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Improving the sustainability of manufactured products: Literature review and challenges for digitalization of disassembly and dismantling processes

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Abstract. Digital technology used today within Industry 4.0 open up new opportunities for most areas of engineering, including the end of life and especially disassembly process, which was identified as the most critical and strategic step in the remanufacturing. The aim of this paper is to identify all I4.0 technologies that have been used in the process of disassembly (with a special focus on sustainability) in order to create a Digital Twin model for disassembly process based on sustainability indicators. In this research, firstly, we present a literature review on the related work based on existing I4.0 technologies in the disassembly process and the issues related to this process. Secondly, an overview of I4.0 technologies used in the optimization of the disassembly process research is presented. Thirdly, a discussion about the use of I4.0 technologies in order to have a sustainable disassembly process and a digital twin is presented. Finally, research questions about the use of I4.0 technologies in a digital twin for disassembly process based on sustainable indicators were conducted in the conclusion.

Keywords: Digital Technology, Industry 4.0, Disassembly, Remanufacturing, Digital Twin.

1 Introduction

The disassembly process is a critical step in the remanufacturing of end-of-life (EOL) products [1] that enables a circular economy (CE) ([2, 3]). In the framework of sustainable development, from an environmental perspective, disassembly process reduces the use and waste of raw materials, increases the utilization of resources, and reduce pollution and emissions ([4], [5]). From an economical point of view, it can reduce product life cycle costs [6], helps decrease product recovery value [7] as well as product production cost. Finally, from a society point of view, it creates new career opportunities and provides a safer, healthier and more ergonomic work environment [8]. However, due to the complexity and uncertainties of the disassembly products [9] this process faces several challenges (e.g. high cost, difficult sequence planning, operators safety and environmental impact). The disassembly process can benefit from the digital technologies within the Industry 4.0

(I4.0) such as Virtual Reality (VR), Augmented Reality (AR), Digital twin (DTW) or Robotics, in order to be optimized and be cost-efficient. I4.0 technologies can also be important enablers for industrial sustainability ([1], [5]) especially for disassembly process by reducing its energy consumption and its environmental impacts.

In this framework, the aim of this paper is to identify all I4.0 technologies that have been used in the process of disassembly (with a special focus on sustainability) in order to create a DTW for disassembly process based on sustainability indicators. In this research, firstly, we present a literature review on the related works based on existing I4.0 technologies in the disassembly process and issues related to this process. Secondly, an overview of I4.0 technologies used in the optimization of the disassembly process research is presented. Thirdly, a discussion about the use of I4.0 technologies in order to have a sustainable disassembly process and a digital twin is presented. Finally, research questions about the use of I4.0 technologies in a digital twin for disassembly process based on sustainable indicators were conducted in the conclusion.

2 Related work

2.1 Disassembly process

The disassembly process is a systematic approach separating a product into parts or removing its components, subsets or constructive parts [10], it plays a key role in recycling of materials and components [11]. However, it is a very critical process due to its high degree of uncertainty caused by the quality and structure of EOL products [10]. Within the framework of this literature review, the issues concerning the disassembly are presented in three categories: Cost / Time efficiency, Operator/ tasks/ safety and Process information.

Cost/ Time efficiency category addresses the issues regarding uncertainty related to the operating time, sequence planning and the process cost.

Operator/ tasks/ safety category addresses the issues that concern the disassembly tasks performed by the operators, their safety, the working environment and conditions.

Process information category deals with issues regarding the decision support information (data about design, materials, the usage, maintenance, and repair of a product throughout its lifecycle).

One of the most promising technologies in overcoming those issues and the sustainable challenges of the disassembly process is the DTW.

2.2 Digital twin

The concept of DTW was firstly introduced by the National Aeronautics and Space Administration (NASA)'s Apollo program in 1962 [12]. Since then, numerous explanations and definitions of this concept have been proposed [12]. [13] defined the DTW as a virtual model that corresponds to physical entities in the real world. Based on information collection and sharing, it can simulate the behavior and performance of the entities in real time. It is used mainly for monitoring, diagnostics, prognostics as well as optimization [14]. Which makes it a very good solution for manufactures to improve the manufacturing pro-

cess [15]. Despite the big potential gain that a DTW can offer to adopt a sustainable approach and to improve the sustainability of manufactured products, there is still a lack of research on this area.

2.3 I4.0 enabling technologies in the disassembly process

I4.0 relies on technologies that enables the connectivity and interaction between all stakeholders involved in manufacturing [16]. In the framework of this literature review, five main technologies were found mostly used in the optimization and problem solving of the disassembly process. Those I4.0 technologies can be classified into Virtual Reality (VR), Augmented Reality (AR), Human Robot Collaboration (HRC), Radio Frequency Identification (RFID) and Operational Research and Optimization-Based approaches.

VR technology is a three-dimensional technology. It is a computer-generated environment that provides to the users the feeling of being present through multiple synthetic feedback sent to sensorial channels like virtual, aural, haptic and others [17].

AR technology can be defined as a Human-machine technology that combines three-dimensional computer generated information and physical real scene, all in real time [18].

Human-robot collaboration (HRC) is a flexible semi-automated approach that aims to provide flexibility in order to reduce the uncertainties and have more adaptability [19].

Radio frequency identification (RFID) is a technology that uses radio waves to automatically read the digital data encoded in the RFID tags or smart labels [20].

Operational Research and Optimization-Based approaches are approaches based on analytical and optimizational methods such as algorithms, in order to optimize the disassembly process.

3 Overview of I4.0 technologies used in the optimization of the disassembly research

The set of 18 documents selected have been analyzed. All the papers were focused on exploring the roles of I4.0 technologies to support, optimize and resolve issues regarding the process of disassembly.

Five main I4.0 technologies have been considered: VR, AR, RFID, HRC and Operational research and optimization-based approaches in the resolution of the disassembly process issues presented in the related work section.

3.1 Cost/ time efficiency

Many researchers studied the use of I4.0 technologies in the optimization of the cost/ time efficiency of the disassembly process. In the VR field [21] developed a system that integrates a virtual assembly and disassembly model into a Computer-aided design/computer-aided manufacturing (CAD/CAM) environment in order to evaluate the products in their design phase for virtual manufacturing. As a result, the cost and time of assembly/ disassembly (A/D) operations were optimized. [22] represented a real-time driving model of the virtual human (VH) and analyzed corresponding VH driving error coming from the

Motion Capture System. The simulation results can be used for process and operation sequence planning, also to optimize operator comfort, visibility, and access to controls.

Regarding the studies that have addressed the use of AR in order to optimize the cost/time efficiency, [23] presented an AR-guided product disassembly (ARDIS) framework with an automatic content generation module that translates a disassembly sequence into AR-based instructions for the human operators.

In the HRC technology, [24] proposed a framework and enabling technologies of cloud disassembly in combination of cloud manufacturing and robotic disassembly in order to improve the disassembly efficiency and generate the optimal disassembly sequence.

The RFID technology was also used in the optimization of the cost/ time efficiency of the disassembly process. The concept of [25] proposed system is that it allows total control over material flow (fixtures, and their elements) which increased the degree of flexibility of the process. [26] presented Advanced Repair-to-Order and Disassembly-to-Order (ARTODTO) model that allowed a lower total cost of the disassembly by determining how to process every EOL product on hand to meet used product and component demands and recycled material demand. [27] proposed a method that aims to facilitate the disassembly strategy and to evaluate the expected profit after product disassembling. It enables to detect and exclude the elements with hazardous substances and exclude them from other materials and minimize the cost.

In the Operational research and optimization based approaches area, [28] proposed a model based on triple bottom line (TBL) dimensions (i.e. human safety, environmental safety and business criteria) that included 22 disassembly criteria. The results of the study implemented for computer disassembly show an improvement in cycle time, a minimization of the amount of wastes and maximization of recovered materials from EOL. [6] proposed a development of a disassembly sequence planning (DSP) model based on a constraint satisfaction problem (CSP) and its solution method, based on a backtracking algorithm. In order to find all of the feasible disassembly sequences as well as the optimum sequence for recycling. [29] suggested an ant colony algorithm in order to obtain a set of optimization program of the disassembly and assembly sequence and other information in the disassembly process

3.2 Operator tasks / safety

Three I4.0 technologies were used in the category of operator tasks/ safety. First, the VR technology where [30] presented a disassembly task evaluation method. It aims to quantify and analyze fatigue induced during disassembly sequence simulation by using the expenditure volume of metabolic and muscle fatigue. [31] developed an operators training system in A/D that exploits an immersive mixed reality system. The application allows operating on a 3D model of a machine, defining the A/D constraints that the operators will respect during the training. Therefore, the operations can be performed and practiced safely, the experience can be repeated several times and incidents can be avoided.

Second I4.0 technology used is the AR technology where [32] presented a model based on AR (self-disassembly) that can be viewed and followed by the operator, based on the laboratory tests that have been performed, this model helps improve the time and costs for

industrial maintenance. As well as the development of the operators' technical skills and a good evaluation of their working conditions' safety.

Last I4.0 technology used is the HRC technology. The concept and initial investigations regarding the implementation of a hybrid disassembly work station with a compliant robot assistant for the task of unscrewing in disassembly with only simple tools. presented by [33] reduces human contact with potentially harmful situations or substances, adds more flexibility to the process, reduces setup, tool replacement time and costs.

3.3 Process information

Regarding the process information category, the VR technology was used by [34] with the aim of the prevention and reduction of negative environmental impacts of all activities related to the production of a new product. [34] proposed a method of ecological-oriented product assessment performed at early stage of design process in order to improve the skills and knowledge of future designer about environmental aspects of the designed product.

Concerning the AR technology, in order to establish an educational environment for producing robots on line and to deliver enough information for the products assembly and disassembly [35] studied a real space robot disassembly and assembly processes and the movement of the robot work in animation.

Regarding the HRC technology, [36] developed a strategy for HRC disassembly using active compliance monitoring of collaborative robots, that delivers enough information for the products assembly and disassembly to assist the human operator with complex disassembly tasks, the collaborative robot compliance capability is used.

Table 1. is inspired by the tables of the eight defined groups of the roles of simulation to support disassembly under a circular economy perspective by [37] in their study about how disassembly process simulation tools have been exploited to foster the adoption of Circular Economy in the Printed circuit board domain through a symmetric literature review. However, Table 1. summarizes and categorizes all the papers studied according to three main issues of the disassembly process in terms of: a) the main proposition of the article and its type (method, approach, system, etc.); b) the lifecycle phase improved through the concerned technology (Design; Assembly; Maintenance; EOL); c) I4.0 technology used and d) the environmental improvement.

4 Discussion

4.1 Sustainable disassembly process

Up to now, the sustainable aspect of disassembly process have been conducted with special focus on reducing the process time and cost [38]. However, the optimization of disassembly plan, sequence and time may lead to an important reduction in energy consumption and environmental impact improvement [8].

According to the literature review above, [6, 7, 22–24, 30, 35, 36] used different I4.0 technologies in order to resolve issues regarding the disassembly process and to optimize the disassembly sequence time and cost. The use of those I4.0 technologies can lead

Table 1. Literature summary.

Disassembly issues	Ref	Paper content	Lifecycle phase concerned by the I4.0 technology for disassembly	I4.0 technology for disassembly	Environmental improvement
Cost/time efficiency	[21]	A system that integrates a virtual A/D model into a CAD/ CAM environment for evaluating products in design phase	Design/ Assembly/EOL	VR	X
	[22]	A model of a virtual real-time human for assembly and disassembly operation in virtual reality environment	Assembly/ maintenance/ EOL	VR	X
	[23]	AR-guided product disassembly (ARDIS) framework with an automatic content generation module	maintenance/ EOL	AR	X
	[4]	Perception, cognition, decision, execution and evolution – circle framework and an approach for HRC disassembly	EOL	HRC	X
	[24]	A study of the framework and enabling technologies of cloud disassembly	EOL	HRC	X
	[25]	A system for identification of machining fixtures, and their elements in an assembly/ disassembly	EOL	RFID	X
	[26]	Advanced Repair-to-Order and Disassembly-to-Order model determining how to process each and every EOL product	EOL	RFID	
	[27]	A method for facilitating the disassembly strategy and evaluation of expected profit after product disassembling	EOL	RFID	
	[28]	A model based on triple bottom line (TBL) dimensions, i.e. human safety, environmental safety and business criteria	EOL	OR & OBA	X
	[6]	A method of a disassembly sequence planning based on a backtracking algorithm	EOL	OR & OBA	X
Operator/tasks/safety	[29]	Ant colony algorithm-based disassembly to obtain a set of optimization program of the disassembly and assembly	Assembly/ EOL	OR & OBA	X
	[30]	A disassembly task evaluation method That aims to quantify fatigue by using the expenditure volume of metabolic	EOL	VR	
	[31]	An operator training system in A/D, by means of a 3D camera placed on the Human Machine Disassembly	Design/ EOL	AR	
	[32]	AR model (self-disassembly) that can be viewed and followed by the operator	Design/ maintenance/ EOL	AR	X
Process information	[33]	A concept and initial investigations regarding the implementation of a hybrid disassembly work station	EOL	HRC	
	[34]	A method of ecological-oriented product assessment performed at early stage of design process	Design/ EOL	VR	X
	[35]	A study in real space robot disassembly and assembly processes and the movement of the robot work in animation	Assembly/ EOL	AR	X
	[36]	A strategy for HRC disassembly using active compliance monitoring of collaborative robots.	EOL	HRC	

to a more sustainable disassembly process by improving its environmental impact through the optimization of the disassembly process. However, other authors have addressed the environmental aspect in the disassembly in a more direct way in their studies. For instance, the PCDEE-Circle (perception, cognition, decision, execution and evolution – circle) framework developed by [4] towards HRC disassembly meet sustainable manufacturing requirements such as minimizing energy consumption under the premise of ensuring safety. The sustainable disassembly line presented by [28] allows minimizing the amount of wastes and maximizing recovered materials from EOL. In the aim of the prevention and reduction of negative environmental impacts of all activities related to the production of a new product during its lifecycle. Also, [34] proposed a method of ecological-oriented product assessment.

4.2 Digital twin for disassembly process

Based on the literature review above, decision-making is one of the most important factors in disassembly optimization. A decision-making based on reliable and up-to-date information allows for the optimization of disassembly sequences and a proper planning of the process. Which leads directly to a less costly and more sustainable process (if environmental issues are taken into consideration). The potential of using DTW is very high in terms of decision-making. However, at the end of life step there is a lot of uncertainty regarding the products [9], their traceability and their information (e.g. information about their recyclability, used materials, management of hazardous substances, etc.). To face this problem, a DTW based on knowledge can be very interesting. Which means that the DTW will rely on knowledge-based technologies that we define as the technologies based on reference database that includes all the products information throughout all its life cycle. The knowledge-based technology will provide the entire product's information despite its unknown traceability, which will allow us to avoid the majority of the disassembly process issues mentioned in the literature review and a good decision-making.

5 Conclusion

This paper presents a literature review about the use of I4.0 technologies in the disassembly and dismantling processes. After analyzing the set of 18 documents selected, that focused on exploring the roles of I4.0 technologies to support the process of disassembly and resolving the issues regarding the cost/ time efficiency, operator/ tasks/ safety and the process information. Five main I4.0 technologies have been considered: VR; AR; RFID; HRC; Operational research & optimization based approaches.

In order to construct a DTW for disassembly and dismantling processes, it is very crucial to implement a variety of enabling technologies such as I4.0 technologies conducted

from the literature review. However, in order to have a sustainable disassembly and dismantling process, it is necessary to rely on indicators of sustainability. Leading us to the following research questions: Are the I4.0 technologies studied above exploitable in a framework of the creation of a DTW model based on sustainability indicators in order to have a sustainable disassembly and dismantling processes? And which sustainable indicators can be beneficial in the case of a sustainable disassembly and dismantling processes?

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