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Exploiting the full potential of I4.0 technologies for products EOL recovery process

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Abstract. The recent advancements of technology have been radically transforming the industrial world and our societies as well. The application of the new technologies is ubiquitous involving various domains from industrial production to everyday life. This paper investigates whether and how it is possible to better support product life-cycle management by exploiting product's enhanced capabilities stemming from an I4.0 ecosystem. To this aim, this paper proposes the new concept of Product 4.0 that is a product archetype combining the functionalities of an intelligent product with those permitted by I4.0 technologies. As Product 4.0 has the potential to benefit the various phases of the product life cycle, this paper also provides further details on the end-of-life recovery options for this new product archetype, by means of an explanatory case dealing with a laser-jet printer.

Keywords: Smart product · Product 4.0 · End-of-Life · Recovery options · Industry 4.0.

1 Introduction

The technological advance of the Fourth Industrial Revolution (I4.0) is bringing strong changes in manufacturing and service industries as well. The potential of I4.0 technologies is apparent in various aspects of industrial operations, such as sustainability, smart products, End of Life (EoL) and remanufacturing.

[7] propose a sustainable I4.0 framework that includes three main components: I4.0 technologies, process integration and sustainable outcomes. The authors also suggest future research developments investigating the implementation of I4.0 technologies for better man-machine and machine-to-equipment integration through the use of sensors. Another important impact of these technologies is on the design of efficient supply chains, which through information gathered from products themselves, logistics and production operations and a seamless integration between the physical and digital worlds could further improve product's lifecycle permitting also a more effective and efficient product recovery at its End of Use (EoU) and/or End of Life (EoL).

Nowadays products are not exclusively composed of mechanical and electrical parts, they have become complex systems that combine hardware, sensors,

data storage, microprocessors, software and connectivity capabilities [15]. Classifying smart products allows a clearer their definition and application. The [16] archetypes are an example of the classification of smart products according to their features.

[8] identify Remanufacturing as a key strategy for the full achievement of Circular Economy, which, in turn, represents an important research area for many companies worldwide and for our societies as a whole. This “smart remanufacturing” review focuses on the remanufacturing industry and the sustainable application of I4.0 enablers. The results are used to create a framework that links to the research agenda needed to fully achieve smart remanufacturing. Other authors have tried to define the types of intelligent recovery options. [1] detailed the characteristics that intelligent reuse, intelligent remanufacturing and intelligent recycling must have in relation to smart products.

In light of the above, there are a lack of articles dealing with these topics in the current literature. Few authors deal with smart products as aggregation systems of innovative technologies. Recovery options exploiting I4.0 tools are little studied in the literature.

According to these premises and within the outlined context, the first aim of this work is to propose the novel concept of “Product 4.0” (P4.0). This concept builds upon product archetypes and explores the augmented capabilities of an intelligent product in a I4.0 environment. In fact, we highlighted the aspect of the smart product with the use of I4.0 tools. Furthermore, this paper has the aim of investigating the possibilities that arise when recovering an intelligent product, at its EoU or EoL, in a I4.0 environment.

The remaining part of this paper is as follows. Section 2 presents the literature review of the I4.0 tools and the recovery options. After defining Product 4.0, section 3 deals with the recovery options with respect to Product 4.0. Finally, section 4 draws conclusions and future development.

2 Literature review

In this section, the relevant literature is presented in two parts. The first part describes the I4.0 tools that can be used in smart products, and the second part will analyse aspects of the different recovery options.

A notable starting point when dealing with so called *Smart Products* and their possible classification is represented by the work carried out by [16]. The authors classify smart products according to 4 archetypes based on 16 criteria/characteristics of the products themselves. The proposed archetypes are classified as follows: *Digital Product*, *Connected Product*, *Responsive Product*, *Intelligent Product*.

The so called smart products are the most used technological products today. The capabilities of these products can be expanded by the integration of more advanced I4.0 tools and with the aspects of the different end-of-life recovery options.

2.1 Suitable Industry 4.0 technologies

From a literature review, we identified those advanced technologies that could be included as additional features to the archetypes proposed by [16] and briefly described above. In particular, we found out that the main tools are: Internet of Thing (IoT), Cloud Computing (CC), Big Data (BD), Digital Twin (DT), Machine Learning (ML) and Human-Machine Cooperation (HMC). The previous innovative tools and technologies were chosen because they are the most representative for an innovative product. Although the IoT technology was swiftly mentioned by [16], any other of the above cited technologies was explicitly considered in the proposed archetypes.

In order to properly ascribe to the various archetypes the different I4.0 tools, we will start this discussion from their very definition. For the IoT, we adopt the same definition as [22] who argues that virtual ‘things’ have virtual identities, physical attributes and virtual personalities.

The BD technology has been largely investigated in scientific literature and, among its different definitions, we consider that provided by [5] who argues that Big Data is a set of techniques and technologies that require new forms of integration to discover great hidden values from large datasets.

According to [12], CC can be defined as “a model for enabling ubiquitous, affordable, on-demand network access to a range of configured computing resources”.

[2] define the DT as a simulation technology available for use in the real system, allowing the equipment’s self-adaptive behaviour. The machine can simulate the different environment, establishing the best decision to make in a particular situation

ML is a subject that studies how to use computers to simulate human learning activities and to study methods of self-improvement of computers to obtain new knowledge and new skills, identify existing knowledge and continuously improve performance and results [21]. From a practical point of view, machine learning allows automatic data processing and can be considered an advanced analysis tool for intelligent production.

We decided to include also HMC as another important advanced technology that features an I4.0 environment. According to [14], HMC is a technology that allows to incorporate more and more decision-making capabilities in both material (e.g. machines, products) and immaterial (e.g. production orders) elements, transforming them into efficient assistance systems to help human beings improve their performance.

Finally, Cyber Physical System (CPS) can be seen as systems of systems, which emerge through complex networking, integration of embedded systems, application systems and infrastructures, made possible by human-machine interaction [19].

2.2 EoL recovery options

Literature reports on several different EoL recovery options for a generic product. [13] grouped these options into ten recovery strategies, including Recovery, Re-

cycle, Repurpose, Remanufacture, Refurbish, Repair, Reuse, Rethink, Reduce. [10] considered only seven recovery options, while distinguishing for recycling between a primary and a secondary type. [18] in their review of key regeneration activities grouped the recovery options into Reconditioning, Dismantling/Disassembly, Refurbishment, Repair, Salvage, Incineration, Resale, Cannibalisation. In addition, the authors interestingly classified extant research papers, according to the level of decision, i.e., whether the recovery option is applied to the entire product or components. [3], while tackling the disassembly problem, identified five options for product recovery, in particular they assigned to each level of disassembly also which elements could be recovered from the product itself, i.e. product, module, part and material level.

For the purpose of this research, we decided to focus only on the main EoL options, i.e. reuse, remanufacturing, recycling, cannibalization and disposal. In accordance with the relevant literature, we adopted the following definitions for the recovery options mentioned above. Reuse is considered to be an operation whereby a few non-destructive improvements are made in order to bring the product back to its initial state. Remanufacturing, on the other hand, is a more complex operation where the product is disassembled and worn or broken components are replaced. Recycling is the operation where raw materials are recovered and a complete conversion is carried out. Disposal is the last possible operation, where nothing can be recovered from the product and it is therefore thrown away. Finally, cannibalisation is the operation that allows us to recover from a product only the components that are still functional and then reuse them on another product as replacement components.

3 Conceptualization of Product 4.0

In a I4.0 environment, we argue that the product, as a whole, along with its parts and components can “interact” with the various resources it encounters during its lifecycle. These interactions turn out to be greatly enhanced or augmented by the implementation of I4.0 technologies. Needless to say, that this enhancement strongly depends upon the embedded capabilities of the product and its parts and components.

As a consequence of the previous considerations and according to the tools of I4.0, we can extend the archetypes of product of [16] in a I4.0 perspective (see Fig. 1). Based on the definitions previously given, we decided to suitably attribute the I4.0 tools among the different archetypes. In fact, the possibility to make different decisions in different situations makes DT a suitable element for the fourth archetype, i.e. Intelligent product. Depending on the definition of IoT and taking into account that most of current products are equipped with Radio Frequency Identification (RFID), sensors and communication technologies [6], the archetype that could exploit at most this advanced technology is the second one, i.e., Connected product. By taking into account the considerations made about BD, we expect that Responsive product is the archetype that could have more advantages stemming from BD technology. It is worth noting here that,

although the first archetype, i.e. the Digital product, already has data archiving capability, the BD technology has not been linked to it as the data involved in this case are not complex or various. Still according to the definitions given above, we can attribute the tools of CC in the third archetype and ML and HMC in the fourth archetype. Once defined, categorized and imputed to the appropriate archetype the various I4.0 tools in a separated way, it can be argued that all these technologies epitomize what literature defines as CPS. This object turns out to be the union of different technological systems, for this reason we decided to group all the I4.0 tools within the umbrella term of CPS.

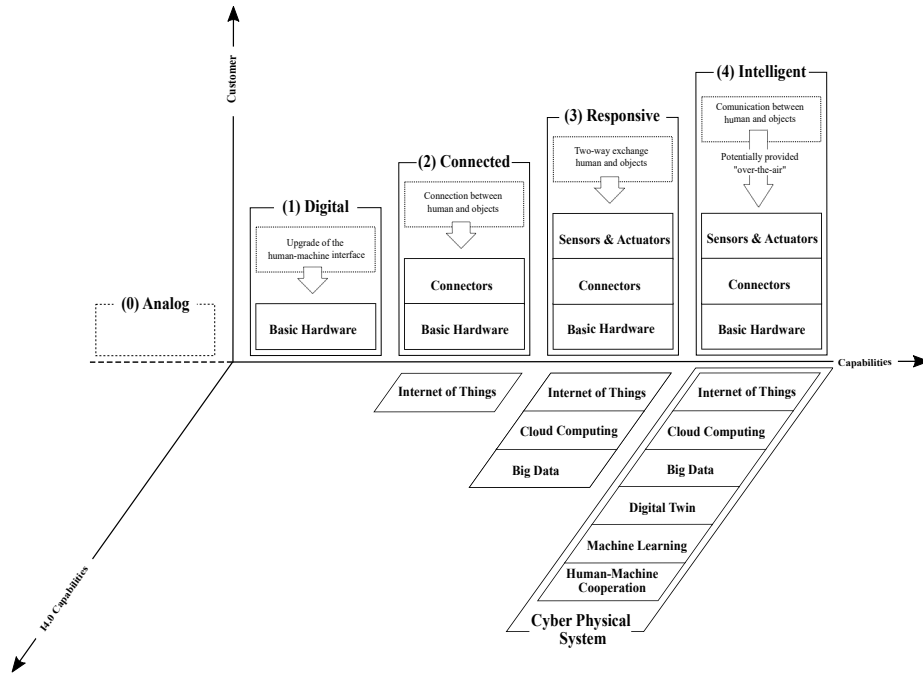


Fig. 1. Extension of [16] archetypes with I4.0 technologies

Fig. 1, turns out to be an extension of the image originally proposed by [16] to pictorially represent the various archetypes of products. We give a three-dimensional representation of the various archetypes by adding an axis, labelled as I4.0 Technologies, along which the innovative tools and technologies of I4.0 are shown in relation to the various archetypes. By jointly considering the capabilities of the fourth archetype proposed by [16], i.e. the Intelligent product, along with the new ones available in the so called CPS while interacting in an I4.0 environment, we could introduce the new concept of *Products 4.0*.

As a consequence of the previous definition, we can argue that the Product 4.0 concept involves not only the product itself but also the ecosystem where

the product life cycle takes place. In fact, it includes *a smart product that can communicate with humans and objects as well, having basic hardware and intrinsic characteristics (sensors, actuators and connections) and implementing I4.0 technologies (IoT, CC, BD, DT, ML and HMC)*.

The enhanced capabilities of Product 4.0 have the potential to deliver several benefits during the product lifecycle. It can also effectively support logistic and production activities and, in general, all the activities involved from product's conception to its EoU or EoL.

In this perspective, P4.0 may represent the hinge upon which circular economy models could rest. In fact, it would lead to a better investigation of product recovery options. In the next section we will investigate and discuss how a P4.0 prototype could be recovered at the end of its life cycle.

3.1 Enhanced recovery capabilities of P4.0

In this section we will show and discuss how the Product 4.0 archetype may heavily revolutionize and streamline the recovery process of a generic product at its end of life. In fact, many factors still prevent the remanufacturing business from reaching its full development [20] and one of these factors is the cumbersome inspection activity required to diagnose the product's health status also identified as product's *quality* in remanufacturing jargon [17].

Traditionally, recovery operations start when the collected product returns to the factory [4, 9, 11].

In order to optimise the recovery of the product, it must necessarily pass through several stages to analyse and investigate its possible problems. These steps are typically: Inspection, Cleaning, Analysis and Verification. Most of these activities are time-consuming for the company involved in the recovery operation.

This recovery process takes place if it is not possible to exploit the product's capabilities inherent to I4.0 technologies. Fig. 2 shows a possible flow chart for product's collection that fully take advantage of I4.0 technologies. Under a P4.0 scenario the use of I4.0 tools and technologies allow us, in general, to reduce and/or greatly simplify many steps of the recovery process if compared to that of "traditional" products. With the capabilities inherent to P4.0, a smart product that interact with a smart environment, we can take advantage of available technologies to collect detailed information about product's health even before it returns to the factory for recovery purposes.

In general, it is possible to gather and exploit two types of data. A first set of information is that pertaining the various products belonging to the installed base and sent by products themselves to a cloud platform. This data usually refer to the average behaviour of the products of the installed base. A second set of information is the product-specific data collected once the product enters the factory and, therefore, it is able to communicate with the Industry 4.0 system.

Thanks to the combined use of these data sets, the diagnostic phase of the recovery process is noticeably simplified and sped up, in fact there is no need to carry out the various levels of inspection and problem analysis as we already

know in advance the health and usage status of the product, which can then go straight to the cleaning stage.

As a consequence, Inspection and Analysis phases may not appear in the flowchart of the recovery process. In order to identify the more appropriate recovery option for the specific product, it is possible to make use of product's status and use data. Depending on product's "health state" and "use" parameters, the different recovery options can be properly chosen. Once defined the product category, it is crucial to identify the "use" parameters and "health state" to better address recovery operations. Specifically, in the case of intensive use of the product and a good health state, it would be viable to first cannibalize the still valuable components, then materials recovery from parts and components, and, finally, the disposal of remaining parts. If the "use" parameters and "health state" are appropriate, product could undergo the reuse option provided that minor repairs and replacements are carried out. If, despite the low values of "use" parameters, the "health state" is not adequate, the product could conveniently undergo the remanufacturing process where it is disassembled at component level, and relevant parts of the product are replaced.

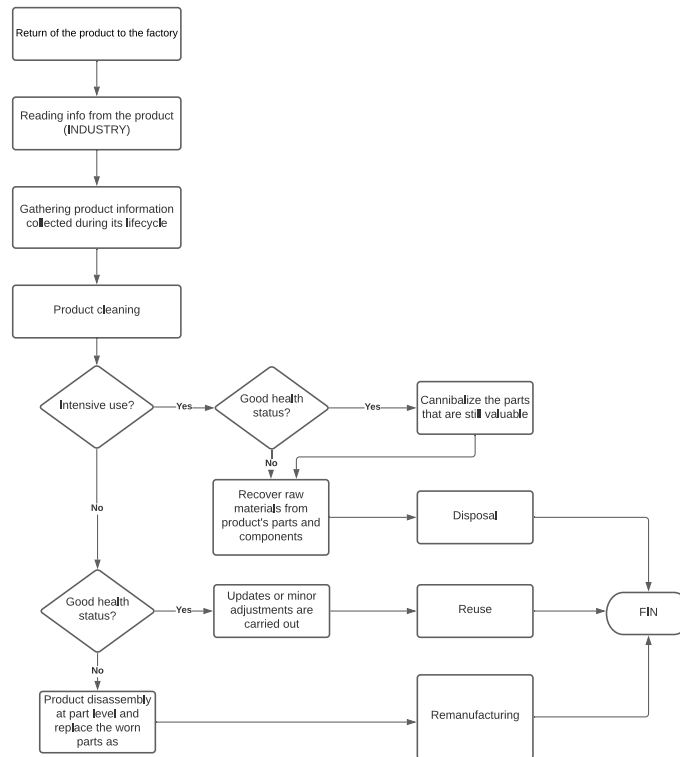


Fig. 2. Example of a flowchart diagram of a recovery process exploiting I4.0 technologies.

It is worth noting that, because of the augmented capabilities of P4.0, it could perform by itself the verification phase that conclude the remanufacturing process.

In order to show the potential of P4.0 in terms of its recovery process, we provide the readers with a simple but effective example. We considered here the case of a consumer electronics product, that is, a multi-function laser jet printer. This kind of products are usually capable of and actually share many information on product use and product performance with Original Equipment Manufacturer (OEM) on the basis of sharing agreements. These agreements are usually framed within a win-win Product Service System logic and are mainly intended to gather information on the installed base in order to deliver more customer value during the product use and, at the same time, to allow the OEM to sell secondary products and ancillary services. In our use case, both the aggregated information about the installed base and the product-specific data may be used to support a more efficient and environmental friendly recovery process.

In fact, some data related to product's operation (e.g., number of printed pages, number of scans on the glass) as well as data coming from product's event log (e.g., document feeder jam, paper jam, supplies status, double feed error) could be put into relation with the general health state of the product and its main modules, parts and components in a cause-effect logic. It is worth noting that, in general, this type of products is made of two types of modules, parts and components: the first type, such as toner cartridges, drums and fuser, are to be classified as "consumables" as they are purchased recurrently during product's lifecycle as part of its regular maintenance. Another type of parts, such as scan unit, transfer module, sheet feeder, edge guides, electric motors and gears, imaging unit are those more likely to be recovered from discarded products provided that a reliable assessment on their status can be performed.

For example, a malfunctioning of the printer's transfer module may be signalled by an abnormal consumption of electrical power of its motors, that can be obtained by minor product's design changes as well as cheap additional sensors to collect those data. While the data related to the "use" parameters (i.e., the number of printed pages, number of scans on the glass) could be already exchanged via a cloud platform during product's life-cycle, when the printer returns to the factory to be recovered, it is also able to exchange stored data of its components with its environment. By jointly exploiting the data related to "use" parameters and those stored in the printer, it is possible to assess the health state of its components in a more reliable manner, thus better supporting the identification of the more appropriate recovery options.

4 Conclusion

The first goal of this paper was to combine advanced industrial technologies with the product archetypes identified by [16] in order to propose the new concept of Product 4.0. To this aim, the tools with the highest potential for implementation

in smart products have been analysed. This analysis identified as the main tools IoT, CC, BD, DT, ML and HMC. The concept of Product 4.0 stems from the combination of the I4.0 technologies with the fourth archetype proposed by [16].

A second goal of this paper was to conduct an exploratory analysis of product recovery scenarios in presence of a Product 4.0 prototype. In particular, the most common product recovery options were presented. We highlighted the potential advantages of recovering P4.0s in comparison with those products not exploiting I4.0 technologies. An explanatory case dealing with laser jet printer allow us to exemplify these benefits.

Future development of this research could focus on the other phases of Product Lifecycle Management, such as Beginning of Life (BoL) and Middle of Life (MoL). With reference to the BoL, the main aspects of product design, creation and verification could be analyzed. In fact, Product 4.0, in order to deliver specified functionalities and to suitably interact with its environment, has to be designed with proper hardware and software features. A further aspect to investigate would be that of properly addressing the design process in order to widen as much as possible the recovery options to which Product 4.0 could undergo at its end of life.

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