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The contribution of Industry 4.0 technologies to developing new services that support sustainable and circular practices – the case of footwear companies

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I would like to dedicate this present study to all the people who, directly or indirectly, had contributed to this journey.

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Abstract

The businesses' change to respond to sustainability issues is more urgent when the focus is on sectors with negative impacts on the environment, high production levels, high volumes of virgin materials utilization and waste. The textile industry, and inherently the footwear, is part of this sectors.

Industry 4.0 technologies have the potential to change business models, favouring sustainable practices. Still, knowing what can be expected in research areas such as business model transformations, organizational configuration, and product innovation, they are still under research. Thus, this study aims to understand how the Industry 4.0 technologies adoption can contribute to developing new services that support sustainable and circular practices in the footwear sector. A qualitative study was conducted, collecting data from interviews to key-informant interviews of Portuguese footwear companies along the footwear value chain.

Findings demonstrate a shared concern regarding sustainability, mainly focused on the environmental and economic dimensions, which is being translated into implementing sustainable and circular practices. The improvement in the process of sharing information (transparency) in the footwear value chain, with the adoption of traceability practices, is seen as a crucial step for sustainable development. Nevertheless, the companies' low level of digital maturity limits the business models transformation. This is reflected in difficulties in identifying and creating services to contribute to sustainable and circular practices. Legislation and a more conscious customer mindset towards sustainability are two critical drivers for this transformation. This study contributes to the literature regarding sustainable business models, enriching the knowledge regarding business models' transformations and the creation of new services with the adoption of advanced technologies. Findings contribute to the understanding of what are the potentialities of Industry 4.0 technologies and digitalization within companies' processes and operations to promote sustainability practices, and to the identification of what can be the expected limitations and difficulties that can be faced during the digitalization path.

Keywords: sustainability, circular Economy, Industry 4.0, traceability, business model innovation, services

JEL-codes: L20; L67; O14; O30; Q55

Resumo

A mudança dos negócios para responder às preocupações relativas à sustentabilidade é ainda mais urgente quando são referidos setores que têm impactos negativos no meio ambiente, com altos níveis de produção, de volumes de utilização de matérias primas e de resíduos. A indústria têxtil, e inerentemente o calçado, é um exemplo.

As tecnologias da Indústria 4.0 têm o potencial de transformar os modelos de negócio, favorecendo práticas sustentáveis. Ainda assim, saber quais podem ser as transformações esperadas no desenho dos modelos de negócio, na configuração organizacional, e na inovação dos produtos carece de investigação. Este estudo tem como objetivo compreender de que forma a adoção de tecnologias da Indústria 4.0 pode contribuir para o desenvolvimento de novos serviços que suportem práticas sustentáveis e circulares, no setor do calçado. Foi realizado um estudo qualitativo, sendo os dados recolhidos através de entrevistas a atores-chave de empresas portuguesas localizadas ao longo da cadeia de valor do setor do calçado.

Os resultados demonstram uma preocupação das empresas em relação à sustentabilidade, principalmente focada na dimensão ambiental e económica, que se traduz na implementação de práticas sustentáveis e circulares. A melhoria nos processos de partilha de informação (transparência) da cadeia de valor do setor, com a adoção de práticas de rastreabilidade, é vista como um passo crucial para o desenvolvimento sustentável. No entanto, o baixo nível de maturidade digital das empresas limita a transformação dos modelos de negócio. Isto traduz-se em dificuldades na identificação e criação de serviços que contribuem para práticas sustentáveis e circulares. A definição de legislação específica e uma mentalidade mais consciente dos consumidores (no sentido da sustentabilidade) são dois fatores críticos para esta transformação. Este estudo contribui para a literatura sobre modelos de negócio sustentáveis, contribuindo para o conhecimento relativo a transformações dos modelos de negócio e a criação de novos serviços com a adoção de tecnologias avançadas. Os resultados contribuem para a compreensão das potencialidades das tecnologias da Indústria 4.0 nos processos e operações das empresas, para promover práticas de sustentabilidade, e na identificação das possíveis limitações e dificuldades das empresas durante o processo de digitalização.

Palavras-chave: sustentabilidade, economia circular, Indústria 4.0, rastreabilidade, modelos de negócio, serviços

Códigos JEL: L20; L67; O14; O30; Q55

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1. Introduction

The textile industry comprises clothes, footwear, and household textiles, having the clothing segment the largest share of textile consumption in the European Union (EU) (EC, 2022). This sector plays an important role in the European manufacturing industry, being composed of more than 160.000 companies and more than 1.5 million employees, and it is mainly based on small and medium enterprises (SMEs). Furthermore, Italy, France, Germany, Spain, and Portugal account for three-quarters of EU production in this sector (EC, 2022).

Despite its importance to the European economy, the textile industry is also known for its negative impacts on the environment, which are difficult to limit due to its global supply chain and network. The consumption of textiles in the EU has the fourth-highest negative impact on environmental conditions (EC, 2022). Being traditionally characterized by a linear model of production, where a product is manufactured, consumed, and disposable, it accounts for high levels of natural resources consumption and high volumes of waste and pollution (European Parliament, 2019). In the EU, 5.8 million tons of textiles are discarded every year and this becomes a problem since less than half of these discarded products are reused or recycled. The fast fashion trend of production and consumption, characterized by rapid production, low prices, and low quality of products, contributes to this negative impact of the textile industry on the environment. This trend is expected to grow, pressed to meet customer demand (EC, 2022). It is known that, if the production model of the industry remains the same, by 2030 the values of water consumption, CO_2 emissions, and waste would increase by at least 50% (European Parliament, 2019).

A transformation of the textile industry production model is needed to ensure a sustainable future for this industry. The introduction of circular activities into the practices of textile companies is crucial to extend the life of products through reuse, repair, and recycling initiatives, which allow to decrease the utilization of natural resources (EC, 2022). In this sense, the Circular Economy represents a new market paradigm, defending a closed-loop supply chain with the main objective to improve resource efficiency and environmental conditions (Rajput and Singh, 2019). Consumers are more aware of certain activities' impacts on the environment since sustainability is gaining importance in society. Companies are also more concerned about their role among different stakeholders, leading to the emergence of the Corporate Social Responsibility concept that illustrates the new vision of companies as profit

organizations with social responsibilities (Thorisdottir and Johannsdottir, 2020).

Advances in technology allow this transformation of business models to occur in a more efficient, successful, and sustainable way. Digitalization impacts the organization along the value chain and the performance of business models, requiring their innovation (Parida et al., 2019). The adoption of some technologies, that have emerged with the Industry 4.0 revolution, is crucial for this adaptation of industries, ensuring the creation of value for both companies and consumers. Industry 4.0 represents the interconnection between physical and digital environments, allowed by advanced technologies (The Internet of Things, cloud computing and analytics, artificial intelligence, and machine learning), which creates an automated manufacturing system, improving operations efficiency (García-Muiña et al., 2020). With these technologies, it is possible to have access to real-time data, which improves businesses' decisions, as it allows avoiding production errors and, with this, waste of materials; customers' experiences, enabling a closer relationship with companies, and allowing more sustainable purchase decisions; and businesses' efficiency, since the connectivity between devices creates a more autonomous production process (Rinaldi et al., 2022). It is expected that Industry 4.0 technologies incorporation by companies will allow an improvement of around 20% in efficiency and will be responsible for more than 20% of the revenue generation, in the next few years (Parida et al., 2019).

The European Commission (EC) has created new projects and initiatives to contribute to the sustainable improvement of production processes, aiming to be climate neutral by 2050 as defined in the European Green Deal (EC, 2022). Regarding the textile industry, the EC has created a Strategy for Sustainable and Circular Textiles, aiming to place in the EU market, by 2030, textile products that are mainly composed of recycled fibers that guarantee that those are recyclable and have an extended lifecycle (EC, 2022). With this, high-quality products will be available in the market for consumers, and producers will take responsibility for their products throughout the value chain. To reach this goal, the EC has been setting requirements for textile products' characteristics. Moreover, transparency regarding the way textile companies dispose of products will be required and the destruction of unsold or returned textile products will be forbidden (EC, 2022).

Digital technologies will be an essential support for this new transparent way of production, by facilitating machines and systems interconnections, and information sharing. Moreover, the digitalization of products information is necessary for these transparent systems to be

efficient, contributing to sustainable development. In this sense, the Digital Product Passport (DPP) - a tool to share product information across the value chain, from all the production phases - will be a future requirement in this sector, to positively contribute to transparency and circular activities (EC, 2022). The EC will require textile companies to introduce and add a specific label to the products, containing information for all stakeholders regarding products' components, materials, information on reparability, replacement parts, and disposal, allowing circular economy practices and more conscious purchase decisions (EC, 2022).

The BioShoes4All[1] is a research project applied to the Portuguese footwear area, supported by the Portuguese Recovery and Resilience Plan and by the NextGeneration EU European funds. It is led by *Associação Portuguesa dos Industriais de Calçado, Componentes, Artigos de Pele e seus Sucedâneos* (APICCAPS) and involves 70 national partners. This project emerges from the DPP relevance. The main aim is to promote bioeconomy, circular economy, and sustainability. One of the main pillars of this initiative is related to the development of a digital platform that enables transparency and traceability of the products' flow along the supply chain, contributing to the circular economy, fostered by the adoption of the DPP tool. This pillar has the contribution of 9 partners, grouped into technological organizations, scientific organizations, and footwear companies.

The concerns that lead authorities to act to build a sustainable future, the role of technologies in the companies' sustainable transformation, and the importance of the BioShoes4All project in the Portuguese context, highlight the importance to contribute to a deeply understanding of technologies' potentialities on sustainability and circularity.
The main aim of this research is to understand how Industry 4.0 technologies can support the development of new services that contribute to sustainable and circular practices in footwear companies. To respond to this aim, this research is focused on the footwear companies, selecting those that have adopted, and intend to adopt, Industry 4.0 technologies. This focus will involve companies that seek to have more efficient processes, and that are concerned with the new market demand, where sustainability plays a crucial role. With the adoption of these advanced technologies, new ways of production, new needs, new relationships among companies, and new services can be created to broaden the focus of companies towards circularity, and social and environmental sustainability issues. Thus, this study aims to answer

[1] BioShoes4All – Innovation and capacity building of the footwear industry for a sustainable bioeconomy

the following research question: How Industry 4.0 technologies adoption can support the development of new services that contribute to sustainable and circular practices in Portuguese footwear companies?

2. Literature Review

This literature review was conducted considering three areas. In the first section, the definition and explanation of key concepts related to the research topic are presented. In the second section, an overview of the footwear sector is described, covering the main production characteristics, its evolution, and future constraints regarding sustainability. In the third and last section, literature results regarding business models' transformations, resulting from the adoption of Industry 4.0 technologies are systematized and presented.

This last section follows a logic of thinking and presenting the literature results from the general to the particular focus. In the first place, the relationship between digitalization and sustainability is described, for a better comprehension of the digitalization impacts on sustainable development. This is followed by the importance of traceability practices, resulting from digitalization, to enable circular models of production. After that, the description of the product modifications with the adoption of traceability technologies, and what can be the consequent business transformation is presented. Table 1 summarizes the literature results of this third section.

2.1. Key concepts

In this section, the concepts of sustainability, circular economy, Industry 4.0 and digitalization value chain, traceability, and product lifecycle management, are briefly presented to better understand the research topic.

The main focus of this study is related to **sustainability** and sustainable development concepts. There is no consensus regarding the definition of sustainability and, in the existing literature, there are various interpretations of the concept (Rogers and Hudson, 2011). Sustainability can be characterized by a balanced consideration of the social, economic, and environmental dimension, to contribute to the improvement of life quality (Jeronen, 2013). As this concept has gained importance among society and organizations, in 2015 the United Nations formulated the Sustainable Development Goals that include the three different dimensions of sustainability: environmental, economic, and social (Carlsen and Bruggemann, 2021). Although often used as synonyms, the term sustainability differs from the sustainable development concept (Ruggerio, 2021). Sustainable development was defined as the development that meets the current necessities without compromising the future ones (Keeble, 1988). This development is the necessary pathway to achieve the main goal of sustainability, considering all three dimensions (Jeronen, 2013). The concept of the triple bottom line was

introduced in 1994 by Elkington (Elkington, 1994), to influence the vision and aims of companies, moving from a financial focus to a broader approach (MacDonald, 2009). Currently, companies measure their success by considering their contributions to the environment, social well-being, and also on the economy (MacDonald, 2009). Sustainability is a complex concept that requires a balanced consideration of these three dimensions (Alhaddi, 2015).

Circular Economy is directly linked to sustainability, being its ultimate goal to contribute to sustainable development. This concept was proposed in China, in 1998, and after that, in 2002, it was accepted as a development strategy (Yuan et al., 2006). The definition contrasts with the linear model of production, where the physical flow of goods follows the model of take-make-dispose (Rajput and Singh, 2019). Circular economy is a closed-loop supply chain based on circular activities of refusing, rethinking, reducing, reusing, repairing, refurbishing, remanufacturing, repurposing, and recycling (Huynh, 2021, p.871; Khaw-ngern et al., 2021; Rajput and Singh, 2019), aiming to minimize resources utilization and waste production while contributing to economic growth (Bressanelli et al., 2017). According to Kirchherr et al. (2017), this concept is translated into business models that reduce, reuse, recycle, and recover materials, replacing the end-of-life concept. In the linear models of production, after the usage phase by the customer, the value of a product or service is lost, while in circular models that value is conserved (Centobelli et al., 2020). According to Stahel (2016), the circular economy business models can be separated by those that extend the lifecycle of the product, through repairing and remanufacturing processes, and by those that, through recycling processes, transform old products into components and resources of a new product. A new vision of preservation and sufficiency characterizes this concept, disrupting the normal way of continually consuming new resources.

As mentioned, different "R" strategies can be adopted by companies to implement circular models of production. The so-called R imperatives have been under research, suffering some evolutions with the inclusion of new strategies that have answered new concerns (Khaw-ngern et al., 2021). Originally, during the 1970s, there was the 3R concept, including the practices of reduction, reusing, and recycling. Nowadays, a 9R concept involves the following actions: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, and recycle. (Khaw-ngern et al., 2021). Recycling is the main circular practice found in the literature, based on the companies' practices, followed by reuse and remanufacture (Panchal et al., 2021). Moreover, the recycle-reuse practice is the most used combination within circular

economy literature (Panchal et al., 2021). These frameworks are essential tools to guide companies in their business transformations (Khaw-ngern et al., 2021).

Industry 4.0 and digitalization

The concept of Industry 4.0 (i4.0) was first introduced by the German Government in 2011, which aimed to renew the German manufacturing system through advanced technologies. According to Lasi et al. (2014), these changes in manufacturing systems can impact both the organizational level (decreasing time of product development, increasing customization, production flexibility, decentralization, reducing hierarchies, and resource efficiency) and technological level (increasing mechanization, automatization, digitalization, and networking). This industrial revolution is characterized by the interconnection between physical and digital environments, through the utilization of information and communication technologies, allowing efficiency and production processes control, which also creates sustainability opportunities (García-Muiña et al., 2020). According to Bertola and Teunissen (2018), smart networks, smart factories, and smart products are the three results of this paradigm. According to the authors, i4.0 is based on 6 principles, namely interoperability, virtualization, decentralization, modularity, service orientation, and real-time capability (p. 358). Moreover, according to Parida (2018), Industry 4.0 allows the delivery of products, systems, and services more customized.

Digitalization is defined by the use of digital technologies to improve and innovate business models and to provide new revenue streams and value, creating new opportunities in the different industrial ecosystems (Gong and Ribiere, 2021). According to Parida (2018), this technological transformation is an inevitable consequence of the fourth industrial revolution that involves three different elements: sensors, devices that enable smart systems and connectivity. Furthermore, digitalization is a disruptive force that has consequences either on the industrial environment but also on society, affecting the employees' skills, customers, and digital knowledge (Parida, 2018). This technological trend brings benefits to society, but it also requires high levels of investments and costs (Reis et al., 2020).

The **value chain** concept must be considered since the transformations in the business models, driven by the adoption of i4.0 technologies, impact its different phases. This term was first introduced by Michael Porter, as a basic tool to analyze the sources of competitive advantage by separating a company into different critical activities (Porter, 2001). The concept

is related to the creation of value at every step of the chain, through the synchronization of the flows of supply with those of value from customers (Feller et al., 2006). The source of value is the customer, through its demand, and the value flows from the customer to the supplier. Specific drivers have pressed businesses to transform their supply chains into value chains. According to Feller et al. (2006), these drivers include the increase of competition and focus on innovation, evolving governance models, globalization, and management trends.

Technologies can also positively impact the companies' **traceability** of their products and components, contributing to more sustainable development. According to OECD (2018), traceability is the capacity to track materials and products and production history along the value chain. Regarding product traceability, it is related to the ability to identify the origin of materials and components, the processes, the distribution, and the location of it after delivery (OECD, 2018). The traceability chain system must enable tracking and tracing of batches and activities (Bechini et al., 2008). To make this possible, the traceability system must combine three elements: products identification methods such as Radio Frequency Identification (RFID); a central database to guarantee an efficient data organization for an easier identification process; and information flow, which requires rigorousness for an accurate traceability system (Bai et al., 2017). According to Bechini et al. (2008), **tracking** a product is following downstream its production path, whilst **tracing** is the opposite, leading to the identification of the product's origin and characteristics.

Another related concept is **product lifecycle management** (PLM), which, according to Terzi et al. (2010), is a lifecycle-oriented business model, based on product information sharing along the entire supply chain, involving different actors, processes, and actions of different phases of the product. The amount of information analyzed is supported by information and communication technologies that contribute to the flow of the products' data through the phases of a product lifecycle: ideation, definition, realization, use, and disposal. The information is then used by different actors at different phases and inside or outside companies. According to Corallo et al. (2020) and Stark (2022), the PLM aims to contribute to business improvement, maximizing product value by increasing product revenues and reducing costs. Furthermore, the PLM strategy allows time reduction and quality improvement.

2.2. Footwear sector

The footwear manufacturing sector covers a range of different materials and is responsible for the production of a broad variety of end products, which translates the complexity of the sector (Staikos and Rahimifard, 2007). The manufacturing process of a shoe may require around 40 distinctive materials (Perez et al., 2022), being textiles, plastics, rubber, and leather, the main materials utilized. According to Staikos and Rahimifard (2007), the production of a simple pair of shoes can be separated into distinctive phases throughout its value chain. According to the authors, the initial phase includes the supply of raw materials, semi-finished products, and components, which will be further controlled to meet the quality requirements of the industry. These different materials and components will pass through distinctive manufacturing operations and, in the end, in the assembly phase, the transformation into finished products occurs. The last phase involves finishing processes and the delivery of the final product to the market.

Worldwide footwear production and consumption continue to expand, having passed the 22 billion pairs produced in 2021, which is still under the pre-pandemic values (APICCAPS, 2022). Given the complexity of materials and components used during the production processes, environmental issues arise with the increase in production and consumption (Van Rensburg et al., 2020). Moreover, the fast fashion trend contributes to a fast turnover and disposable of these products, which results in high levels of waste (Van Rensburg et al., 2020).

Efforts to limit the negative impacts of this industry on the environment are being done, with the improvement of materials efficiency, the adoption of recovery techniques of useful materials, and the elimination of hazardous materials (Mia et al., 2017). Despite that, the continuous growth of the sector limits its environmental gains, being the waste generated at the end-of-life phase as the main environmental challenge (Mia et al., 2017).

Effective changes need to occur in the footwear sector since sustainability concerns among society are pressing companies to assume their responsibilities (APICCAPS, 2014). According to this study, consumers are expecting more and more for companies to transparently report their activities' impacts. Information regarding the manufacturing processes, materials and products' origins, and working conditions will be a requirement (Footwear Consumer, 2030).

2.3. Business model transformation driven by the adoption of Industry 4.0 technologies

In this section, literature results regarding business models' transformations driven by the adoption of Industry 4.0 technologies are presented. First, the literature results regarding the effects of digitalization on sustainability are presented, focusing on the transformation that needs to occur in business models. Then, the literature results focused on the role of traceability, enabled by advanced technologies, in the circular economy tendency, is presented. For this, some examples of technologies that enable traceability and practical examples of industries that have adopted traceability technologies are described. Furthermore, as a consequence of available real-time data, product innovation is a new requirement for companies to satisfy the current necessities of the market and to contribute to social and environmental sustainability. In this sense, literature results regarding product innovation are presented. Finally, a brief overview of the current situation of companies regarding the adoption of advanced technologies is presented. The presentation of literature results regarding the difficulties that companies face during digitalization and modernization processes, highlighting the differences in digital maturity between companies at different stages, have contributed to the final section.

2.3.1. Business model innovation driven by the adoption of technologies and the contribution for sustainability

Starting from the technological advances' effects on business models and their relationship with sustainability, according to Pedersen et al. (2018), companies that innovate their business models tend to demonstrate high levels of corporate sustainability, demonstrating a positive relationship between business model innovation and sustainable practices. According to Acciarini et al. (2021), companies that innovate are the ones that pay more attention to the triple bottom line of sustainability, as sustainability represents a key driver for success. The innovation of businesses, which is related to the development of new ways to deliver and capture value (Pedersen et al., 2018), depends on their capability to adopt disruptive technologies and on the collaboration across the stakeholders in the industrial system, that allows introducing new components into individual elements or across elements (Parida et al., 2019). According to Lacy et al. (2014), these disruptive technologies that allow companies to transform their businesses can be grouped into three different categories: digital technologies, which enable the exchange of important information among different users, machines, and management

systems, allowing a connection with the customer, even after the sale phase; engineering technologies, which allow the production of new goods through advanced recycling and collection mechanisms; and hybrid technologies, that through the utilization of both digital and engineering technologies, increases the control over assets and material flow within the value chain, supporting the collecting, treating and reprocessing phases. The adoption of those disruptive technologies contributes to the optimization of the existing business models, or to their transformation, or even to the development of new ones (Acciarini et al., 2021), allowing companies to find new ways to create and deliver value to customers.

The digitalization era has, as its major contribution, the fourth industrial revolution (Khan et al., 2021). According to Acciarini et al. (2019), digitalization represents a disruptive transformation that forces companies to innovate their business models. In a context where companies have to deal with a big amount of data, the technologies that have emerged with this industrial revolution have contributed to a more effective and efficient way of utilizing the information, through the interconnection between digital and physical dimensions. With this, companies that adapt, to incorporate in their operations the most advanced technologies, benefit from a better flow of data that positively impacts the efficiency of the operations, improving economic results. According to Tang et al. (2022), Industry 4.0 improves companies' operations, financial performance, and environmental performance. Digitalization functionalities of data collection, connectivity among different units, and data transformation into valuable insights, contribute to the creation of value (Ranta et al., 2021). According to Parida et al. (2019), digitalization facilitates value-creating and value-capturing. For Ranta et al. (2021), digitalization contributes to value-creating and capturing through savings from products tracking and waste and surplus reduction, the improvement of inventory management, quality and durability, material processing efficiency, value chain collaboration, logistics, advanced control of material, new products categories and service alternatives, and materials and components reuse and remanufacturing. Moreover, the interconnection between devices positively affects sustainability, as emissions and the resources' utilization are reduced, allowing the transition of business models from linear to circular ones (Rajput and Singh, 2019).

Business model innovation focusing on the circular economy requires companies to rearrange their value chains, to improve circularity and to create value (Ranta et al., 2021). Huynh (2021) has described three digital-based circular business models in the fashion industry: the

blockchain-based supply chain model, the service-based model, and the pull-demand-driven model. These models are created benefitting from digital technology functionalities, that impact the upstream side of the value chain, in the first case, the downstream side in the second model, and in the last one, which is a more radical transformation, digital technologies impact all the value chain. The pull-demand-driven model, based on 3D printing, Artificial Intelligence (AI), and automation, is characterized by real-time demand-driven production, contributing to a circular production model, which provides customers with higher quality products.

According to Todeschini et al. (2017), certain macro-trends are pressing enterprises to transform their business models. Some examples are the increasing consumer awareness regarding sustainable issues, the circular economy tendency (Brennan et al., 2015), the increasing importance of Corporate Social Responsibility among companies, sharing economy tendency, collaborative consumption, and technology innovation (Todeschini et al., 2017). For the authors, these tendencies create important opportunities for companies, for example, a higher focus on social issues and service-based models' creation. Also, the volatility and rising of resources and materials' prices represent important changes in the market that are pressing companies to transition towards a circular economy (Lacy et al., 2014; Bressanelli et al., 2017). Lacy et al. (2014) highlighted the capabilities required from companies that, together with the adoption of disruptive technologies, allow them to successfully innovate their business models, supporting circularity. In the first place, there is a need to change the business planning and strategy, as companies have to be inserted in a collaborative circular network to understand where value is created and, consequently, invest in those activities. Secondly, companies have to rethink and innovate product development, adapting it to circular practices. Moreover, is also important to make sure that the inputs utilized are renewable, and waste is not generated during production, which could imply a change from large and few suppliers to heterogeneous, many and small sources. Also, companies need to invest in customer engagement and education to improve the lifecycle management of products and, at the same time, they have to learn from customers' preferences in a way to adapt products and services. Finally, according to the authors, companies need to be able to invest in reverse logistics and return chains.

2.3.2. The role of traceability, enabled by advanced technologies, in the circular economy

As a consequence of the adoption of advanced technologies in production processes, traceability is also considered a requirement to enable a circular economy (Giovanardi et al., 2022). According to Kristoffersen et al. (2020), tracking products, components, and materials, a result of the use of digital technologies, can enable the transition to a circular economy. Through the collection of product information, traceability positively contributes to recycling processes, improvement of resource management and decision-making (Agrawal et al., 2018; Kristoffersen et al., 2020). Various technologies were created to control the flow of products and their components through the different phases of the supply chain, resulting from advances in digital technologies. The product information is useful for a wide range of stakeholders, including end consumers, surveillance authorities, retailers, repair companies, and waste management companies (Adirson et al., 2021). Some examples of these technologies are the bar codes, defined by the GS1 patterns, Quick Response (QR) codes ,and the Radio Frequency Identification (RFID) System (Bai et al., 2017). The latter has proven to have some environmental benefits in the apparel industry. According to Denuwara et al. (2019), the RFID system can help to identify the origin of a garment, its composition, the journey through the supply chain, and the recyclability of the product, which simplifies the recycling process, attracting potential investors in textile recycling. Moreover, this system provides real-time demand and it helps to forecast it, improving inventory accuracy, which leads to waste reduction and cost efficiency (Denuwara et al., 2019).

Companies are starting to introduce these technologies to control products along the different phases of the chain, helped by the adoption of disruptive technologies since they bring economic, environmental, and social benefits (Agyabeng-Mensah et al., 2020). Giovanardi et al. (2022) describe the advantages of traceability information on the façade sector[2]. The authors highlighted the increase in the efficiency of supply chain management, the reduction of resource consumption, the extension of service life, and the support of new business models as some benefits.

Given the benefits provided by the availability of product information on the economic,

[2] The façade sector involves activities and operations responsible for the design and maintenance of buildings enclosures. It is a niche sector of the building industry.

environmental, and social domains (Agyabeng-Mensah et al., 2020), the European Commission has developed an Ecodesign Directive, establishing specific design requirements for sustainable products available on the European market. It is known that more than 80% of the environmental impacts of a product are determined during the design phase (EC, 2014). This initiative is part of the European Green Deal, a plan that aims to transform "Europe into the first climate-neutral continent in the world" by 2050 (EC, 2021). The main aim of the Ecodesign Directive is to contribute to the environmental sustainability and circularity of products, by making them more "durable, reusable, reparable, upgradable, recyclable" (European Parliament, 2022). Among the different rules and initiatives included in it, rules regarding a Digital Product Passport (DPP) are proposed. The DPP is related to the digitalization of material and product information (Walden et al., 2021) and aims to contribute to transparency and traceability, by providing to different actors, internal or external the supply chain, with relevant products' lifecycle data (Adirson et al., 2021; Plociennik et al., 2022). By providing transparent information regarding products' "origin, composition, repair, and dismantling options", supply chain actors can rethink their decisions, contributing to sustainable development (Adirson et al., 2021). Moreover, information regarding repair and reusable options contributes to the development of new and circular business models (Adirson et al., 2021; Walden et al., 2021; Plociennik et al., 2022) and to share information regarding the sustainability aspects of products and materials (Gotz et al. 2022).

A practical example regarding the adoption of this type of tool can be identified in the automotive industry, with the adoption of the International Material Data System to timely share, throughout the entire supply chain, information regarding the products' material, to meet a specific rate of reuse and recovery defined by the EU (Walden et al., 2021). Also, a digital passport for batteries (Digital Battery Passport) for industrial and electric vehicles batteries will be mandatory under the EU Battery regulation, to enhance transparency regarding batteries' characteristics, allowing the transition to circular and sustainable battery chains (Berger et al., 2022).

The configuration of a DPP depends on the type of product and on the industry (Adirson et al., 2021; Walden et al., 2021), which limits its adoption on a large scale. Despite that, this is a powerful tool that contributes to more sustainable and circular models of production and consumption (Berger et al., 2022), and has the potential to reduce costs and efforts (Adirson et al., 2021). According to Walden et al. (2021), the DPP allows traceability, due diligence efforts, services related to circular economy, higher levels of recycling, reliable

information available for public and private stakeholders, and better market surveillance mechanisms.

Still, some of the companies lack structured data and information reliability, limiting their transition to a circular model of production (Giovanardi et al., 2022). According to Hastig and Sodhi (2020), to guarantee the success of these systems' implementation, companies need to ensure digital capabilities, supply chain actors' goals alignment and collaboration, technological readiness, supply chain standardized practices, and best practices of data collection and traceability processes, internal and external leadership regarding the supply chain for a successful engagement and communication with the partners, and regulation of the traceability efforts. Furthermore, the focus of companies that aim to integrate circular activities in a successful way must be on the products' innovation and also, on businesses models that provide high-quality products capable to be on the market for long periods of time (Ingemarsdotter et al., 2020).

The complexity of interconnections within companies' supply chains and the globalization of businesses can contribute to less transparency of operations and unsustainable practices (Oguntegbe et al., 2022). Given the increased importance and interest of the whole society in sustainable development, practices, and sustainability reporting, there is a risk of misleading information by companies regarding the impact of their operations on sustainable dimensions (Moodaley and Telukdarie, 2023). This is commonly referred to as greenwashing, which is an unethical company behavior, resulting from a combination of two behaviors, namely a bad environmental performance and a positive communication about it (Delmas and Burbano, 2011). With this, companies can target consumers that are attracted by sustainable products and charge higher prices, which is known as a profitable marketing strategy called "eco-opportunism" (Nygaard and Silkoset, 2022). To combat asymmetric information, that incentivizes this type of unethical behavior (Nygaard and Silkoset, 2022), technology plays a crucial role by allowing traceable information along the supply chain, contributing to a more transparent interaction between all the stakeholders involved in it and supporting the sustainability claims (Kumar et al., 2017). Furthermore, as the consequences of this unethical behavior affect other firms operating in the same supply chain network, companies must invest in their responsibility and ethical conduct as well as in the entire network (Oguntebe et al., 2022).

2.3.3. Product Innovation and the contribution for sustainability

The paradigm of the companies has changed. Currently, the focus on cost efficiency, quality, and time to market is not anymore sufficient to guarantee their competitive advantage in the future. Globalization and the competition increase press companies to innovate their offerings (Dahmani et al., 2021). The survival of companies, in a future guided by sustainable and digital transitions, relies on their ability to adapt (Hallstedt et al., 2020).

Companies need to focus on product innovation, to meet the new customer requirements, which are focused on the value to serve and not on the product itself (Terzi et al., 2010; Dahmani et al., 2021). By these, products cannot be any more just tangible objects that generate money when they are sold. Instead, new products need to be composed of both tangible and intangible parts, representing a transformation to the product-service paradigm (Terzi et al., 2010). Digitalization allows the incorporation of software into products and contributes to the increase of revenues coming from services (Hallstedt et al., 2020). Improvements in products design are crucial to the development of smart products and are positively related to the integration of Industry 4.0 technologies (Dahmani et al., 2021). According to Liu and Zhao (2022), this new way of looking at products allows companies to increase their profits and improve value. For this new concept to be possible, product data needs to be available for any stakeholder involved in the supply chain and outside it (Gaiardelli et al., 2021).

Intelligent or smart products have a physical and information-based representation, being able to communicate within the context where it is inserted, to retain and store information, and to allow its lifecycle data to be available to the stakeholders, being a source of sustainable value, differentiating themselves from traditional products that only provide basic functions (Yang et al., 2009; Romero and Noran, 2017). For this to happen, these products must have a mechanism to support the lifecycle data transmission. By having the capacity to sense, store and share information about themselves or about the context where they are inserted, servitization and circularity business opportunities are created (Romero and Noran, 2017). For the authors, servitization business opportunities are related to the possibility of "maintenance, repair and overhaul", and circularity business opportunities can be achieved through "reuse, refurbishment, remanufacturing, recycling". Servitization is considered a business model innovation, where companies move from a product-centered towards a product-service system (PSS) business model, where value is created through the integration of products

and services (Yang et al., 2018; Frank et al., 2019; Kohtamaki et al., 2020; Dahmani et al., 2021; Vargas et al., 2022). Yang et al. (2009) have also identified some product-related services enabled by these products, such as remote diagnosis, remote monitoring, rental and sharing, analysis of user patterns, end-of-life treatment, and better service. Moreover, the authors highlighted some advantages of these services for companies' performance. For instance, the remote diagnosis enables companies to make the maintenance of the products when it is needed, rather than at a regularly scheduled maintenance way, which improves the cost efficiency of a company. Regarding the end-of-life treatment service, through the product's components information, the product design phase can be improved by adapting their solutions in a way to positively contribute to environmental sustainability.

These products contribute to the improvement of the decision-making process in the direction of sustainability concerns (Turner et al., 2022). According to the authors, a dynamic Life Cycle Assessment is enabled by smart products, as they hold information regarding the products' materials and components and the carbon embedded in them, the emissions released during the manufacturing and production phase, and energy use patterns, which provide an estimation of the potential environmental impact of a product or service throughout the entire lifecycle. This data is a useful base for designers and manufacturers that can improve their operations and decisions, contributing to sustainable production (Turner et al., 2022).

The adoption of advanced technologies by companies is still at an early stage, existing an unbalanced adoption level between start-ups and incumbents, which led to different opportunities for business transformations (Huynh, 2021). According to Todeschini et al. (2017), incumbents tend to innovate their business models by proceeding cautiously, with small initiatives, whereas start-ups are more innovative and tend to identify new opportunities to change. However, according to the authors, incumbents can effectively establish competitive advantages, whilst start-ups are less successful, which highlights the importance of strategic collaborations between different types of companies. Moreover, the implications of digital technologies on circularity, specifically knowing what can be the expected transformations in business model design, organizational configuration, and product innovation, are still under research (Chiaroni et al., 2021; Ranta et al., 2021). This limits the reconfiguration of companies and the emergence of new services and solutions to contribute to traceability and circularity, incentivizing companies to act and adapt only in the short-term, instead of having a long-term strategy plan.

Table 1. *Literature results summary table*

Business Model Innovation driven by the adoption of technologies and the contribution for sustainability	Companies that innovate their business models tend to: - demonstrate high levels of corporate sustainability (Pedersen et al., 2018) - pay more attention to the triple bottom line of sustainability, as it represents a key driver for success (Acciarini et al., 2019)
	Digitalization: - a disruptive transformation that forces companies to innovate their business models (Acciarini et al., 2019); digital-based circular business models can change the upstream, downstream or the entire value chain (Huynh, 2019) - facilitates value creating and value capturing through: - savings from products' tracking and from waste and surplus reduction - the improvement of inventory management, of quality and durability, of material processing efficiency, of value chain collaboration, of logistics - advanced control of material - new products' categories and service alternatives - materials and components reuse and remanufacturing (Parida et al., 2019; Ranta et al., 2021) Industry 4.0: - facilitates the interconnection between devices - contributes to sustainability, as emissions and resources' utilization are reduced - allows the transition of business models from linear to circular ones (Rajput and Singh. 2019)
	Macro-trends that are pressing companies to transform their business models (Brennan et al., 2015; Todeschini et al., 2017): - increasing of consumer awareness regarding sustainable issues - circular economy tendency - increasing importance of Corporate Social Responsibility among companies - sharing economy - collaborative consumption - technology innovation
	Capabilities required for business models transformation (Lacy et al., 2014): - adoption of disruptive technologies - business planning and strategy change - product development - rethink suppliers - customer engagement and education investment - investment on reverse logistics

The role of traceability, enabled by advanced technologies, in the Circular Economy	Traceability practices: - enhance transparency (Kumar et al., 2017) - a requirement to enable circular economy (Giovanardi et al., 2022); contribute to recycling processes (Agrawal et al., 2018); contribute to reducing resources consumption (Giovanardi et al., 2022) - contribute to the improvement of resource management and decision making (Agrawal et al., 2018; Kristoffersen et al., 2020) - increase the efficiency of supply chain management - increase transparency and contribute to the greenwashing practice combat (Giovanardi et al., 2022; Kumar et al., 2017) - support new business models (Giovanardi et al., 2022)
	Technologies that support traceability practices: bar codes, Quick Response (QR) codes, Radio Frequency Identification (RFID) system (Bai et al., 2017) - RFID system (Denuwara et al., 2019): - recycling possibilities as the main advantage - improves demand forecast accuracy - improves inventory accuracy - allows waste and cost reduction
	DPP: - aims to contribute for transparency and traceability (Adirson et al., 2021; Walden et al., 2021; Plociennik et al., 2022) - contributes to a sustainable development and to the development of new and circular business models (Adirson et al., 2021; Walden at al., 2021; Plociennik et al., 2022; Berger et al., 2022) - contributes to due diligence efforts, services related to circular economy, recycling practices, reliable information for public and private stakeholders, and better market surveillance mechanisms (Walden et al., 2021) - the configuration of a DPP depends on the type of product and on the industry (Adirson et al., 2021; Walden et al., 2021), which limits its adoption in a large scale
	The product information is useful for: - stakeholders, including end consumers, surveillance authorities, retailers, repair companies and waste management companies (Adirson et al., 2021)

Product Innovation and the contribution for sustainability	Intelligent/Smart products: - composed by both tangible and intangible parts (Terzi et al., 2010); digitalization allows the incorporation of software into products (Hallstedt et al., 2020); require improvements on products' design and are positively related with the integration of Industry 4.0 technologies (Dahmani et al., 2021) - are able to communicate, share and store information, and allow products' lifecycle data to be available to the stakeholders (Romero and Noran, 2017) - a source of sustainable value (Romero and Noran, 2017) - contribute to the improvement of the decision-making process in the direction of sustainability concerns (Turner et al., 2022) - to meet the new customer requirements, which are focused on the value to serve and not on the product itself (Terzi et al., 2010; Dahmani et al., 2021) - requires product data availability for all stakeholders (Gaiardelli et al., 2021)
	Intelligent/Smart products enable product-related services: - remote diagnosis, remote monitoring, rental and sharing, analysis of user patterns, end-of-life treatment (Yang et al., 2009)
	Servitization: - a business model innovation, where companies move from a product-centered towards a product-service system (PSS) business model (Yang et al., 2018; Frank et al., 2019; Kohtamaki et al., 2020; Dahmani et al., 2021; Vargas et al., 2022) - maintenance, repair and overhaul, reuse, refurbishment, remanufacturing, recycling possibilities (Romero and Noran, 2017) - value is created through the integration of products and services (Yang et al., 2018; Frank et al., 2019; Kohtamaki et al., 2020; Dahmani et al., 2021; Vargas et al., 2022)
Difficulties	Unbalanced level of advanced technologies adoption between start-ups and incumbents: - different opportunities for business transformations (Huynh, 2021) - incumbents tend to innovate their business models by proceeding cautiously, whereas start-ups are more innovative; incumbents effectively establish competitive advantages, whilst start-ups are less successful (Todeschini et al., 2017) - importance of a strategic collaboration between different type of companies (Todeschini et al., 2017)
	Implications of digital technologies on circularity, specifically knowing what can be the expected transformations in business models design, the organizational configuration and product innovation are still under research (Chiaroni et al., 2021; Ranta et al., 2021)

Source: Author own elaboration

3. Methodology

The research methodology adopted in this study is presented in this section. In the following sections the research design, data collection and data analysis method, and the research quality are described.

3.1. Research design

This research has, as the main objective, to understand how the adoption of Industry 4.0 technologies by companies in the footwear sector can support the development of new services that contribute to sustainable and circular practices. Given this, the following research question was defined: How Industry 4.0 technologies can support the development of new services that contribute to sustainable and circular practices in Portuguese footwear companies?

According to Saunders et al. (2016), exploratory studies are adopted when the author seeks to deep understand a certain issue or phenomenon. Since the aim of this study, is to explore and to understand how the adoption of i4.0 technologies can support the development of new services that contribute to sustainable and circular practices, has an exploratory nature, a qualitative research was considered suitable (Creswell and Poth, 2016).
Considering the implications of digital technologies on circularity, specifically knowing what can be the expected transformations in business models design, organizational configuration, and product innovation are still under research (Chiaroni et al., 2021; Ranta et al., 2021), it was essential to understand this from an empirical perspective. According to Lune and Berg (2017), qualitative techniques contribute to a more in-depth understanding of the perceptions of the selected sample. The interview research method was used, selecting a research sample composed of key informants of small and medium companies of the Portuguese footwear sector. These key informants were selected from the companies' consortium of the BioShoes4All project. Companies are located in the different value chain phases, from materials and components production to the final product production, being one of the companies focused on the technological area. The interviewees selected are responsible for the sustainability department, operations department, research and development department, and design processes. A purposive sample was used as participants were selected following relevant criteria to the objective of the study, given their functions in the companies and their role in the project (Guest et al., 2006). Confidentiality during the interviews was guaranteed

through an informed consent signed by all the participants, which assured ethical processes.

3.2. Data collection

To have some guidance on the topics to address during interviews and to allow more detailed and complementary insights from the interviewees, semi-structured interviews with open-ended questions were conducted (Saunders et al., 2016). The interview guide was structured with three distinct parts, corresponding to the three main topics: sustainability and advanced technologies adoption, circular economy, traceability, and DPP. The results of the literature review were used to develop the interview guide (Appendix A)

Among the BioShoes4All project consortium, twelve key informants from seven companies contributed to the interviews, and the selected participants are involved in the project, which ensured useful insights to this study. Details regarding the companies and the key informants are presented in Table 2 and Table 3, respectively. For the companies' identification, the letter C represents the companies, and the number after that indicates their number. Regarding interviewees and to preserve their privacy, the letter I represents the interviewees, and the following number indicates the interviewee number, per company. Eleven interviews were performed through video calls, using Microsoft Teams platform, and one was conducted in written form. They took place between March and May of 2023, having an average duration of 33 minutes. All the interviews conducted in the virtual mode were audio-recorded, with the interviewees' permission, and written after that for a precise data analysis.

Theoretical saturation, the point where new information during data collection has little contribution to the analysis (Guest et al., 2006), has defined the number of interviews for this study. After twelve interviews, the information shared regarding the main topics discussed was not different from the previous one or had little input.

Table 2. *Companies' characteristics*

Company	Plant location	Value chain position	Turnover (2021)[a]	Employees (2021)[a]	Company size
C1	Vila do Conde	Footwear component producer	10 M€	121	medium
C2	Braga	Technical footwear producer	16 M€	144	medium
C3	Aveiro	Footwear component producer	2 M€	37	small
C4	Porto	Footwear component producer	7 M€	81	small

C5	Porto	Footwear producer	24 M€	325	medium
C6	Aveiro	Footwear producer	8 M€	127	small
C7	Porto	Software producer (national leader in the footwear sector)	700 K€	13	micro

[a.] Source: SABI Database

Table 3. *Interview characteristics*

Interviewee	Function/Role	Interview mode	Duration
I1C1	Director of the Sustainability Department	Video call	35 min
I2C1	Design Manager	Video call	50 min
I1C2	Director of the Sustainability Department	Video call	45 min
I2C2	Operations Department	Video call	30 min
I3C2	IT Department	Video call	30 min
I1C3	Environmental Manager	Video call	32 min
I1C4	R&D Technical Director	Video call	25 min
I2C4	Project Manager	Video call	25 min
I3C4	Director of the Sustainability Department	Video call	44 min
I1C5	Responsible for the development of rubber materials	Written	-
I1C6	Commercial Director	Video call	22 min
I1C7	CEO	Video call	24 min

3.3. Data analysis

The NVivo software was utilized to allow a thematic data analysis. Before that, it was crucial to transcript the interviews and to carefully read all of them, to better understand the topics covered. With this reading, the identification of patterns and common themes was possible (Saunders et al., 2016). The coding scheme was data-driven, utilizing terms used by the interviewees in order to involve their voices and opinions (Saunders et al., 2016).

To have a global vision of the subject, the main addressed topics of Sustainable Development, Technologies, and Business models' transformations were coded and, in each of the codes, subcodes were created for deeper analysis (e.g.: circularity, economic dimension, greenwashing).

3.4. Research quality

Trustworthiness in qualitative research is guaranteed when the following criteria are fulfilled: dependability, credibility, transferability, and confirmability (Lincoln and Guba, 1985). The dependability of the findings is assured providing detailed information regarding the research methodology and processes used for data collection and analysis (Bitsch, 2005). Different techniques can be adopted to contribute to the credibility of a research, that include prolonged engagement, persistent observation, peer debriefing, negative case analysis, progressive subjectively, member checks, and triangulation (Bitsch, 2005). For this study, during the research process, a continuous sharing of information between the researcher and the supervisor has taken place, to have different insights for the study. Moreover, the selected interviewees have different backgrounds and experiences, contributing to a broader and more complete vision of the subject. A transparent process of data collection, through the sharing of an informed consent document between the researcher and the informants, guaranteed the voluntary participation of the interviewees and their honesty. Transferability is harder to guarantee when the sampling process is purposive (Bitsch, 2005). To contribute to this quality criteria, a detailed description of the research context was done. Finally, to ensure that findings are based on the interviewees' voice, and not on the researcher's prejudices, some responses of the informants were cited.

4. Findings

The data collected in the interviews are presented in this section, being organized according to the following structure: 1) the importance of sustainable development, and the sustainable practices implemented and planned; 2) the adoption of i4.0 technologies; 3) the importance of traceability; 4) transformations of the business models; and 5) the future of the footwear sector.

4.1. The importance of sustainable development

Sustainability practices are a current focus of the companies, driving their practices and operations, and the COVID-19 pandemic is identified as an accelerator of this paradigm (I2C1). According to I2C1, *"the sustainability movement has intensified at the time of the pandemic"* by involving more and more the governments, where new policies and strategies were developed, and influencing how people think and act. Moreover, for I2C1, sustainability does not represent a trend, that tends to disappear and eventually come back, rather it represents a new social paradigm that changes how people and companies act. There is a sustainability department in almost all companies where interviewees work (C1, C2, C3, and C5), even though in some cases it has been recently created. In C2, this department was created after the pandemic phase, and it is still at an early stage of development. The rise of the customers' concerns regarding this issue and, consequently, the evolution of the market demand is recognized by all the companies' interviewees as a driver of the companies' paradigm change. Sustainability is currently a crucial dimension of their decision processes, influencing not only production decisions but also organizational practices. Pressed by the end users, companies in the footwear value chain have been changing their purchase criteria and priorities, searching for suppliers that are committed to (and implemented) sustainable practices, pressing them to change their materials, production processes, and operations (I1C1, I1C3, and I1C6).

For two of them (C1 and C4), sustainability represents an expressed value that guides the internal practices, business vision, and strategy, as they believe that their presence in the market is only assured with the development and implementation of sustainable practices. The commitment of the companies' boards is referred to by some of the interviewees (I1C1, I2C1, I1C4, and I2C4) as a crucial support and employees' orientation for the implementation of sustainable practices since the top-down approach guarantees the compliance of those practices and control its implementation. Still, the compliance of sustainable practices

is seen, by I1C6, as a temporary market tendency that the company has to follow to ensure its profitable presence in the market: *"It has been a path that follows the market trends. There is no need to move in that direction if the whole involvement of the economy is not centered on that."*.

4.1.1. Sustainable practices planned or implemented

The concerns of the footwear companies regarding sustainability are reflected in planned and implemented practices that affect, not only the production phase, but also the design and production planning phases, the post-production phase, and the entire companies' structure functionality. The environmental and the economic pillars of sustainability are the ones most referred to, respectively, by the companies' interviewees when describing their sustainable practices' impacts. The practices in the social dimension were mentioned only by I1C6, highlighting their investment in the well-being of the employees by promoting a safe and fair work environment.

Apart from the circular practices, described below, related to the production processes, energy efficiency and water treatment represent two important priorities about sustainability and to sustainable development. The commitment to produce energy based on renewable sources is starting to be translated into investments, as in the case of C2, C4, C5, and C6. In this sense, I2C4, I3C4, I1C5, and I1C6 have mentioned a growing investment by their companies, in recent years, in solar panels. For I1C2 and I1C5 the main aim of these investments is the reduction of their carbon footprint. On the other hand, I1C4, I2C4, and I1C6 only mentioned the advantage of energy costs reduction. Given the high levels of water consumption, I1C3 stated that the reuse of wastewater is a priority of the company.
I1C4 and I2C4 mentioned the certification ISO 14000 implementation – a series of norms that establish guidelines on environmental management for companies - as a sustainable practice of the company, since it was an internal option and not mandatory for the business, highlighting the importance to be one step forward regarding the market demand.

4.1.2. Circular practices

The product design phase was identified, by I2C1 and I1C2, as a crucial stage to invest in circular practices. *"It is at the product design phase that we can contribute to the circular economy, and not just after it. We can contribute to it by designing something that is easily returned, disassembled, to be easily recycled or reincorporated in something else."* (I1C2).
Both companies are changing their traditional design models, where the focus on product

design goes only to the utility dimension of the product. In the past, the focus was on the types of materials utilized, and not on the environmental consequences and destinations of materials in the product end-phase. Instead of that, these companies are starting to approach the eco-design vision, where there is a careful planning of the product, before it is manufactured, regarding the impacts of it on the environment, aiming to extend the product lifecycle as much as possible. According to the interviewees (I2C1 and I1C2), this strategy allows the use reduction of virgin materials and waste reduction, both at the production and the consumption level and, consequently, a reduction in production costs. With this new way of designing products, I2C1 and I1C2 mentioned that products can be more easily recycled, and kept into a circular model of production, which reduces production emissions since the production levels decrease. This new design vision of companies (C1 and C2) contributes to the maximization of the product's value, which is related to the PLM concept.

Recycling is the main circular practice implemented by the companies (C1, C3, C4, C5, and C6), investing in waste management strategies. In these companies the surpluses generated during the production phase are reintegrated into the production for the development of the same type of products, such as leather or synthetic components or final shoes, having a certain percentage of recycled material. The economic benefit related to the reduction of materials utilization and the elimination of the necessary treatment of the waste generated is referred to as the main advantage of this practice (I1C1, I1C3). However, the generation of waste is inevitable by these companies (C1, C3, C4, C5, and C6) since it is not possible to recycle all the production excess, given the specific characteristics of the materials. The aim to produce a product 100% recyclable and circular is identified by I2C1 and I1C2, highlighting the importance of the eco-design practice. *"A shoe is constituted by numerous and different materials (…) and disassembling it is a hard task. In this sense, we are trying to design a product that makes it easier, by simplifying and reducing the materials."* (I1C2).

There are circular practices implemented involving other partners within the value chain, such as components' suppliers, distributors, clients, and end consumers. One of these practices was described by I1C1: through a reverse logistic system, the final products that have some defects or that were not sold return to the producing company and are dismantled and crushed to be reintegrated into the production process.

At the same time, product quality is becoming a concern, and according to I1C2, it is difficult to achieve the required quality patterns of the sector with recycled products. According to

this interviewee, the incorporation of recycled materials into products will negatively affect their quality, as they will become less resistant and durable. Still, the interviewee mentioned that the company cannot ignore the actual concerns regarding sustainability development, highlighting the necessity to find an equilibrium between the required criteria for a shoe (functionality, comfort, quality), and the increasing market demand regarding sustainability: *"We have to find the midterm between the functionality of the product and to what it has to answer."* (I1C2). However, for I1C1, the challenge can be the product's visual aspect, since it could be affected when recycled components are incorporated, which makes it difficult to attract clients. According to the interviewee, products composed of recycled components are hardly free from visual defects that, according to I1C1, could be related to differences in the product colors.

Furthermore, two interviewees, I1C3 and I1C6, mentioned the implementation of the repurposing strategy, among their circular practices, as the generated surpluses are used for another purpose, internal or external the company's operations. I1C3 mentioned the future possibility to transform their production surpluses, that in C3 are composed of leather, into agricultural fertilizer, which requires an important investment in sophisticated machinery for the leather grind. Regarding the C3 main activity, the leather treatment, this is in itself a repurpose practice since it depends on the surpluses generated by the food industry (cowhide). In this sense, the footwear sector is capable to valorize an excess generated in an industry characterized by environmentally sustainable problems. On the other hand, I1C6 stated that in C6 they are currently utilizing their leather surpluses for the production of footwear accessories.

4.2. The adoption of i4.0 technologies

The adoption of advanced technologies and continuous technological investment is, according to all the interviewees, a crucial step to take to implement these sustainable practices, by changing their processes and operations, and having sustainability as the main aim of that change. *"Industry 4.0 and digitalization are hand to hand with sustainability, being crucial to define measures for circularity."* (I1C5).

According to I1C1, I2C1, I1C2, I1C4, I2C4, I3C4, I1C5, and I1C6, processes efficiency and productivity improvements are the main positive impacts of technology adoption. The adoption of advanced machines and systems contributes to:

- the production time reduction, that affects directly the related costs necessary for the development of a specific task (labor and energy consumption). (I1C1, I2C1, I1C4, I2C4, I1C5, I1C6)
- the reduction of production waste (I1C2, I1C4, I3C4, I1C5)
- the process quality improvement, by reducing the errors that are inherent to human labor. (I2C1, I2C4, I1C5)

All the companies from the footwear value chain (C1, C2, C3, C4, C5, and C6) have already implemented, or intend to implement, advanced machines and intelligent systems, or just seek to invest in some systems' updates, aiming to mainly have and promote both economic and environmental benefits. The implementation of intelligent cutting machines, using artificial intelligence, was referred to by I1C6. I1C1 mentioned a future company's investment in a Life Cycle Assessment system to assess the environmental impacts of their products, which requires investment in sensors and control systems. Moreover, to reincorporate the generated surpluses, machines are allocated in the production phase to gather the excess of a specific component and to reincorporate a predefined part of it in the next production according to its characteristics (I1C1 and I2C1). Also, a virtual reality system is used by C1 and C6 in the design phase, as a prototyping technique. According to I2C1, this is *"a technological method adapted to sustainability."*. I2C1 and I1C6 mentioned the positive impacts of this method on the economic and the environmental dimension of sustainability. With this, the necessary product modifications that can normally appear from clients during the visualization of a future product can be done without wasting raw material or energy. According to I2C1, the errors and defects of a product are detected after its production. In this sense, as the production only starts when the necessary adjustments are done in a digital form, helped by the virtual reality system, the time of the production phase is reduced, which is translated into a production costs reduction.

According to I1C2, I2C2, and I3C2, the Portuguese footwear sector is labor-intensive, and workers have low education levels. These characteristics can hamper the digital transformation of the sector, since the operators are consequently, in the majority of the situations, averse to change. Therefore, technology adoption, as well as the implementation of sustainable and circular initiatives, can be more difficult to implement.
Still, in a global vision, the footwear sector is investing heavily in technological innovation and process improvement, and according to I2C2 and I3C2, the national footwear sector

must follow this tendency to remain competitive and to avoid losing its unique quality.

4.3. The importance of traceability

Transparency refers to the information communication to internal and external stakeholders, that allows them to understand what is and what is not done in a company, and it contributes to operational and sustainable goals (Garcia-Torres et al., 2022; Gold and Heikkurinen, 2018). The transparency improvement of the value chain is identified as a direct consequence of traceability, and the interviewees see transparency as a necessity for the sector evolution in a sustainable way. According to I2C2 and I3C2, traceability is a necessity for the footwear sector and technological innovation has helped in this sense. For these interviewees, traceability is a by-product of innovation that has a positive impact both on sustainability and on the internal operations of the company.

Regarding the internal operations, tracing products and components allows a major control of the production processes, the identification of production problems and their efficient resolution, enabling a continuous improvement of internal processes (I1C1, I2C2, I3C2, I1C3, I1C4, I2C4, I3C4, I1C6, and I1C7). According to I1C2, I2C2, I3C2, and I1C7, traceability processes positively impact warehouse management. For these interviewees, the possibility to follow the production path facilitates logistical control, contributing to the just-in-time practice, which is a success factor for a company. Moreover, according to some interviewees, clients are also positively affected by a more transparent value chain. The quick and easy identification of production problems, allowed by the interconnection between machines, contributes also to the improvement of the services offered (I1C4 and I2C4). Customers' claims regarding a certain product are solved efficiently, as companies have the possibility to check the specific characteristics of a certain production (which processes and components were utilized) and to identify the origin of a certain problem and act to correct it. In this sense, a transparent value chain contributes to the strengthening of the relationship with consumers (I1C3).

Furthermore, the transparency of the production processes allows clients and consumers to be more aware of the products' characteristics, and their impacts on sustainability, which contributes to a more conscious and informed decision-making process resulting in more sustainable choices (I1C2, I1C4, and I2C4). According to these interviewees, this will, in turn, influence companies' decisions regarding products' materials and processes choices to be

more sustainable (I1C2, I1C4, and I2C4).

I1C2, I1C4, and I2C4 mentioned the importance of production transparency as a proof and a guarantee of the products' quality and the products' commitment regarding sustainability to the end consumer. These interviewees also stated that the companies' commitment to transparency can represent an opportunity for them to increase their visibility as truly sustainable companies and to differentiate their products in that way, attracting consumers concerned with this issue, identifying the investment in production processes' transparency as a marketing strategy. In this sense, these interviewees highlighted the importance of traceability practices to combat greenwashing within the sector. I1C1, I1C4, and I2C4 stated that their clients, positioned as footwear producers at the end of the value chain, pretend to offer sustainable products to the end consumer, as they recognize that those products are receiving more and more attention from the market. According to these interviewees, sometimes the real concerns of those clients are *"marketing issues"*. Some clients just want to prove the minimum required levels of sustainable criteria, investing the least amount of money possible on that since recycled materials are more expensive, but selling those products as sustainable ones. According to I2C1, this practice leads to the presence of *"lying products"* in the market that, according to the interviewee, are the majority. Investing in traceability along the value chain, providing greater transparency of the production processes, according to I1C4 and I2C4, is crucial to communicate the truth regarding sustainable practices and to increase consumer awareness regarding that.

Despite the sector's low level of digital maturity, the majority of the companies (C1, C2, C3, and C5) have digital traceability systems implemented in their operations where they can control the different production orders, from the moment where they enter the company until its delivery to the next level of the value chain. The RFID technology was mentioned by I1C1, I2C1, I1C2, I2C2, and I3C2 as an identification technology essential for the traceability processes. However, the other two companies (C4 and C6) still rely on manual traceability systems, highlighting (I1C4, I2C4, I3C4, and I1C6) the extreme importance of digitalization and Industry 4.0 technologies for traceability and, consequently, transparent practices.

As a digital tool that contributes to the transparency of information, almost all interviewees were familiar with the Digital Product Passport (DPP), and they recognized its importance

for the footwear sector. Among the interviewees who knew this tool (I1C1, I2C1, I1C2, I2C2, I3C3, I1C5, and I1C6), I1C2, I2C2, and I3C2 referred to the textile industry, specifically the garment segment, as a pioneer for the implementation of it, that will influence the footwear industry for its adoption, since it is a related sector that depends also on the consumption of textiles. These interviewees identified it as a crucial step to take to coordinate all the value chain stakeholders to invest in sustainable development. The interviewees' opinions differed when identifying who would be positively affected by the DPP. The majority of these interviewees (I1C1, I2C1, I1C2, I2C2, I3C3) mentioned the utility of the DPP mainly for the end consumer that, according to I1C1 and I2C1, can contribute to the implementation of circular practices since the information shared involved the product' components and characteristics, but also possibilities of what to do after its usage, which can help to manage its end-of-life. They mentioned that, by knowing this, the relationship between producers and consumers is strengthened and the management of the products after the usage phase is more sustainable, avoiding waste production and, instead of that, contributing to the practice of the "R" strategies. On the other hand, I1C5 and I2C5 distinguished the value of the DPP for the end consumer and the company. According to them, the DPP represents, above all, a marketing tool for the end consumer, whereas for the company it has a major value since *"all this traceability that we have is now a click away that can be shared with everyone."*. Nevertheless, I1C6 stated that this tool does not represent a necessity for the end consumer, since *"there is a lot of information given to the customer that is not useful to the final consumer. The consumer buys by will and emotion"*. Instead of that, for I1C6 the DPP implementation can be useful only for the justification of the product value.

Although these traceability advantages are recognized by the interviewees, the majority of them has identified some characteristics of the sector that limit these practices along the value chain and, consequently, the adoption of the DPP tool.

The main difficulty identified by the interviewees is related to security concerns of sharing and exposing the information (I2C1, I1C2, I2C2, I3C2, I1C4, and I2C4). According to the interviewees, this mindset of the Portuguese footwear sector, makes it characterized as a very closed and non-transparent sector. Also, the coordination of all the value chain stakeholders' mindsets, crucial to the implementation of these practices and to move to an open and transparent sector, is a very difficult task given the dimension and complexity of the footwear value chain (I1C4, I2C4, and I1C7). The sector complexity derives mainly from the product

complexity since dozens of materials are necessary to produce a shoe, which requires the coordination of many distinctive companies (I1C7). Moreover, the economic dimension was identified as a difficulty that limits the implementation of traceability practices, since it requires restructuring of the corporates' organization and the implementation of heavy information systems (I2C1, I1C2, I2C2, I3C2, and I1C7). Regarding this difficulty, I1C7 highlighted the importance of having an organized structure within companies. Furthermore, the low level of digital maturity of the sector was also mentioned as a limitation for the implementation of these practices (I2C2, I3C2, I1C4, I2C4, and I1C5).
Only one interviewee (I1C6) stated that the footwear sector is a very open one, where is easy to have access to information since there is no fear of sharing it.

4.3.1. Legislation

To overcome the limitation of the footwear sector regarding its transparency, hindering its transformation to become more sustainable with the creation of new business models and services, I2C1, I2C2, I3C2, I2C4, and I3C4 mentioned the necessity of legislation. These interviewees highlighted the importance of mandatory impositions from the European Union as a solution to transform the footwear sector into a transparent one. *"A European standard that is transposed to the national level is a development driver because it forces us to improve certain practices."* (I2C4). With legislation regarding how to share information, companies from the sector *"act according to the same rules, which is fairer for businesses."* (I2C4).

4.4. Transformations of the business models

As already mentioned, the positive impact of technology adoption on sustainable development is recognized by all the interviewees. Nevertheless, for two companies of the consortium (C5 and C6), the impact of the adoption of advanced technologies is not translated into transformations of their businesses with an impact on sustainability and circularity through the creation of new services. I1C5 was not able to identify any possible creation of a new service that could positively impact sustainability. It was also noticed that for companies positioned in the first tiers of the value chain (C1, C3, and C4), the possible creation of services favoring sustainable and circular practices is not an intuitive process, mentioning that companies positioned near the end consumer are more able to create those services and to transform their business in that sense.

The creation of a reverse logistics system was mentioned by I1C1, I2C1, I1C2, I2C2, and I3C2 as a business model transformation focused on circularity that could take place with the investment in systems and advanced technologies. Through information transparency and sharing, which is facilitated with the adoption of the DPP, the client is able to manage the product after its usage phase, giving back the product to the production company that becomes responsible for its treatment. Recycling of the product's components or continuous product repair are two services that could be created when the product re-enters the company (I1C1, I2C1, I1C2, I2C2, and I3C2). According to I2C2 and I3C2, fashion footwear is an easier product to recycle, as it involves fewer components in its composition when compared to other types of products, for example, technical footwear.

With the investment in virtual reality, I2C1 mentioned the possibility to integrate the client as a *"designer 2.0"*. Through a digital platform where it is possible to see an existent product, its characteristics, and components, the client can be involved in the design phase of the next product by combining different design and materials composition alternatives available in that platform. As a consequence, the relationship between the company and the client is strengthened, with the possibility of a co-creation activity between the two economic agents, and the client becomes more aware of the product's characteristics, becoming more concerned regarding its sustainable impacts.

Information sharing, allowed by digitalization, can facilitate the coordination and proximity of the sector's companies (I1C7). Information sharing regarding the production capacity and its specifications of different companies, through a central digital platform of the footwear sector, could facilitate a sharing of their production levels by the different companies according to their production response capacity. In this sense, companies having an excess of their production capacity during a certain period of time can be helped by those who have that production capacity. According to this interviewee, the secret to this sector's success depends on its capacity to be coordinated, and the production-sharing services that can be created with the investment in transparent information systems are crucial for that. The central idea is for companies to transform their competitors into key partners of their businesses, increasing the capacity of response and, consequently, the revenues.

According to I1C4 and I2C4, it is essential to implement the product-as-a-service paradigm in society, as a way to contribute to sustainability and circular practices. By maintaining the

product's ownership on the company side, whilst the customer's necessity is fulfilled through the utilization of that product instead through its purchase, circular activities are promoted. At the end of the utilization, the customer gives the pair of shoes back to the company, and the same product can be reutilized by another consumer. According to these interviewees, the PLM becomes the central focus of the businesses to maximize the product's value, apart from maintaining a close relationship with their customers.

4.5. The future of the footwear sector

Although we live in a more concerned society regarding sustainability issues, where clients and customers represent an increasing pressure for companies demanding sustainable products, there is still some path to follow (I2C1).

Some interviewees mentioned that clients and consumer education regarding sustainability is crucial for the companies' transformation in this sense, which requires an effort not only from companies but also from the governments. According to I1C4, consumers must be held responsible for their purchasing decisions, paying an extra amount of money for a sustainable product to incentivize sustainable business models to emerge. A more aware, informed, and concerned society is a driver for the businesses' transformation (I2C1). According to I1C4, legislation is important, not only for the orientation and organization of the sector, but also for the education of society because *"if everyone follows the same path, the consumer feels more guided"* and learns how to select a sustainable product.

Apart from this society sensibilization regarding sustainable development and consumption, I1C2 and I1C4 mentioned the importance to educate society to change their vision of the products, for an easier transformation of businesses into the product-as-a-service business model. For them, the DPP has a strong potential to contribute to this change since it is a *"product lifecycle management tool"* that guides clients and consumers during the utilization of the product, and after its usage for a devolution of it to the company. In this sense, I2C1 highlighted the positive impact of legislation as a *"method to change the mentality of society."*.

5. Discussion

The Portuguese footwear sector is characterized, according to the collaborators, by a low level of digital maturity, despite its high-quality level of products. This is a result of low education levels, mainly among the higher positions of the companies, which makes the sector averse to risk and change, restricting its innovation and digitalization. There has been a qualitative improvement of the employees, but is still insufficient and limits the management decisions of the sector (Melo and Duarte, 2001).

Despite this negative perspective of the Portuguese footwear sector, the selected informants had demonstrated practical initiatives implemented in their companies, that aim to change this vision. Technological investments to innovate companies' businesses seek to positively contribute to sustainability, being the environmental and economic dimension of sustainability the main focus of companies' innovation. In fact, according to the literature, companies that innovate their business models tend to demonstrate high levels of corporate sustainability, paying more attention to the triple bottom line of sustainability (Acciarini et al., 2019; Pedersen et al., 2018). According to the interviewees, business innovation is a result of some current market concerns that are translated into pressures for companies to change. The main pressure identified is the increasing demand, from their clients, for sustainable products which is a result of a more concerned and informed society regarding sustainability issues. Despite the growing concern of society regarding sustainable issues, interviewees have recognized the need to invest more in customer education. Among the companies' necessities to support their business transformations, customer education was identified as a crucial one, apart from technological investments (Lacy et al., 2014).

The legislation was mentioned by some interviewees as an essential support for the sustainable transformation of companies, which was not identified in the literature. The intervention of the authorities was referred to as crucial to a fair business's evolution, as companies have to implement and adopt the same rules and guidelines, which helps to reduce the sharing of misinformation avoiding the greenwashing practice within the sector. In this sense, legislation helps the sector to innovate most fairly and transparently, and contributes to the education of customers as they have access to the truth regarding products' characteristics. This represents a support for sustainable business transformation, being a result of this study that is not evident in the current literature.

Sustainable transformation of the companies is translated into practices that are part of the so-called R imperatives, demonstrating a cause-effect relation between technological innovation and circular economy (Rajput and Singh, 2019). Among the R strategies that are identified in the literature, recycling is the main one implemented by the selected companies, which revealed a growing concern regarding waste management. Additionally, the "reduce" strategy adoption is mentioned in the results, where the eco-design paradigm adoption plays a crucial role. Regarding the eco-design paradigm, for some interviewees this vision is considered the initial step to take to invest in a circular economy, aiming to extend the products' lifecycle. This is in line with the literature, that according to Yang et al., 2009, product design improvement positively impacts environmental sustainability through a better management of the end-of-life phase of the product. Also, the "repurpose" strategy, where different destinations are given to the production excesses (shoe accessories, and agricultural fertilizer), is mentioned in the results of this study. In line with these results, according to the literature, the most common "R" strategy found among companies "is recycling" (Panchal et al., 2021). For the interviewees, economic benefits are an important factor when implementing circular practices. The reduction of virgin materials utilization and the consequent reduction of production costs are the main economic benefits mentioned.

The improvement of communication between machines and systems, as a consequence of technological innovation, also contributes to traceability improvements of the processes and operations, favoring the transparency of the footwear value chain. Advantages of traceability are identified both at the company level and at the consumer level, contributing to the increase of sustainable production and consumption. Despite the low level of digital maturity of the footwear sector, the majority of companies has digital systems implemented to support traceability practices. Nevertheless, the concern to become a more common and efficient practice is shared by all the interviewees, highlighting the importance of legislation for fair transparency. A continuous improvement of internal processes, efficient warehouse management, better services provision, the contribution to a decision process focused on sustainability, and the reduction of greenwashing strategy are the main advantages mentioned by the interviewees as a consequence of traceability practices implementation and transparency. Interviewees identified economic and environmental benefits as a consequence of adopting traceability technologies, while not identifying the social dimension as mentioned in the literature (Agyabeng-Mensah et al., 2020). The DPP was identified by the majority of

the interviewees, except for I1C6, as an essential tool for the sector transparency, crucial for both companies and the end consumer, which is in line with the literature (Adirson et al., 2021). The contribution to sustainable production and consumption, and to circular practices were highlighted by the interviewees as the main advantages, which is also evident in the literature (Adirson et al., 2021; Walden et al., 2021; Plociennik et al., 2022; Berger et al., 2022).

Nevertheless, for some of the selected companies (C5 and C6), it was difficult to identify, in practice, what services could be created inside their companies to contribute to sustainable and circular practices. Other companies' interviewees mentioned the investment in reverse logistics as a possible business model transformation that could create new services, promoting circular practices, for example, recycling and repairing. The investment in reverse logistics is identified in the literature as a capability that companies need to have to transform their businesses, focusing on sustainability (Lacy et al., 2014). Furthermore, the increasing companies' interconnection, allowed by i4.0 technologies, was identified as a driver for the sector coordination and for the creation of shared services among the companies. Difficulties in identifying new services and business models are also related to the fact that products must start to be seen as service enablers. As stated in the literature, the integration of services into products requires product innovation, through the incorporation of i4.0 technologies, to create smart products that can communicate with different stakeholders and create product-related services (Terzi et al., 2010; Yang et al., 2018). This paradigm change, according to the interviewees, depends mainly on the legislation and education factors that contribute to the efficient technological investment of the companies and to change the mentality of consumers regarding products, respectively.

6. Conclusion

The main aim of this study was to understand how Industry 4.0 technologies can support the development of new services that contribute to sustainable and circular practices in the specific case of footwear companies. This research is focused on companies in the footwear sector that have adopted, and intend to adopt, Industry 4.0 technologies, and that aim to have more efficient processes, and to respond to the new market necessities. Sustainability and circularity concerns are playing an increasingly crucial role in the market, changing customers' preferences and behaviors, and pressing companies to transform their operations and businesses.

Findings revealed a shared concern among footwear companies regarding sustainability issues. The potential of advanced technologies adoption to sustainable practices implementation was identified by the selected companies. Companies are making investments in technologies, focused on the environmental and the economic impacts. Virgin materials consumption reduction, efficiency and productivity improvement, the consequent decreasing of production costs, and emissions reduction are the main advantages identified by the companies regarding technologies adoption. Still, results showed a perception of low digital maturity level in footwear companies, mainly due to a labor-intensive sector composed by a workforce with low levels of academic education.

Despite the Industry 4.0 technologies potential to change business models, favouring sustainable practices, knowing what can be expected in research areas such as business model transformation, organizational configuration, and product innovation, they are still under research (Chiaroni et al., 2021; Ranta et al., 2021). The results demonstrated interviewees have difficulties in identifying possible transformations on business models and new services creation, driven for example by technologies adoption, that could contribute for sustainable and circular practices. The majority of the interviewees has mentioned that this difficulty is a consequence of the lack of knowledge related to sustainability, in addition to the low level of digital maturity of the footwear sector. They have identified the definition of specific legislation and a more conscious customer mindset (toward sustainability) as two critical drivers for this transformation.

Although the important findings regarding the contribution of Industry 4.0 technologies to the business models' transformation, some limitations of this study were identified. The

qualitative nature of this research limits its generalization. However, the analysis of the analysis of the footwear sector under the BioShoes4All project can represent a comparative situation for future research with a focus on different sectors. Moreover, due to convenience aspects, the number of companies participating in the study were limited to the consortium of the BioShoes4All project, which may limit the results obtained. Nevertheless, the consortium was constituted by companies located in different positions of the footwear value chain, contributing for a broader perspective of the sector.

With this research, an overview of what is the actual position of the Portuguese footwear sector regarding digitalization and sustainable development was made, including different companies positioned along the footwear value chain. The sample diversity, with the contribution of key-informants involved in different departments inside the companies (sustainability, operations, commercial, design, IT) contributed for a more complete overview of the current situation. This study contributes to the literature regarding sustainable business models, by providing practical insights regarding business models' transformations and the creation of new services with the adoption of advanced technologies. From a practical perspective, the research findings contribute to the understanding of what are the potentialities of Industry 4.0 technologies and digitalization within companies' internal processes and operations to promote sustainability practices. Consequently, the results identified what can be the expected limitations and difficulties that companies can face during the digitalization path.

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Appendix A. Interview guide

I. Professional experience

- What is your role in the company? How long have you held this position in the company?
- Describe briefly your career path.

II. Sustainability and the adoption of advanced technologies

- Can you describe the sustainable development practices implemented in your company?
- Are you or have you been involved in any of these practices? If yes, please describe your involvement.
- How are these sustainable practices aligned with the company's mission/value/goal? Describe the evolution that has taken place in this sense.
- Describe the transformations in the production process that have arisen with the adoption of advanced technologies.
- Describe how you consider that the changes brought about by the adoption of Industry 4.0/digitalization technologies positive contribute to the sustainable production?
- Can you describe how these transformations have brought benefits or created value?

III. Circularity

- Describe your company initiatives (with internal and external impact) in favor of circularity. Describe the role of technologies in this change.

IV. Traceability and the Digital Product Passport

- What is your opinion on the traceability of products/components?
  - Advantages, disadvantages, barriers and challenges
  - Do you have traceability practices in your production process? What technologies are used?
  - Have you heard about the digital product passport? In what scope?
  - What is the importance of this tool for the footwear sector? What should change or improve in your company and in the footwear sector for an efficient adoption of it?
  - What kind of information should be collected and shared?
  - What difficulties and challenges can your company feel in the implementation of these traceability processes?
  - Through the information provided in the implementation of traceability processes, what

new services could be created by your company?

- Who could benefit and in what way from these new services?
- With these new services, what business models could be created?

V. Final question

- Would you like to add something to the issues addresses in this interview?