A PLM Vision for Circular Economy

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Abstract. Due to growing concerns with sustainability issues and the emergence of the Circular Economy (CE) paradigm, combined with recent technological changes and consequent increase in competitiveness, there is a pressing need to redefine the Product Lifecycle Management (PLM) approach. PLM needs to incorporate aspects that would enable the shift to this paradigm, such as enhanced collection and evaluation of information coming from production processes, distribution, retail, consumers, and collaboration in an extended enterprise context, by implementing enabling technologies such as the Internet of Things (IoT) and Big Data. This paper proposes a vision, based on the state of the art, for a CE enabled PLM, having the Portuguese footwear industry scenario as a reference.

Keywords: Product Lifecycle Management, Circular Economy, Collaboration, Information Management, Footwear Industry, Industry 4.0, IoT, Big Data

1 Introduction

Today, the concept of Product Lifecycle Management (PLM) is being redefined by the shift from the mass production paradigm to a new personalized, on demand, customer-driven and knowledge-based production paradigm [1], which requires the enhancement of information coming from design, production processes, distribution, retail, consumers, among the whole product lifecycle, from its initial inception to its end of life. The increase in complexity of products has led to enterprise unbundling, with most companies focusing on their core activities and externalizing support activities, leading to a value chain distribution among several organizations. In this decentralized knowledge intensive environment, collaboration between the stakeholders involved in all product lifecycle activities, in an extended enterprise context (network of retailers, consumers, producers, among others) is a challenge that needs to be addressed in PLM, enabled by technologies such as the IoT and Big Data. At the same time, new challenges related to growing concerns with sustainability issues and the increasing significance of Circular Economy (CE) concept are emerging, which require improved products that can be used for longer, with multiple lifecycles. This scenario poses challenges to future PLM systems, especially those intended for SMEs, which have limited internal resources and strongly rely on collaboration with external partners, suppliers and customers.

This paper proposes a vision for a CE enabled PLM, targeting SMEs needs, having the Portuguese footwear industry as a reference in order to illustrate the current scenario, and is structured as follows. The Portuguese footwear industry, which consists mainly of SMEs, is a success story in the Portuguese industry, being responsible for the greatest positive contribution to the Portuguese trade balance. Leading European footwear players, such as Portugal and Italy, pursue a strategy based on technological innovation, quality-competition, and product differentiation. Differentiation is a crucial factor for the fashion cluster, as a result of accelerated changes in consumer preferences and fashion trends [2]. These changes require a reduction of the footwear development cycle, with repercussions to companies' strategies and PLM approaches.

The volume of business growth in the footwear sector witnessed in recent years, together with product differentiation and a decrease in time to market, translates into an almost exponential increase of references, each one with a reduced production volume. This new reality, while enhancing new opportunities for the most dynamic footwear companies, entails enormous organizational and technical challenges regarding product data management throughout the entire product lifecycle.

Moreover, the increase in complexity of footwear products led to specialization and consequent unbundling. Currently, few footwear companies internalize all their processes, leading to a value chain distribution among several organizations (from the end customer, either an individual store or a distribution chain, through the manufacturer and its partners, often in the form of subcontractors, to raw material suppliers), which greatly increases the need for interaction between agents, with large amounts of data, information and knowledge being constantly exchanged. In this heterogeneous and dispersed environment, the alignment of people, information and processes poses a big challenge. In order to be competitive in the described context, companies must manage their value chains effectively, with the aim of reducing lengthy product development cycles and costs, while improving quality [3].

Traditionally, the management of this dynamic in SMEs is done in a very ad-hoc way, without any specific methodologies, usually by using tools designed for personal productivity (text documents, spreadsheets, e-mail messages). This approach, in addition to requiring a huge consumption of human resources, greatly limits the ability to exploit the value associated with the increase in data exchanged, and its transformations into information and even knowledge. Many SMEs have strong gaps in management and execution of activities with a strong collaborative nature, both horizontally (intercompany relations along the value chain) and vertically (information exchange between business processes within the same organization).

Today's knowledge-intensive product development setting requires a computational framework that allows the acquisition, representation and reuse of product and process knowledge. In a manufacturing environment, all product information should be shared along the value chain and continuously synchronized with updates. During product utilization, product data must be used by the service chain in order to provide support. Sharing and managing product data, information and knowledge is the cornerstone of PLM [3]. PLM is defined as business strategy for building and sustaining a product-centric knowledge environment, seeking to integrate people, processes, resources and information. A PLM environment allows collaboration between multiple stakeholders of a product along its lifecycle [4]. Over the last two decades, PLM emerged as a strategy to enable end-to-end product development [5]. Ideally, companies manage products from cradle to grave as part of their PLM strategy, according to a linear model in which products are developed, manufactured, used and disposed. However, environmental problems such as biodiversity loss; water, air and soil pollution; resource depletion; excessive land use, among other sustainability issues, are increasingly compromising the earth's life-support systems, pressing the need to transition to more sustainable paradigms [6]. To address these issues, the concept of Circular Economy, while not entirely new, has recently been gaining importance. Based on different contributions [6] define Circular Economy as "a regenerative system in which resource input and waste, emission and energy leakage are minimized by slowing, closing and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing and recycling" [6]. Ongoing European Project FUTURING – Futuring European Industry [1]defines an approach for the definition of CE that is structured in Building Blocks, Pillar Actions and impacts on Profit/ Planet/ People, covering the extent of CE. The Building Blocks represent the different dimensions of CE, defined as Science & Technology, Business & Innovation, Human Being & Society, Policy & Finance, Environmental Sustainability, Education & Training. The Pillar Actions describe some complimentary ways to implement CE – Regenerate, Share, Optimize, Loop, Virtualize, Exchange. A fundamental principle of circular economy is that after the utilization phase, products should be returned to manufacturers instead of being disposed, creating new flows of recyclables with extremely high values. Therefore, circular economy will require new PLM enabling solutions and supporting services [5].

According to a study conducted by McKinsey & Company [7], companies can benefit largely from consumer-focused lifecycle thinking and cross-functional collaboration, as it helps capturing more value from the resources they consume. Some companies are already adopting circular economy practices to create durable products that are easy to reuse or recycle and profitable, by devising a highly collaborative product development process that helps determining sourcing requirements, production methods, marketing, sales and other aspects of how products are created and managed at the end of their lives. However, these aspects are far from being a reality in PLM solutions designed for SMEs, and even in PLM solutions overall [8] [9]. The rest of the paper is organized as follows: sections 2, 3 and 4 cover a brief literature review regarding PLM and its main aspects: data and information management and collaboration; section 5 provides a vision for the support of Circular Economy in PLM; the paper concludes with final remarks on the contributions of this study, and interesting fields for further research.

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2 PLM and PLM Systems

In the last few years, PLM has become the paramount management approach in engineering in the manufacturing industry [8]. According to Stark [4], PLM is the business activity of managing a company's products all the way along their lifecycles; from the very first idea until products are retired and disposed of, in the most effective way. PLM is an integrated paradigm that includes a consistent set of methods, models and tools for managing product information, engineering processes and applications along the phases of product lifecycle [8]. The core functionalities of PLM systems include information management, process management and application integration, as well as a set of additional PLM methods and tools such as engineering collaboration support, user access management and data analysis, reporting and visualization [8].

As clearly defined by Stark [4], the generic product lifecycle has five phases: Imagine, Define, Realize, Support/ Use, Retire/ Dispose. During the imagination phase, the product in an idea. In the "Define" phase, ideas are translated into detailed descriptions. By the end of the realization phase, the product is ready be used by the customer. During the use/ support phase, the product is being used by the customer. Ultimately, the product reaches a phase in which it is no longer useful, and is retired by the company or disposed by the customer. The specific activities that occur across the lifecycle phases can be different, depending on the particular industry. PLM activities enable a company to grow revenues by improving innovation cycles, reducing time-to-market for new products, and providing support and new services for already existing products [4]. PLM can improve the development of new products and reduce manufacturing costs by controlling products' data throughout their lifecycle [10].

The main weakness of current PLM solutions is poor support of product lifecycle phases and activities besides product development [8]. Another problem of available PLM solutions is their very high complexity and the huge customizing efforts that are necessary. The total costs involved in the installation, usage and maintenance of PLM systems means that the most powerful and popular PLM systems are only affordable to large companies, and a mirage for SMEs [11]. In recent years, light and low cost PLM solutions have started to appear in the market for SMEs [12]. However, according to studies carried out by several authors [9], SMEs continue to consider PLM solutions complex, with high cost and high dependence on software services, which constitutes a barrier to the adoption of this technology. In this context, one of the biggest challenges in PLM is the reduction of costs related to IT technology and infrastructure investment, as well as the development of easy-to-use, intuitive software with features that are very oriented to the real needs of organizations, with the objective of enabling their adoption by SMEs, which represent 99% of the European Union's manufacturers [13].

3 Data and Information Management in PLM

The Industry 4.0 term, which originates from a German government strategy project [14], defines the complete digitization and integration of the industrial value chain.

The technical foundation for Industry 4.0 is the combination of information and communication technologies with automation technologies, embodying the Internet-of-Things (IoT) and Internet-of-Sevices (IoS). The combination of these technologies enables high levels of network communication, encompassing people, equipment, products, services, as well as business-to-business communication. This way, it becomes possible to create intelligent supply chains, covering all phases of the product lifecycle - from the initial idea to the end of its life, through development, production, use and service [14]. The Reference Model for Industry 4.0 - RAMI 4.0, consists in a three-dimensional coordinate model that describes all the important aspects of Industry 4.0, in order to reach a common understanding of required standards and use cases. According to RAMI 4.0, presented in Fig. 1- *RAMI 4.0*, the complex interrelationships can be decomposed into elementary clusters: "Layers" axis, "Life Cycle & Value Stream" axis and "Hierarchy Levels" axis [15].

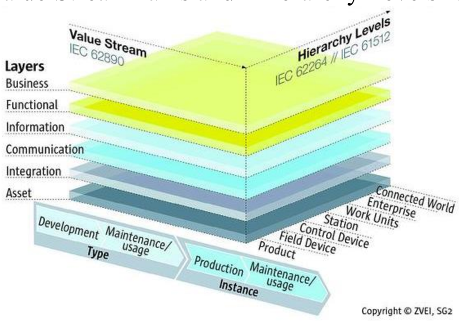

Fig. 1- RAMI 4.0

RAMI 4.0 maps the relationship between the lifecycle of products and value streams, the hierarchical levels of business information systems connected via the Internet, and the IT structure of an Industry 4.0 component. The description of the product lifecycle is done considering that a product has a lifecycle as a virtual “type” (during the design and development phases) and as a physical instance (after the manufacturing phase, through use, service and end of life). During the entire product lifecycle, as a type and an instance, the data generated in the process chains is processed by PLM systems, creating product-service centered collaboration among the connected world [16].

Due to technological advances and the emergence of the Industry 4.0 paradigm, which generate and must deal with extremely high volumes of data, new opportunities for the application of PLM in areas such as SMAC (Social, Mobile, Analytics, Cloud), Internet of Things (IoT), Big Data and Smart Products have recently emerged. PLM has been evolving continuously towards a digital paradigm, under which products are managed throughout their lifecycle using digital information and communication. The reporting of product performance using technologies such as the IoT, GPS and RFID, which allows real-time perception of its performance and customer satisfaction level, is a pressing trend [4].

The aim of the IoT application in PLM is to establish a smart information cycle along the whole product lifecycle. From data sensed and communicated by smart products, manufacturers can understand products’ behavior when they are being used by the customer. From the analysis of product data, innovative new products and services can be identified in order to better fit customer's requirements. In the product's end of life, components can be identified and tracked, which can lead to better decisions being taken regarding how to treat products in an environmentally correct way. These aspects can reduce costs and improve compliance with environmental rules and regulations [4].

Top PLM manufacturers are already defining visions for enabling digitalization in their PLM solutions. Siemens Automation is building a "Smart Innovation Portfolio", with the aim of activating digitalization in manufacturing. Siemens AG's "Digital Enterprise Software Suite" extends digitalization from development and operation through production [17]. PTC FlexPLM, a powerful retail oriented PLM, is leveraging PTC's own IoT technology, ThingWorx [18]. However, the integration of these aspects in PLM is at an early stage, and far from becoming commonplace in PLM solutions for SMEs. According to Li [10], in recent years researches related to the increase of data have been conducted in the field of data mining and knowledge management. However, the utilization of Big Data in PLM significantly falls behind other areas. Most manufacturers do not store data or have limited knowledge about how to use these data, which makes the manufacturing chain not efficiently connected, with data being generated, transmitted and stored unsuccessfully. Additionally, the existing studies about Big Data and PLM are exclusively concerned with the development lifecycle phase, and have not been explored from the whole lifecycle perspective [10].

4 Collaboration in PLM

In nowadays global economy, manufacturing companies must be considered in the context of their input to the whole value chain. Extended or virtual enterprises, which consist of connected chains of suppliers, manufacturers, assemblers, distributors and customers, compete to provide customized products and services to competitive markets [19]. Virtual enterprises and manufacturing networks have been largely discussed in the last decade [1]. According to Camarinha-Matos [1], "a Virtual Enterprise represents a temporary alliance of enterprises who join to share skills or core competencies and resources in order to better respond to business opportunities, and whose cooperation is supported by computer networks". An extended enterprise is defined as a particular case of a virtual enterprise, which arises when an organization "extends" its boundaries to all or some of its supply chain stakeholders [1]. Due to the growing complexity of products, their variability and the continuous transformation of customer needs, product lifecycle has become increasingly challenging, requiring collaboration between heterogeneous teams, holding expertise in different fields [20]. Internally, collaboration among associated departments, such as marketing, development and production, is the most crucial factor in the successful on-time delivery of new products to market, which is one of PLM goals [21]. Externally, collaboration among various stakeholders, such as customers, suppliers and other partners, such as service suppliers, is also a contributing factor to improve processes efficiency and customer satisfaction.

Therefore, the modern product lifecycle is characterized by an interdisciplinary interaction between a large number of actors, intra and extra organization, such as departments, customers, suppliers and partners, in an extended enterprise environment. Traditionally, PLM solutions focus on collaboration between various departments of the same company. However, as a business integration platform, PLM systems must take into account the entire network of partners and customers, in order to improve information access and sharing inside the company and outside the company [22]. This way, PLM can provide the capability of collaborative creation as well as management and use of product data, information and knowledge in a virtual enterprise environment, merging people, processes and technology [23].

Siemens PLM software solution for apparel, footwear and accessories provides the supply chain stakeholders (buyers, designers, merchandisers and managers) with a central location to effectively manage the fashion product development process, enabling collaboration across the supply chain [17]. PTC Flex PLM integrates internal and external teams, as well as third-party customers [18]. However, fashion industry PLM solutions aimed at SMEs, such as Infor Fashion PLM, are more focused on devising collaboration within the enterprise, by linking planning, design, development and execution on a common platform [24]. The effective implementation of an extended PLM raises a concerning challenge, which is the need to process information gathered from multiple sources into knowledge for making effective decisions in real-time. This technical challenge addresses the goal to integrate the collaborative network partners' information systems, so that cooperation can occur flawlessly [1]. The interaction between the various agents is marked by the use of IT tools such as CAD, CAE and CAM, among others, which creates a very heterogeneous data scenario [8].

5 Vision for the Support of Circular Economy in PLM

As evidenced in the previous sections, recent work shows that PLM is evolving from a system mainly supporting product development and engineering processes to a platform destined at encompassing the whole product lifecycle. This future PLM platform is about integration, collaboration and connectivity of devices, across disciplines and enterprise borders, supported by enabling technologies such as the IoT and Big Data [25]. Scarcity of materials and energy resources, combined with rapid degradation of the environment, is pressing the reformulation of economic and industrial systems. As briefly mentioned in the opening section, nowadays most manufacturers still follow a linear model of production, in which materials are extracted, turned into products, used and discarded, with their value being lost, according to a "take, make, use and throw away" approach. The Circular Economy approach, which includes reuse, recycling and remanufacturing principles, presents an opportunity for manufacturers, since it enables the creation of flows of valuables capable of generating new business opportunities. However, there are challenges in closing the loop [25], particularly the information gaps along the end-of-life stages of product lifecycle. The development of efficient and robust PLM systems for Circular

Economy will require excellence in IT, supporting collaboration among the extended enterprise and management of multiple lifecycles [25]. In this context, a Circular Economy PLM Strategy is defined along these lines [26]:

Mission: To provide products capable of satisfying customer needs, while taking full advantage of the company's sustainable production system and innovation competency, considering all impacts along the lifecycle.

Vision: To generate data, information and knowledge within the supply chain and to manage it from the perspective of sustainable product design and development, manufacturing, distribution, use and service and recycling and recovery.

Objective: To share data, information and knowledge of all the product lifecycle phases among all the stakeholders (internal and external); to encourage collaboration between customers, designers, producers and suppliers; and to enable sustainability through environmentally conscious products and processes.

Fig. 2. CE enabled PLM concept illustrates the concept of managing the entire product lifecycle from a Circular Economy outlook, supporting and driving the value chain. This concept is focused on the footwear industry scenario.

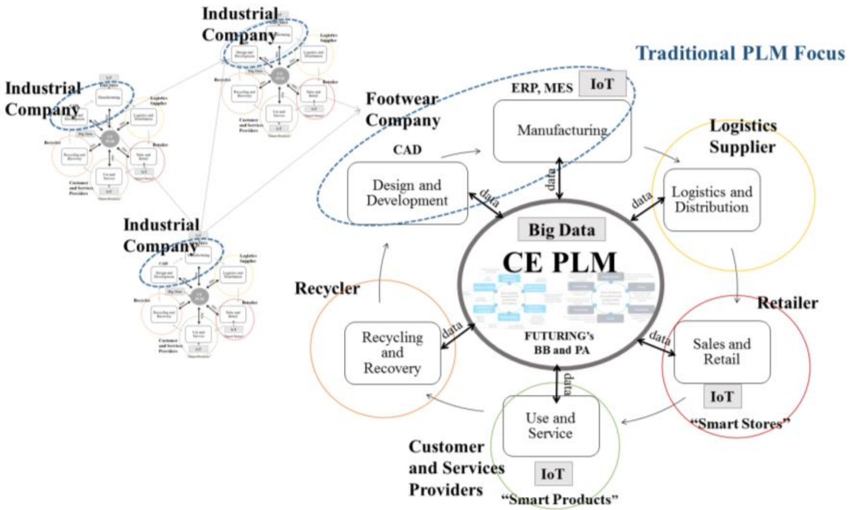

Fig. 2. CE enabled PLM concept

The vision for a CE-enabled PLM proposed in this research encompasses the CE dimensions defined in the scope of the FUTURING approach, represented by Science & Technology, Business & Innovation, Human Being & Society, Policy & Finance, Environmental Sustainability and Education & Training Building Blocks (BB) and the Pilar Actions (PA) needed to implement CE - Regenerate, Share, Optimize, Loop, Virtualize, Exchange. The vision is grouped into four categories: Enabling technologies; Types of products; Product lifecycle phases and stakeholders; Virtual enterprises and industrial symbiosis. Each category is described below.

Enabling technologies. There is a consentual opinion among various authors [4][5][7][27] that digital technologies are the main drivers to the transition to the Circular Economy paradigm in PLM. The Internet can link together multiple supply chain partners, improving transparency and helping optimize cost, service, agility and resilience [27]. The use of the IoT technology is especially important during the Manufacturing, Sales and Retail and Use and Service product lifecycle phases, as shown in Fig. 2. CE enabled PLM concept. During the Manufacturing phase, the IoT helps optimizing production efficiency, by using data across the manufacturing value chain. During the Use and Service phase, the IoT enables companies to track their products, offering numerous opportunities to get an improved understanding of products behavior, as well as to manage their related services. At the store level, during the Sales and Retail phase, the IoT enables the collection of valuable data regarding consumers' preferences.

Due to recent technological advances and the evolution of PLM into a digital paradigm, under which products are managed using digital information and communication, the volumes of data generated along the whole lifecycle are increasing at a high rate, which poses an opportunity for the application of Big Data in PLM [4]. There is the need to analyze and extract information from the large volumes of data collected along the product lifecycle, in order to capture knowledge that can lead to improvements in product lifecycle's activities all along the supply chain. Therefore, a CE enabled PLM should support IoT and Big Data technologies integration.

Types of Products. A next generation PLM should support "smart products", embedding information devices such as RFID or on-board computers, capable of tracking and tracing all the product information over the entire lifecycle in real-time. PLM solutions should also manage intangible products such as software or services, and in a more complex level PSS (Product Service Systems) [8].

Currently, there are concluded and ongoing R&D projects that address product and stores sensorization. Shoe-ID project, concluded successfully, addressed the incorporation on RFID technology in the initial phase of the footwear production cycle, in order to simplify the whole supply chain follow-up, from manufacturing to the final consumer [28]. The ongoing project FASCOM aims at creating a solution that enables the collection of sales related data from the store and its access by product developers, manufacturers and distributers [29]. Data collected from the store regarding the perception of products by customers, as well as reasons for lost sales, can provide valuable information to designers and manufacturers that can lead to improvements in the development of new products. The integration of these technological solutions with PLM solutions is not yet explored and therefore is an area for further research. A CE enabled PLM should support smart products and smart stores, connected by the IoT.

Product Lifecycle Phases and Stakeholders. As previously stated in Section 4, currently the focus of SME oriented PLM solutions is within one manufacturing company, which may include various distributed locations [8]. A CE-enabled PLM approach for footwear industry should integrate all supply chain stakeholders along the whole product lifecycle: logistics suppliers, materials suppliers, retailers, manufacturers, customer and recyclers.

Specific models, methods and tools from actual PLM solutions are mainly focused on product design and development, providing little or no support to other lifecycle phases [8]. CE-enabled PLM platforms must provide support in managing other downstream product phases such as manufacturing, distribution and logistics, sales and retail, use and service, recycling and recovery, focusing on value-added activities. A CE enabled PLM system should consider not only the management of a single life cycle but multiple product life cycles in which the products used can be changed or reconfigured in a sustainable way. These aspects are represented in Fig. 2. *CE enabled PLM concept*. As previously mentioned, PLM platforms must support smart, connected products and stores enabled by the IoT, improving product design through feedback on in-use performance and durability. This information flow should continue seamlessly through reuse to the end of use, with further feedback to the designer and producer, supporting improved design and material choice. In the design and development phase, components normalization and modularity aspects must be considered, thinking of the products end-of-life from an early stage, which can include reuse, remanufacturing, recycling and disposal. In the CE context, the use and service phase is particularly relevant, since the product and its related services must be managed in order to provide customer support. CE enabled PLM systems should focus on generating product data during utilization and end-of-use phases, which is more complex than generating product data at the development and manufacturing phases. Data, information and knowledge flows break down after the delivery of the product to the customer, preventing the feedback of data, information and knowledge from service and recycling providers back to designers and manufacturers [30]. CE PLM solutions should close this information gap, feeding information about in-use and end-of-use to inform product development, materials selection and support circular business models. The recycling and recovery phase is characterized by various scenarios, such as product reuse with refurbishing, components reuse with disassembly and refurbishing, material reclamation with disassembly and disposal with or without incineration, material reclamation without disassembly, remanufacturing [30]. Therefore, in the recycling and recovery phase PLM systems must be capable of managing activities related to materials recovery, recycling, remanufacturing and disposal.

Virtual Enterprises and Industrial Symbiosis. Industrial symbiosis engages traditionally independent industries in a collaborative approach to competitive advantage by involving tangible exchange of materials, energy, water, and byproducts. The key elements to successfully implement industrial symbiosis are collaboration and the synergistic potential offered by geographic adjacency [31]. Relating this concept to the virtual enterprise concept, there are some opportunities in extending PLM not only to the company's supply chain, but also to other companies with whom they have resources synergies. The aim would be to establish a knowledge base that would involve a network of enterprises, offering the necessary conditions to efficiently promote the sharing information regarding materials, water, energy and infrastructure, with the intention of achieving sustainable development in a collaborative way [32]. This is especially relevant for SMEs, which have limited internal resources, since it reinforces their capacity without the need to make large investments. Fig. 2. CE enabled PLM concept illustrates the concept of connecting multiple enterprises with symbiotic relationships, incorporating this data in PLM.

6 Conclusions

A CE enabled PLM would be a fundamental tool to improve companies' competitiveness in a collaborative and sustainable way, particularly footwear industry SMEs, which have complex interactions along the supply chain. Due to the growing market demands in this field, translated by product differentiation and a reduction in time to market, as well as increasing environmental awareness, there is a need to implement a new PLM paradigm. This circular PLM paradigm should be focused on generating data, information and knowledge within the organization and its stakeholders and manage it along the product's multiple lifecycles, from the perspective of sustainable product design and development, manufacturing, use and service, recycling and recovery. Technologies such as the IoT and Big Data will have a major role in enabling collaboration throughout the whole lifecycle. Although the design and development phase can be defined as the main phase responsible for driving the sustainability impact [26], future works must be done regarding its connection with other critical lifecycle phases such as use and service and recycling and recovery. Currently, efforts are being made in the development of technological solutions aimed at supply chain integration and smart products and stores. However, the integration of these technologies with PLM is nonexistent and therefore should be explored. The integration of a knowledge database regarding industrial symbiosis in PLM is also an area for further research.

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