembly and reuse.

6 CONCLUSION

The footwear redesign project was developed and implemented in the short term by the research partner company with the active participation of the authors of this article. The choice of DM via DF strategies for the footwear redesign was made by the company's designers and leaders and worked within the context of the research application, once the shoe prototype was developed.

This project was able to generate solutions for the local production of shoes for the research partner through the association of the principles and concepts of DE through DM via DF strategy. Even though the project resulted in the redesign of a shoe that incorporated the greatest number of viable strategies oriented towards DE in the short-term, environmental, social, and economic concerns in the development of the sector's products must be also oriented to change patterns that result in the reduction of excessive consumption.

However, the company did not make profound changes to the existing production chain, a new local stakeholder was involved within the shoe redesign project in order to strengthen and value local resources and also skills and competences, in a collaborative process, an important step towards making the production less centralized and more local. It was observed that micro and small businesses have inherent characteristics such as agility in the decision-making process and greater proximity to their immediate market, which can facilitate the implementation of DM.

Hence, it is possible to conclude that similar companies in the footwear sector can act as agents of change in the current production and consumption patterns from the perspective of DM via DF strategy. Given the results presented, it's possible to infer that the footwear sector can benefit from strategies focused on policies, programs, and projects to improve sustainability, as well as the formation of DM organizations within cooperatives, local production arrangement models, and even geographical indication labels. These strategies can foster a more distributed model of economic activities within a given region, promoting greater resilience

at the local level. The work also broadens the discussion to the possibilities of a more distributed design, mainly through vernacular design, open-source platforms and approaches and tools that can facilitate footwear co-creation processes in the sector

Nevertheless, the solution for the integration of DM and DF strategy in the sector also has repercussions on discussions about changing lifestyles and the development of new business models, as every activity implies an impact. Although digital technologies can support the implementation of distributed manufacturing, it is important to note that they also incur an indelible environmental impact. Thus, further research is recommended to understand the electronic waste associated with these technologies and its high energy consumption.

Additionally, the search for the production or provision of locally-based services may require knowledge and material or cultural resources that cannot be available locally. Therefore, it is considered that the implementation of this concept does not necessarily imply a positive impact if it is not the result of a careful design and planning process. Nevertheless, micro and small businesses in the footwear sector have specific needs and need personalized measures to implement the DM via DF strategy in their processes.

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