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Product Biography Information System: A Lifecycle Approach to Digital Twins

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***Abstract*— This paper introduces the concept of product biography information system (PBIS). The findings emerge from a design science research project conducted in a paper pulp company integrating the PSI-20 stock market index of Euronext Lisbon. The results include a reference architecture and design principles for the development of PBIS supported by blockchain and multiple generations of digital twins. For theory, PBIS offers an extension to product lifecycle management, ensuring that products lives are memorized in its sociomaterial context of production, logistics, and use. For practice, we show how organizations can design new enterprise systems that capture complex product biographies taking advantage of Industry 4.0. The findings are relevant for the innovation of product-service systems that adhere to the emerging challenges of sustainable development and traceability.**

Keywords—product biography, lifecycle management, digital transformation, memorization systems, industry 4.0, blockchain, digital twins

I. Introduction

Product innovation is increasingly digitalized, supported by smart and interconnected products that reduce the gap between producers and consumers [1]. On the one hand, producers need real-time information on how products are sourced, transformed, and experienced by customers. On the other hand, the society needs to ensure sustainability by tracing "things" that gain new lifecycles that were not available in the past. The new technologies emerging from the fourth industrial revolution (Industry 4.0), for example, internet of things, mobile systems, blockchain, or cloud computing, are changing the landscape of industries worldwide, increasing the decentralization of production systems and end-to-end digital integration [2], [3].

Product lifecycle management (PLM) has been the central enterprise information system solution to manage lifecycles of traditional products, defined as "*a business strategy for creating and sustaining such a product-centric knowledge environment. It is rooted not only in design tools and data warehouse systems, but also on product maintenance, repair and dismissal support systems*" [4]. However, PLM mostly focus the design and manufacturing stages [4], based in document management and workflow functionalities that do not support the current needs for agility [5]. It is surprising that leading PLM solutions still aim at the internal company needs of product design and development (e.g. compliance management, CAD, and technical documentation), missing crucial features of technology planning, or post-sales [6]. Current PLM systems are not taking full advantage of continuous/remote monitoring and the capacity of Industry 4.0 to record the entire product lifecycle since its early stages (e.g. raw materials).

Aiming to address the shortcoming of current PLM systems and the need to holistically manage how products evolve in increasingly dynamic environments, we introduce in this paper the concept of product biography information system. It differs from the current approaches to managing product lifecycles by (1) considering that products may have multiple lives (generations), changing its original characteristics over time, (2) products and services are increasingly intertwined, (3) products or services have an integrated and mutual influence with the social environment, and (4) product-service biographies are not only important for producers and partners, but also to the society as a whole (e.g. compliance to regulations and societal challenges of resource protection). The new PBIS have the tremendous responsibility to address the challenges of sustainable development, transparency, and memorization of important events (e.g. changes in the physical or digital dimensions). Accordingly, we have formulated the following research objectives:

RO1: *Evaluate the potential of biographies for the memorization of product characteristics and events in phases of stabilization and destabilization of its lifecycle;*

RO2: *Propose a reference architecture for product biography information systems supported in two key technologies: blockchain and digital twins.*

The remainder of this paper is presented as follows. Next, we present the design science research approach [7] conducted in a major paper pulp company aiming to memorize the entire lifecycle of their products (starting in the tree growing stage) at

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a global scale. Subsequently, we present the reference architecture for PBIS, followed by a discussion of the findings at this stage of our work. The implications for theory and for practice and the study limitations follow. The paper closes with the key conclusions and opportunities for future research.

II. Research Approach

Design science research (DSR) has its foundations in the work of [8] aiming to produce scientific knowledge from the design of specific sociotechnical artifacts [7]. Models, technological rules, and design principles are typical outcomes of nascent theories in DSR [9] that include six core dimensions [10]: (1) problem description, (2) input knowledge, (3) research process, (4) key concepts, (5) solution description, and (6) output knowledge.

Our research takes place in one of the major industries in Portugal producing paper pulp. Starting its operation in 1965, the company produces over 700.000 tons of paper pulp that exports all over the world. Sustainable development is one of their major priorities nowadays. First, the company must ensure the certified origin of the wood and the adoption of good forest management practices (e.g. reforestation, environmental responsibility). Second, the production process needs to guarantee the desired cost efficiency and quality of the product. Finally, packaging, maritime transport, and storage of paper pulp should be closely monitored to certify that the end customer receives the product in the best conditions.

The above-mentioned priorities are challenging to a multi-plant process industry that need to obtain a reliable biography of their products during the entire lifecycle. For example, (1) the wood comes from multiple suppliers and it is impossible to monitor each tree, and (2) the product may travel for months around the globe before arriving to its final destination (paper producers). The main stages of paper pulp production are illustrated in Figure 1.

Fig. 1. Paper pulp lifecycle

Wood is the main raw material to produce paper pulp sheets (a thicker version of the commercial paper). In our case company, the paper pulp is packaged and transported by ship to multiple ports around the globe, where it remains stored in local warehouses until required by the near paper producer.

We sought inspiration in the emerging concept of product biographies [11] to guide our design science research process. The proposed technological solution is based in two key concepts of Industry 4.0, namely, the distributed ledger technology (blockchain) "*to develop trusted and autonomous relationship among different components of smart factories, suppliers and even customers*" [12], and the digital twin, "*an integrated multiphysics, multiscale, probabilistic simulation of a complex product, which functions to mirror the life of its corresponding twin*" [13]. Usually presented as a three-dimensional replica of physical objects, digital twins use real-time data obtained from sensors that monitor object operation (e.g. growth parameters), its environment, and other similar twins (the fleet, as presented by [14]). The main outcome of our research is a product biography information system instantiated in the paper pulp company. Next, we present a review of foundational literature for our work.

III. Background

A. Memorization at the Core of Information Systems

In 1975 Jean Louis Le Moigne presented his vision of information systems as the memorization systems of organizations that permit to keep in memory (1) the transactions with the environment, (2) the particular events that may be needed to recall for a period of time, and (3) the common (voluntarily or imposed) rationale that the organizational members share [15], [16]. Much has changed in the past forty years but the traces from the past are more important than ever for the effective support of processing systems and decision making in organizations.

Memorizing the story of specific groups (e.g. organizations), persons, or events, as happens with the production of autobiographies, biographies, or memoirs, requires a careful selection of information that can be relevant for the future. Also, the process of collecting, storing, and processing that information can be challenging, requiring reliable sources, mechanisms of archive that allow safety and integrity of data, and effective flows of information to support the users' needs.

As the social and the material (physical and digital materialities) became increasingly intertwined in the ongoing digital transformation [17], [18], "stories" are no longer restricted to human actors. It is possible to make a parallel on how "things" are constructed, opening an opportunity for the concept of biography of things. As stated by [19], "*things can be said to have 'biographies' as they go through a series of transformations from gift to commodity to inalienable possessions, and persons can also be said to invest aspects of their own biographies in things*". For example, the work of [20] takes advantage of the internet to create an augmented memory system where users can share stories about specific objects. On the one hand, objects are an inherent element in social memories. On the other hand, experiences, events, and cultural attributes are not indissociable from the (physical or digital) "things" that compose the reality.

The advent of the circular economy and the decentralization of production systems made possible by the fourth industrial revolution makes the biography of things a key topic for the following years. This claim is supported by the work of [11] showing how products can have multiple biographies within its changing lifecycle in the circular economy. The concept of ownership of a specific product also becomes blurred with the concept of sharing economy, as happens with major companies like Uber or Airbnb, allowing "things" to be temporarily shared by multiple users. Moreover, emerging technologies such as the internet of things and 5G are creating opportunities to collect real time data about different phases of the "life" of increasingly digitalized products.

B. Biographies of Everything: Sociomaterial Perspective of Humans and Things

Industrial products are constantly altering their physical state and characteristics. Therefore, it is important to memorize their changes over time. However, the transaction of products and services requires temporary stability of its characteristics [21]. The concept of biography can be applied to services [22] and enterprise systems that evolve according to the users' needs, revealing a mutual influence with the organizational practices [23]. The contributions of these authors reveal that a biographical approach attempts to capture moments of stabilization and destabilization of the system under evaluation. For example, [22] shows how a service evolves trough the sourcing process, alternating between phases of destabilization (e.g. shifting from the supplier selection to the contract agreement) and stabilization (e.g. contract). The work of [23] about the biography of a SAP ERP implementation describes similar moments of destabilization (e.g. software package adaptation) and standardization.

The materials are increasingly intertwined with physical and digital elements [17] that produce new forms of product interaction and experience. Therefore, enterprise systems should consider biographies as a multidimensional concept that needs information from different sources, particularly information that allows contrast of opinions (e.g. perception of employee and the supervisor; designers and end users perceptions) to improve products over time and ensure that its changes, sometimes disruptive as happens in circular economy (e.g. integration of a product or some of its parts in another product or service with different purposes from its original conception), can be memorized and shared to each stakeholder.

The traces of things are not restricted to its physical changes, as happens with circular economy. One example is the social experiences, for example, particular events that deserve to be memorized about a product [20]. Another example is the opinion about specific product / service by its users, allowing to qualify its performance and assisting future users, as happens in models of sharing economy. The stakeholders of product/service biographies vary. For example, consumers may have interest in the biographical records (e.g. used car); product suppliers may want to confirm the product performance under specific conditions and create improvements; or the governmental authorities may want to access specific events or characteristics of the product use to confirm compliance to regulations (e.g. truck inspections).

Biographies are relevant for social, physical, and digital elements [17], [19], [24], as presented in this section. There are moments in the life that involve changes (destabilization) but also stable configurations of the product characteristics [21], being important to memorize its alternations and the rationale shared by its users [15]. Moreover, biographies must ensure trust in the information collected that may involve manual records by product users [20] or automatic records using IoT [11] to create a comprehensive memorization system. The major gap found in the literature is the lack of contributions showing how to create product biographies in practice.

C. Biographical Sources of Products

Two main sources of information can be identified to the creation of biographies. The autobiography (first person) refers to the automatic data acquisition system that can be implemented in the product, for example, using sensors to monitor its use or the context of use (environmental parameters). In the case of a vehicle, it refers to the sensors of speed, emissions, and external aspects such as temperature and rain. The biography "third person" occurs when the memorization includes the social experiences of interaction with the product, for example, classification of goods in online stores.

Both sources have challenges. On the one hand, the reliability of autobiographies depends on the quality of measurements (e.g. calibration of the sensors). On the other hand, the reliability of third person memorizations depends on personal interests (e.g. the opinion about the product coming from a competitor may be biased) and use. It is different to obtain data from the product user or from an amplifier in social network environments. Therefore, companies must be careful in the classification of the sources of data for the memorization process.

There are costs involved in memorization that must be evaluated. First, although the cost of storing information in servers has decreased, there are computational costs involved in communications and information processing. For example, the use of blockchain technology is interesting for critical information, but the energy/processing consumption may be excessive to non-critical information [25]. Second, recording information (manual or sensor based) is time consuming and it is important to identify when the data should be recorded and what type of data can be valuable. Third, the format of memory information (e.g. basic data or processed information) must be defined to support decision making with minimum effort.

IV. Product Biography Information Systems: The Paper Pulp Case

Our design phase has started with the identification of the parameters required to describe the multiple digital twins of the paper pulp lifecycle. Three main types of physical twins are identified, namely, the tree (raw material), the factory (process, machines), and the final product. Although the smart factory concept is already under development in the case company (e.g. automatic data acquisition for lot processing), the other twins are problematic. The cost of obtaining real-time data from each tree or each paper pulp package (700.000 tons/year) is prohibitive. Therefore, the team considered the option of creating a variant of digital twin (by definition, a replica of the physical object) that represent a group of similar physical objects. This vision can be implemented with autobiography (automatic data acquisition using IoT and cloud) in specific zones of the forest and a "third person" collection of data via manual input (e.g. laboratorial tests, transport records). The same concept is applied to the paper pulp package "twin" using RFID tags and a black box in selected packages of each lot.

Figure 2 presents a reference architecture for the product biography information system, extending the model presented by [26] for smart production-logistics system in a scenario of (1) first person and third person sources of information, (2) different generations of digital twins for the process and product logistics,

(3) compliance to contracts and regulations, and (4) a global scenario of operations around the globe with different requirements of parameter monitoring and communication constraints (e.g. lack of real-time communication during specific stages of ship transport).

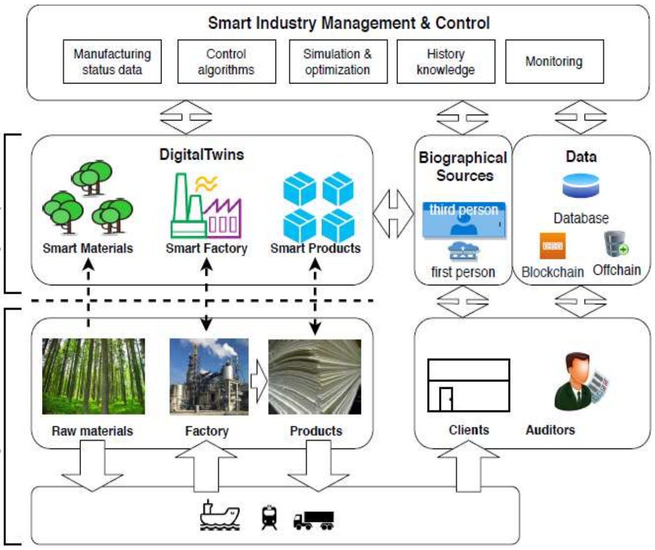

Fig. 2. Product Biography Information System – A Reference Architecture

The physical world and the logistics between stages of the lifecycle (e.g. transport of wood or paper pulp) is presented in the bottom of Figure 2. The clients and auditors have access to the product biography and are also allowed to include manual records (e.g. nonconformance). A single digital twin to record biographies was not possible to implement due to the significant changes in the product lifecycle and the global scale of its movements. Therefore, we used three different generations of twins, according to the product lifecycle: tree (smart materials) – smart factory – smart product (paper pulp package). Two strategies are implemented, namely the smart materials & products cyberspace, which are monitored with an IoT black box using sensors to monitor the most critical parameters (e.g. humidity and temperature). The "black box" is not implemented in all the items (tree or packages) but attached to specific (nucleus) locations: a) a representative area of the forest and b) a paper pulp package that integrates a lot with similar biography.

The smart factory digital twin includes multiple layers of smaller scale digital twins, for example, electric engines (our case company has over 5000) or more complex machines. On the right of the model we represent (1) the biographic sources: product "first person" via IoT sensors and "third person" (human) with manual input of data; and the data (blockchain or off chain). Only the most critical data is stored in the blockchain (e.g. for customer complaints management) considering the need to reduce processing costs in this type of infrastructure, which demands for periodic (human) audits, as already happens today. Finally, the management and control functions are presented on the top of Figure 2, including, for example, monitoring, warnings, simulation, and digital traces.

Figure 3 presents an IoT prototype for the paper pulp digital twin (autobiography). For sake of simplicity, we are not detailing the third person data (e.g. laboratorial tests, audit reports) and the forest digital twin (for an example of remote monitoring parameters of eucalyptus please see [27]), focusing on the paper pulp final product that has particular constraints, for example, the need to store data in high seas and the location tracking and environmental parameters of the cargo.

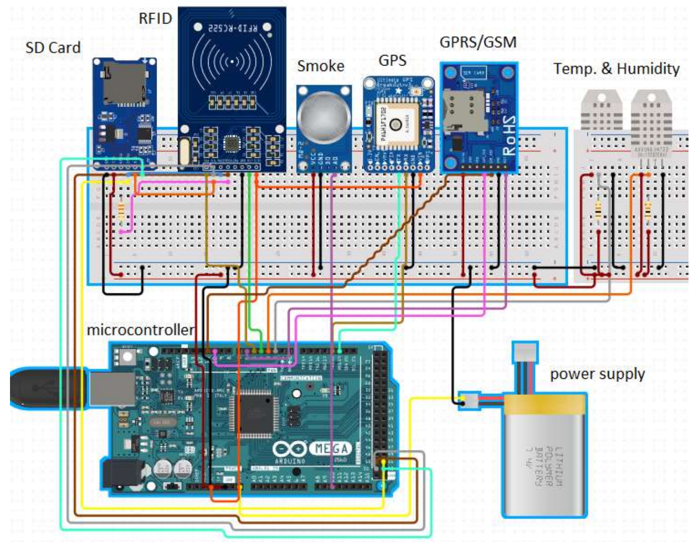

Fig. 3. Final Product Autobiography - IoT Prototype

The prototype presented in Figure 3 uses a microcontroller for testing purposes, two redundant sensors for temperature and humidity (cross-check evaluation of measures), shields (RFID to track location changes, GPRS/GSM to send warnings to the port or the factory or store data in the blockchain/off-chain database, and GPS to locate the product), battery, and SD card for offline data storage. Nevertheless, this instantiation is illustrative because each company has its specific supply chain transformations and parameters that need to be identified.

V. Discussion

Three main design principles were identified:

Design Principle 1 (DP1): Consider one digital twin for each major transformation in the product lifecycle. It was impossible to use a single digital twin to implement a PBIS. Therefore, two strategies are considered, namely, (1) the multiple digital twin generations (one for each major transformation phase) and (2) the nucleus digital twin concept – a digital twin that mirrors a group of similar physical objects. Although some mass production products (e.g. cars) are suitable to implement a single digital twin, numerous series of small products may require a different strategy. It was not economically feasible to implement an IoT box to collect data from each paper pulp package.

DP2: Identify the most critical data for each digital twin life and the possibility for first person and third person biography collection. In our case company, forestry data is vast (diseases, temperature, interventions, soil) and obtained in multiple locations. Not all data is essential, but (1) the origin certification, and (2) the sustainable practices are vital. Therefore, georeferentiation was important in the first and third generation of the digital twins. In our case study, temperature and humidity is determinant for the paper pulp package because most of their customers complaints were related to an excessive weight of the material (due to water absorption during transport or storage at the port). The proposed prototype identifies when the product is at risk of increasing the weight, trace changes in environmental parameters for traceability, and make warnings (may occur on the opposite side of the globe).

DP3: Identify the blockchain, off-chain, and human/non-human compliance checking. There are risks in automatic data collecting processes. In our prototype we considered redundant sensors to contrast the measures (major differences may reveal problems in sensors). Moreover, human audits cannot be replaced to confirm the system usage in practice. In the case company, regular evaluations of practices in the field or at the port (e.g. storage conditions) are necessary.

PBIS can be adapted to different industries following the proposed design principles. Cases requiring significant transformations within the product lifecycle are the most promising. For example, food supply chains can implement digital twins' generations for greenhouse, factory, and product distribution, memorizing the lifecycle relevant for the customer (e.g. sustainable agriculture), regulators, inspectors, and hazard response. The pharmaceutical industry is another critical sector that requires full traceability of resources (analog to the trees in our case company), transformation, and logistics. The three smart elements (materials, factory, product) apply to both examples, but the focus of each sector may vary. For example, pharma may extend PBIS adoption for medicine adherence (e.g. smart pillbox digital twin for autobiography and mobile app for memorization of adverse reactions) going beyond logistics and reaching the use and disposal phase of the product lifecycle.

A. Implications for Theory

A novel concept of product biography information system is introduced. Product-centered knowledge is foundational to modern PLM systems that became popular with the need to manage information about the lifecycle of complex products. Several researches found opportunities for PLM improvements, namely, focusing in later stages of the lifecycle [6], going beyond workflow functionalities [5]. New questions emerged [4]: "*How a seamless link between consumers/users and designers/producers of 'things' can be realized in almost 'real-time'? How this may happen when service providers are involved (e.g. in maintenance) in this communication loop? […] How this new social context may contribute to move our societies towards a 'sustainable production and consumption' paradigm? What are the most appropriate business models to support such changes? How the involvement of consumers/users in the value chain of 'things' lifecycles may be taken into account?*".

Our work sheds light on the role of PBIS to address some of these questions. First, we discuss design principles that include a decentralized, real-time link between producers and other product stakeholders, taking advantage of IoT, cloud, and blockchain that enable the fourth industrial revolution. Second, we suggest specific touchpoints of the product-service system lifecycle that are particularly fit to establish the link: digital twin generations. Moreover, our study illustrates the societal challenges that can be addressed by PBIS and how the involvement of multiple stakeholders can occur during phases of stabilization (e.g. smart factory operations) and destabilization (e.g. lot separations during transport requiring a digital twin in each of its parts) of specific products.

B. Implications for Practice

Current enterprise systems are not prepared to deal with all the possible events and experiences that humans and non-humans face within their lifecycle. Moreover, the memorization of transformations that occur must be able to capture "first person" and "third person" sources of data and anticipate future needs of the business. A segment of that information needs to be trustable to third party entities, requiring a memorization system based in blockchain. However, the vast majority of data does not need to be immutable and may be added to the digital twin interface via mobile apps or other interfaces to complement "first person" evidence.

IT providers have two options to include PBIS in their development agenda. The first can be accomplished by redesigning current PLM systems to include modules of biographical information and extensions to "third party" loops of information between producer and consumers. Our work can assist managers in the identification of structural transformation touchpoints during product lifecycle (requiring different digital twin generations), with a real case scenario. Another option is the creation of separate PBIS systems that integrate operational data from different enterprise systems such as PLMs, HRMs, ERPs, CRM, or SCM, integrating the information in a architecture for biographies of humans and non-human elements of the organization, using "first-person" and "third person" (e.g. operators, assessors, or customers feedback about product performance) sources to create rich pictures about the "life" of the essential assets of the organization.

The quality of managers decisions is heavily dependent in the underlying memorization system of the organization [15]. Current enterprise systems evolved significantly to support operational data and big data structures to deal with the problem of quantity of data available. Yet, the design of modern enterprise systems must include biographies. Therefore, managers need to reflect about the potential of data that needs to be accurately captured, stored (immutable or not), presented during the decision-making process, and used to promote organizational intelligence. PBIS provide support to the later using loops of information to (1) improve producers knowledge of their products and (2) ensure transparency and disclosure to third party entities (e.g. government assessors or insurance companies).

C. Limitations

Our study has limitations that must be acknowledge. First, PBIS is a new concept introduced in this paper, based on a literature review and the results of a design science research project in a paper pulp company. It will be necessary to test PBIS in other sectors of the economy that present different product lifecycles and economical concerns. Second, the model is still in a conceptual stage and the prototype design must be implemented in the field, which is already planned. The company confirmed the interest in testing the black boxes for autobiography acquisition and the accessibility of ports to cooperate in the research, namely, using the RFID tracking for the paper pulp packages and the necessary maintenance of the black boxes during storage periods. The boxes may return to the factory for use in other lots and reducing the cost of the solution. Third, we could not evaluate the concrete benefits for the end customer (e.g. preventing complaints about extra weight due to wetting) that will only be possible during field implementation.

VI. Conclusion

This paper presents a new concept that promises to change PLM systems, by including product biographies in the agenda of sustainable industry practices. Product biographies supported in blockchain and digital twins allows memorization of critical events and attributes that can (1) classify stable forms of product/service lifecycle and (2) guide destabilization moments.

There are several opportunities for future research. The most immediate is the deployment of the proposed architecture in our case organization. The system will be evaluated in its social context. However, the most promising opportunities emerge from the concept itself. First, it is necessary to evaluate how (and if) current enterprise systems can incorporate biographies in their structure (e.g. events about people, manufacturing issues, external feedback) and how to represent the product biography digital twin (e.g. a 3D presentation of the product that reveals traces of its past and the preceding generations of its digital twins, for example, the trees that originated the paper pulp lot). Second, it is interesting to understand how PBIS interfaces could be created, the functionalities to the users and the effective support to decision making. Digital twins are now common, but multiple generations of digital twins within the product lifecycle are new to the literature of this field. The interfaces open a third avenue for future work, namely, the adoption of artificial intelligence techniques in biographical data, for example, to suggest product changes or anticipate transformations in the product lifecycle stage. The fourth research opportunity lies in the impact of organizations and its products/services for societal challenges. The memorization of product/service information, in different stages of the lifecycle, can contribute to energy reduction practices (as already happens in automotive industry, informing the driver about its performance) and environmental impact (e.g. memorizing data that can be used to redesign products that consume less natural resources such as water, or produce less contaminations to the environment). Other industry cases may be more suitable for this purpose. Finally, additional research is necessary to evaluate how PBIS are used in different social contexts, for example, to change current models of contract warranty (e.g. extending warranties when the biography reveals a correct use of the product) or regulatory activities, for example, audits by government assessors and certification entities.

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