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Enabling servitization by retrofitting legacy equipment for Industry 4.0 applications: benefits and barriers for OEMs

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Abstract

In the wake of industry 4.0, many industries have started to pivot towards digital, collaborative, and smart manufacturing systems by connecting their machinery as part of the Internet of Things (IoT). IoT has the potential to provide visibility and improve manufacturing systems through data collection, analysis, and subsequent actions based on insights generated from large amounts of manufacturing data. Even though comparatively newer equipment come readily equipped with embedded sensors and industrial connectivity necessary to connect to the IoT environment, there are many manufacturers (equipment users) who rely on long standing "legacy systems" that offer no or very limited connectivity. In this context, solutions mostly result in the development of low-cost retrofit or upgrade kits that allow integrating legacy equipment into Industry 4.0 environment and thus enable digital servitization. Servitization is a transformation journey that involves firms developing the capabilities they need to provide technical and data-driven services that supplement traditional product offerings. However, retrofitting solutions of legacy equipment rarely involve Original Equipment Manufacturers (OEMs) who may otherwise leverage the opportunity to create and capture unique value by retrofitting and then provisioning data-driven value-added services for the manufacturers. Hence, the primary objective of this paper is to identify and analyze the available literature on retrofitting and upgrading of the legacy equipment for Industry 4.0 integration. In doing so, this study also investigates the potential opportunities and challenges of OEMs in supporting the Industry 4.0 transition of legacy equipment in a servitization context.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Technological advances such as sensors systems, Internet of Things (IoT), cloud computing, Artificial Intelligence (AI), and machine learning are fueling the fourth industrial revolution, also known as Industry 4.0 [1]. Literature argues that Industry 4.0 technologies will transform the paradigm of manufacturing and allow unprecedented levels of operational efficiency, Overall Equipment Effectiveness (OEE), and growth in productivity [2]. The implementation of the Industry 4.0 paradigm requires the integration of Information and Communications Technology (ICT), data science, and robotics to enable sharing of data on a massive scale among different industrial systems (machine tools) and devices that compose a smart manufacturing system.

In case of comparatively newer industrial equipment, the machinery producers (OEMs) can leverage product connectivity to create and offer technical and data driven services based on the continuous data flow generated by various sensors within the equipment. Even though new industrial equipment is designed to be Industry 4.0 ready, there are still a large number of legacy systems operational in the industries. These systems are not capable to be integrated into the Industry 4.0 environment [3] [4]. Considering that the replacement of these legacy systems is not a feasible solution, a possible alternative is to develop low-cost retrofit or upgrade kits that

allow the integration of the legacy equipment into the Industry 4.0 environment. Nevertheless, given the investment risk and lack of technical expertise, it can be a very complex and non-trivial task to configure legacy equipment for the new industrial ecosystem.

This challenge, however, provides the OEMs with an opportunity to create and capture unique value by upgrading and retrofitting the legacy equipment and then provisioning data-driven value-added services for the manufacturers (equipment users) [5]. In general, services are often resistant to the economic cycles that drive equipment purchase and hence services have the potential to provide a more stable source of revenue with higher margins compared to equipment sales [6]. OEM's involvement in retrofitting activities and service provision makes even more sense given the increasing trend of manufacturing servitization. This trend describes manufacturing firms increasingly pivoting towards service-based value propositions in order to improve customer relationship and attain competitive advantage in the market [7] [8]. Servitization is also becoming an effective strategy for OEMs to create new and resilient revenue streams from the installed base of long lifetime equipment [13]. Given the demand of technical and data driven service offerings, OEMs are increasingly recognizing the potential of servitization. Consequently, OEMs have started to invest in new technologies that foster connectivity and digital innovation [9]. Indeed, digital innovation enables different services, such as remote monitoring [10], big data [11], or predictive analytics [12].

Nevertheless, it seems that none of the previous studies have investigated the potential opportunities and challenges of OEMs in supporting the Industry 4.0 transition of legacy equipment that do not have connectivity capabilities. In this context, the objective of this paper is twofold. First, we plan to identify and analyze the literature related to retrofitting and upgrading of legacy equipment for enabling IoT connectivity. Second, we plan to investigate the potential benefits and barriers of OEMs in retrofitting legacy equipment in the context of servitization. To this end, we first develop a broad search string containing all the important keywords and then perform a literature review in two scientific databases, i.e., Web of Science and Scopus.

This paper is structured as follows: section two details the literature review methodology. Section three presents findings based on the synthesis of the relevant literature. In section four we put a special focus on the servitization potential and challenges of the OEMs in supporting the Industry 4.0 transition by means of retrofitting legacy equipment and provisioning data-driven services.

2. Literature review methodology

This literature review consists of three main steps: (i) database and search string selection, (ii) screening literature for relevancy to retrofitting legacy equipment for Industry 4.0 environment, and (iii) synthesis of the selected literature and generalization of the findings.

In the first step, we selected Web of Science (WoS) and Scopus as our primary database due to their comprehensive coverage of the focus area and high quality of papers.

Following, we used the search string "(upgrad* or retrofit*) and ("industry 4.0" or "internet of things" or "smart manufacturing" or "cyber physical system*" or "cloud manufacturing" or servitization or "smart service*" or "data-driven" or "product service system*")" as an initial screening criterion. This step resulted in 518 papers from WoS and 886 papers from Scopus.

In the second step, after reading the titles and, if needed, the abstracts of the resulting papers, one of the authors identified 31 papers from WoS and a second author identified 28 papers from Scopus that are considered relevant based on their title and abstract. After removing duplicates, this step resulted in a total of 39 unique papers. These papers were then carefully read in order to carry out a detailed content-based selection. During this step, only papers that focused on retrofitting solution were selected for further consideration in this paper. This step led to a final list of 20 relevant papers as a basis for our study.

In the third step, the authors separately summarized the key contents of each of the papers in a structured way. Finally, the authors extensively discussed and refined the results, which allowed the authors to generalize the findings that are presented in the next section.

3. Findings

Based on the analysis of 20 relevant papers, we were able to identify two distinct categories of research streams. The first stream of research focused on providing *integration of various old equipment in the entire plant*. The papers covering this domain mainly aimed at developing and implementing retrofits in order to provide connectivity and collect data from the existing set of legacy equipment within the plant to achieve a more transparent production system, which is a prerequisite for industry 4.0 implementation [14][15][16][17]. The second stream of research focused on *developing and implementing retrofit solutions for specific legacy equipment* with the aim to support various data-driven applications such as output quality inspection, predictive maintenance, etc. [18][19][20]. In this second category, the researchers also focused on the applications of data analytics tools for creating value for the manufacturer [21][18]. Considering the different processes manufactures followed to achieve Industry 4.0 solutions, what clearly emerges is that, on the one side, there is a set of solutions aimed at connecting all relevant equipment within a plant. This can be argued as an "*Industry 4.0 push*". On the other side, different implementations aimed at creating data-driven applications for a particular legacy equipment to exploit the collected data, which can be argued as a "*Need-based pull*". Fig. 1 illustrates these two different approaches identified from the synthesis of the two research streams.

Even though the triggers for the decision of undertaking an industry 4.0 retrofitting project varied, the architecture underlying the proposed solutions remained similar. In majority of the cases, the authors asserted the need of sensors, connectivity, data storage, data processing, and analytics to support Industry 4.0 applications [21]. In some cases, the authors considered cybersecurity issues [22] and also emphasized the necessity to create communication protocols that are compatible with the existing infrastructure and standards [14]. Alongside these projects, different competences

interacted to reach the solutions, comprising industrial engineering, mechanical and mechatronics engineering, information technologies, and data science [18]. Moreover, understanding and leveraging standard algorithms and tools of data analytics were assumed very difficult for many manufactures. Interpreting the collected data and creating value from them need expertise and a high level of know-how [19].

Different technical solutions exist for retrofitting machinery by leveraging low cost technology and open source components [17]. We could divide the retrofitting approaches into three broad categories:

- Addition of smart sensors and/or edge gateways: in this approach, flexible and low-cost solutions are developed using IoT sensors and smart gateway to gather data [15][23][45]. Gateways are also used alone in some cases to directly collect data from PLC or other data source already present in the site.
- Retrofit kits: those solution are deployed by a third party provider as a complete package of sensors, connectivity, control, data analytics [18][24].
- Video cameras: Another approach is the utilization of industrial cameras to monitor operation and capture data form both workforce and equipment [25].

What emerges is that the difficult part in retrofitting and enabling Industry 4.0 solution is not only related to the monetary cost or technology themselves, but also related to technological expertise and know-how on the convergence of various competencies and time required to build a solution suitable for the manufacturer-specific needs.

One specific aim of this research was to understand the contributions of OEMs in supporting the Industry 4.0 transition for legacy equipment in the context of servitization. To this end, we included keywords related to servitization in the initial query of the literature review. However, findings indicate that none of the papers included or even just referred to the (machine tool) OEMs, who sell the production equipment to the manufacturers of end products (users). Several papers propose the adoption of ready-to-use toolkits that enables a manufacturer to connect its equipment within the plant to a server or the internet. These toolkits can be seen as a specific technology produced and sold regardless of the machinery type and its producer. Even the papers that presented a single equipment oriented retrofit solution never mentioned the specific participation of an OEM at any point during the development process of the solution. However, the OEMs are also leveraging industry 4.0 technologies to connect new products and, based on data analytics, offer new services and solutions. Hence, it is logical to assume that the OEMs have the potential to provide additional value to the manufacturers in retrofitting solutions aimed at data collection and analysis.

Given the fact that the existing literature on the upgradability and retrofitting solution towards Industry 4.0 do not include the OEM and the service perspectives at this point, this research investigated OEM's potential in providing connectivity and data analytics services to the manufacturers of end products. We argue that the "*Servitization-push*" can be a new trigger in addition to Industry 4.0 push and need-based pull. In order to support this argument, the potential benefits that can be derived from OEM's direct involvement during the Industry 4.0 transition for legacy equipment have been analyzed. Additionally, we analyzed the challenges that OEMs may face in providing retrofitting and provisioning data-driven services.

4. Discussion

OEMs are usually financially stable businesses and are historically recognized as machinery approved vendors. Their relationship with the end-users of machinery (i.e., manufacturers) is usually limited since they rely on other intermediaries (e.g., system integrators) for final sales and installation of their machinery and products. These intermediaries offer support, service, and spare parts to the customer. Furthermore, they directly in touch with the market and have a better overview and relationship with the final customer (user). Activities that initiate some contact between OEMs and customers are the services, which can vary from warranty to maintenance offers or the selling of product's functionality. Nevertheless, OEMs are equipping their machinery with new technologies that enable them to gather a continuous stream of data from their end-users, exploring many benefits and opportunities for manufacturers. Indeed, OEMs can expand their business into the service areas and establish long-term relationship with the customers by offering services based on a continuous stream of data

The same reasoning is applicable for the existing plants where legacy equipment is present. These equipment usually were built in such ways that only the OEM has the complete know-how and comprehensive domain knowledge on them. Thus, OEMs have the capability to help their customers with data acquisition and analytics services based on their specific operations comprising both new and legacy equipment. Considering this perspective, OEMs' servitization emerges as a new trigger for retrofitting legacy equipment. As depicted in Fig. 2, OEMs are able to reach a level of product connectivity that can support the development and delivery of new services that can create value for their customers.
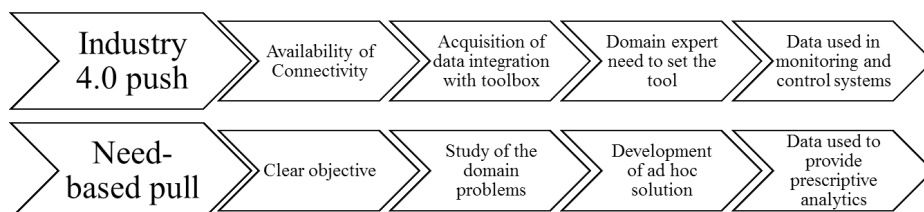
Industry 4.0 push	Availability of Connectivity	Acquisition of data integration with toolbox	Domain expert need to set the tool	Data used in monitoring and control systems

Need-based pull	Clear objective	Study of the domain problems	Development of ad hoc solution	Data used to provide prescriptive analytics

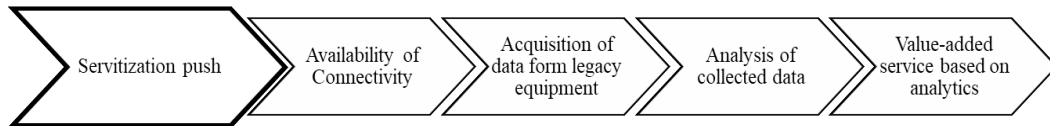Fig. 1. Main trend emerging form the review

Fig. 2. Proposed new perspective to consider

4.1. Potential benefits for the OEMs and the end-users

Most of the identified benefits are based on the fact that OEMs have significant expertise on their own machinery. Their extensive knowledge of the equipment reduces the level of complexity of data gathering and analytics as well as service development (compared to service providers without that deep knowledge). Moreover, the deep knowledge of machineries enhances also the reliability of the solutions. Another assumption is that the OEMs will have access to data of multiple customers and installed equipment that are operational in different plants across various industries. This allows them to create a rich dataset (in terms of number of data points but also diversity and balance), which is the foundation of good data analytics. It is worth to mention that the development of quality solutions is not possible without direct interaction with the customer and the understanding of their needs. Nonetheless, once a solution is developed it can be replicated in a similar environment. Moreover, the manufacturer can benefit from equipment upgrades as well as services that arise from those solutions. Indeed, OEMs can expand their usual business to the service domain. Table 1 enumerates different benefits both for the manufacturer and for the OEMs, especially considering differences in relation with the development of a similar project without their involvement.

4.2. Factors that determine barriers and challenges

Based on the literature in servitization and digital services, we have investigated the key factors that determine barriers for OEMs in offering Industry 4.0 retrofit solutions and digital services. Six different factors have been identified and are explained below.

Technical competences. As a first step, the technological challenges emerge. Indeed, OEMs need to develop the building blocks that are needed to support digital solutions. Considering a standard infrastructure as the one illustrated in Fig. 3, it can be noticed that different dimensions emerge. They go form the sensors needed to retrieve information, to the connectivity and data transmission layers, platform and data storage, the application development as well as analytics capability and tools until arrive at the customer interface while being under the constraint of the security dimension.

Security emerges as one of the most important challenge to face. The high volume of sensitive user data should be secured and protected [26][23][27]. Researchers consider security and privacy as one of the main issue in the implementation of Industry 4.0 [28] and some possible solution have been proposed towards a holistic security framework for Industrial IoT systems [29].

Table 1. Benefits of the implementation of a retrofitting solution for legacy equipment form OEMs

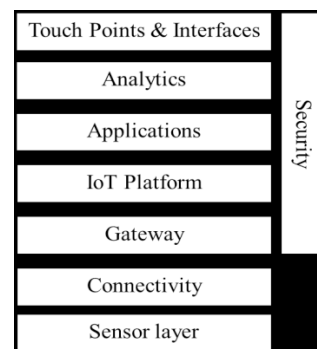|	Example of benefits
OEMs	• Close contact with customers leading to improved retention and market share. • Visibility on customers, installed base and its status and operations • Possibility to use data to develop customer profiles and propose ad-hoc solutions • New revenue streams from the retrofitting solutions and data driven services. • Consolidated market of spare parts thanks to real-time condition monitoring • Possibility to improve service delivery processes and scheduling based on the actual condition of the installed base • Increased opportunity to sell new equipment at the end of life or provide disposal services • Possibility to understand customer processes and receive valuable feedback leading to improved equipment design.
Manufacturer (end-user)	• Rely on the OEM's domain knowledge on the equipment and expertise in solutions that they previously implemented for similar industries and end-user • Access to proactive services, e.g. predictive maintenance • Access to new services, e.g. OEM can collect data on equipment fault in different customer plants and under different environments and after analyzing the data they can suggest best operational practices to the equipment users • Access to equipment upgrades, i.e. based on the customer data OEMs can develop customized upgrade solutions to enhance the performance and functional capability of the equipment. • Possibility to have a continuous update of the existing solutions and access to new solutions, thanks to a continuous point of contact with OEMs

Fig. 3. Standard architecture providing connectivity, data flow & analysis

Another criticality that directly emerge considering the need of data collection and analysis is data standardization. *"Variety"* and *"Veracity"* of data constitute a challenge when

data need to be integrated. Particularly, *"Variety"* refers to the fact that data are generated in large amount [30] from different sources and formats, and contain multidimensional data fields including structured and unstructured data. "Veracity" highlight the importance of quality data and reliability of data sources given that data need to be acquired, cleaned and organized in a standard format to enable analysis and sharing [31]. Moreover, considering legacy equipment with respect to new machinery, integration interfaces and communication protocols may require additional effort for their implementation.

Service culture, mentality and structure. The transformation of an equipment seller into a product-service system provider has been recognized as a complex process [32]–[35]. Some of the challenges include:

- Reshaping the product-focus mentality and culture.
- Acquiring the capability to develop bundle solutions that provide both product and service to the customer.
- Rethinking business models, which may significantly change the revenue and cost structures.
- Creating a closer relationship with the customer.
- Structuring the organization in a way that can support service design and operations.

Extending the scope of service. Connectivity and IoT solutions open up opportunities for the OEMs to not only offer services but also think beyond their traditional focuses [36] [37]. Digitalization can shift service boundaries beyond maintenance activities, giving the possibility to explore services supporting the customer in their operations. This requires the need to enter in the customer context and set a continuous relationship with them [38]. Moreover, considering the opportunity to retrieve data from external sources or companies, the scope of service provision increases.

Data exchange. "Data exchange" refers to the fact that data is shared between different actors, and it leads to different challenges to overcome. First, considering the customer's perspective, the fear in sharing data need to be mentioned. Customers are concerned that their data might be accessed and manipulated with malign intentions. They are also worried that the OEMs can potentially have visibility on the sensitive customer operations [34] [21] [22]. Additionally, from the OEM's perspective, the implementation of a data-driven solution requires historical data that can be difficult to retrieve in case of legacy equipment. Moreover, considering exchange of data in a one to one relationship between customer and OEMs, and also between different partners and OEMs, brings with it the data ownership dimension where it is difficult to decide and set norms, roles, and rules of data rights [41].

Lack of system level vision. Even though retrofitting allows the OEMs to gain equipment level transparency, it is not possible for an individual OEM to gain system level perspective. This is because a plant usually involves equipment from many different OEMs and current industrial production lines are mostly based on heterogeneous structures and architectures regarding communication protocols, control systems or electrical and mechanical components [23]. As a result, the integration of these different technologies is nontrivial, and the OEM's scope of service provision gets limited to equipment level. However, if different OEMs come forward and share machine level data between themselves, it may enable them to collaboratively develop system level services for individual customers.

Network reshapes. One of the critical choices for the OEMs refers to the downstream supply of technology and capabilities. OEMs need to decide whether to outsource these competencies or to develop them in-house [42]. The main trend in this direction for OEMs is to collaborate and cooperate with new technological partners and suppliers. Relationships with customers need to be reshaped since OEMs should better understand the customer processes and maintain a continuous contact created by the streams of data. Finally, digitalization changes also business models [43] and especially affect how value is created among different stakeholders in the offering. The relationships shifted from individual contribution by single firm to collaborations and integration of value chain partners to stimulate and achieve digital servitization [44] [42].

These six factors represent aspects that demine barriers for OEMs in offering Industry 4.0 retrofit solutions and digital services. As previously explained, they have been defined based on literature in servitization and digital services. Nevertheless, we argue that the factors that determine challenges can be translated also in the context of retrofitting solutions, which is not available in the analyzed literature today.

5. Conclusion

The presented research focuses on the role of OEMs in retrofitting and upgrading legacy equipment towards industry 4.0 applications. Particularly, the emphasize is given on the enabling of manufacturing servitization instead of on the technicality of retrofit solutions. One important gap identified from the literature review is the lack of OEMs' involvement in such projects. Further analysis of literature helped to identify two main triggers "Industry 4.0 Push" and "Need-based Pull" that drove manufacturers to undertake retrofit projects. Given that, we proposed the scope of a third trigger "Servitization-push", which refers to the fact that OEMs can leverage the opportunity to create and capture unique value by retrofitting and then provisioning data-driven value-added services for the manufacturers. In order to support the "Servitization-push" as a new trigger, the authors explained the benefits of retrofitting for both OEMs and manufacturers in the context of servitization. Considering the fact that, at the best of authors knowledge, "Servitization-push" is not commonly provided for legacy equipment, last contribution of this paper is related to the identification and synthesis of factors that may determine the challenges and barriers of OEMs in providing these solutions. Specifically, these factors have been classified in accordance with four different domains, i.e. "technological", "service-related", "digital service" and "legacy equipment retrofit". It is found that all of the factors have influence on the "legacy equipment retrofit", highlighting the fact that various challenges for the OEMs exist. As a next step, we plan to provide empirical validation of the identified benefits and challenges by conducting case studies and expert interviews involving both OEMs and users of industrial equipment.

References

[1]   S. Mittal, M. A. Khan, D. Romero, and T. Wuest, "Smart manufacturing: Characteristics, technologies and enabling factors," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 233, no. 5, pp. 1342–1361, 2019.

[2]   L. Thames and D. Schaefer, "Industry 4.0 - An Overview of Key Benefits, Technologies, and Challenges.pdf," in *Cybersecurity for Industry 4.0*, Atlanta: Springer International Publishing, 2017.

[3]   J. Hagerty, "U.S. Manufacturing Is Rolling on Aged Wheels.," 2014.

[4]   R. G. Lins, B. Guerreiro, R. Schmitt, J. Sun, M. Corazzim, and F. R. Silva, "A novel methodology for retrofitting CNC machines based on the context of industry 4.0," *2017 IEEE Int. Symp. Syst. Eng. ISSE 2017 - Proc.*, 2017.

[5]   M. A. Khan, S. West, and T. Wuest, "Midlife upgrade of capital equipment: A servitization-enabled, value-adding alternative to traditional equipment replacement strategies," *CIRP J. Manuf. Sci. Technol.*, 2019.

[6]   R. Oliva and R. Kallenberg, "Managing the transition from products to services," *Int. J. Serv. Ind. Manag.*, vol. 14, no. 2, pp. 160–172, 2003.

[7]   T. S. Baines *et al.*, "State-of-the-art in product-service systems," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 221, no. 10, pp. 1543–1552, 2007.

[8]   T. Baines and H. W. Lightfoot, "Servitization of the manufacturing firm: Exploring the operations practices and technologies that deliver advanced services," *Int. J. Oper. Prod. Manag.*, vol. 34, no. 1, pp. 2–35, 2014.

[9]   T. Baines *et al.*, "Towards an operations strategy for product-centric servitization," *Int. J. Oper. Prod. Manag.*, vol. 29, no. 5, pp. 494–519, 2009.

[10]   A. G. Frank, G. H. S. Mendes, N. F. Ayala, and A. Ghezzi, "Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective," *Technol. Forecast. Soc. Change*, vol. 141, no. January, pp. 341–351, 2019.

[11]   T. Grubic and J. Peppard, "Servitized manufacturing firms competing through remote monitoring technology An exploratory study," *J. Manuf. Technol. Manag.*, vol. 27, no. 2, pp. 154–184, 2016.

[12]   D. Opresnik and M. Taisch, "The value of big data in servitization," *Int. J. Prod. Econ.*, vol. 165, pp. 174–184, 2015.

[13]   M. Ardolino, M. Rapaccini, N. Saccani, P. Gaiardelli, G. Crespi, and C. Ruggeri, "The role of digital technologies for the service transformation of industrial companies," *Int. J. Prod. Res.*, vol. 56, no. 6, pp. 2116–2132, Mar. 2018.

[14]   D. Bakir, R. Bakir, and F. Engels, "Industry-Integrator as retrofit solution for digital manufacturing methods in existing industrial plants," *Procedia Manuf.*, vol. 17, pp. 1009–1014, 2018.

[15]   D. Lucke *et al.*, "Implementation of the MIALinx integration concept for future manufacturing environments to enable retrofitting of machines," *Procedia CIRP*, vol. 79, pp. 596–601, 2019.

[16]   F. Orellana and R. Torres, "From legacy-based factories to smart factories level 2 according to the industry 4.0," *Int. J. Comput. Integr. Manuf.*, vol. 32, no. 4–5, pp. 441–451, 2019.

[17]   F. Bosi *et al.*, "Cloud-enabled Smart Data Collection in Shop Floor Environments for Industry 4.0," *2019 15th IEEE Int. Work. Fact. Commun. Syst.*, pp. 1–8, 2019.

[18]   M. A. García-Garza *et al.*, "A Case about the Upgrade of Manufacturing Equipment for Insertion into an Industry 4.0 Environment," *Sensors*, vol. 19, no. 15, p. 3304, 2019.

[19]   C. Voell, P. Chatterjee, and A. Rauch, *Closing the Lifecycle Loop with Installed Base Products*, vol. 540, no. July 2018. Springer International Publishing, 2018.

[20]   A. Sepehri, Z. Chu, G. Ren, and N. Sepehri, "Condition Monitoring of Industrial Machines Using Cloud Communication," *2018 IEEE 9th Annu. Inf. Technol. Electron. Mob. Commun. Conf. IEMCON 2018*, pp. 1318–1323, 2019.

[21]   P. Strauß, M. Schmitz, R. Wöstmann, and J. Deuse, "Enabling of Predictive Maintenance in the Brownfield through Low-Cost Sensors, an IIoT-Architecture and Machine Learning," *Proc. - 2018 IEEE Int. Conf. Big Data, Big Data 2018*, pp. 1474–1483, 2019.

[22]   H. Lödding, R. Riedel, K.-D. Thoben, G. von Cieminski, and D. Kiritsis, "New Threats for Old Manufacturing Problems: Secure IoT-Enabled Monitoring of Legacy Production Machinery," *IFIP WG 5.7 Int. Conf. APMS 2017*, vol. 513, pp. 298–305, 2017.

[23]   B. V. Guerreiro, R. G. Lins, J. Sun, and R. Schmitt, "Definition of smart retrofitting: First steps for a company to deploy aspects of industry 4.0," *Lect. Notes Mech. Eng.*, no. 201519, pp. 161–170, 2018.

[24]   Y. C. Fan and J. Y. J. Chang, "Embedded smart box for legacy machines to approach to i 4.0 in smart manufacturing," *MATEC Web Conf.*, vol. 185, 2018.

[25]   N. Control, C. N. C. Machine, and M. E. Smes, "A Low-Cost Vision-Based Monitoring of Computer," 2019.

[26]   H. Jónasdóttir, K. Dhanani, K. McRae, and J. Mehnen, "Upgrading legacy equipment to industry 4.0 through a cyber-physical interface," *IFIP Adv. Inf. Commun. Technol.*, vol. 536, pp. 3–10, 2018.

[27]   S. Tedeschi, C. Emmanouilidis, J. Mehnen, and R. Roy, "A design approach to IoT endpoint security for production machinery monitoring," *Sensors (Switzerland)*, vol. 19, no. 10, 2019.

[28]   D. Preuveneers and E. Ilie-Zudor, "The intelligent industry of the future: A survey on emerging trends, research challenges and opportunities in Industry 4.0," *J. Ambient Intell. Smart Environ.*, vol. 9, no. 3, pp. 287–298, 2017.

[29]   A. R. Sadeghi, C. Wachsmann, and M. Waidner, "Security and privacy challenges in industrial Internet of Things," in *Proceedings - Design Automation Conference*, 2015, vol. 2015-July.

[30]   S. Fosso Wamba, S. Akter, A. Edwards, G. Chopin, and D. Gnanzou, "How 'big data' can make big impact: Findings from a systematic review and a longitudinal case study," *Int. J. Prod. Econ.*, vol. 165, pp. 234–246, 2015.

[31]   M. O. Gokalp, K. Kayabay, M. A. Akyol, P. E. Eren, and A. Kocyigit, "Big data for Industry 4.0: A conceptual framework," in *Proceedings - 2016 International Conference on Computational Science and Computational Intelligence, CSCI 2016*, 2017, pp. 431–434.

[32]   G. Allmendinger and R. Lombreglia, "Four Strategies for the Age of Smart Services," *Harv. Bus. Rev.*, vol. 83, no. 10, pp. 131–145, 2005.

[33]   M. Bastl, M. Johnson, H. Lightfoot, and S. Evans, "Buyer-supplier relationships in a servitized environment," *Int. J. Oper. Prod. Manag.*, vol. 32, no. 6, pp. 650–675, 2012.

[34]   S. Brax and K. Jonsson, "Developing integrated solution offerings for remote diagnostics: A comparative case study of two manufacturers.," *Int. J. Oper. Prod. Manag.*, vol. 29, no. 5, pp. 539–560, 2009.

[35]   T. Grubic and J. Peppard, "Servitized manufacturing firms competing through remote monitoring technology.," *J. Manuf.*

Technol. Manag., vol. 27, no. 2, pp. 154–184, 2016.

[36] A. Rymaszewska, P. Helo, and A. Gunasekaran, "IoT powered servitization of manufacturing – an exploratory case study," *Int. J. Prod. Econ.*, vol. 192, no. February, pp. 92–105, 2017.

[37] M. Zambetti, R. Pinto, and G. Pezzotta, "Data lifecycle and technology-based opportunities in new product service system offering towards a multidimensional framework," in *Procedia CIRP*, 2019, vol. 83, pp. 163–169.

[38] H. Gebauer, M. Paiola, and N. Saccani, "Characterizing service networks for moving from products to solutions," *Ind. Mark. Manag.*, vol. 42, no. 1, pp. 31–46, 2013.

[39] K. Matthyssens, P., Vandenbempt, "Moving from basic offerings to value-added solutions: Strategies , barriers and alignment.," *Ind. Mark. Manag.*, vol. 37, pp. 316–328, 2008.

[40] M. E. Porter and J. E. Heppelmann, "How Smart, Connected Products Are Transforming Competition.," *Harv. Bus. Rev.*, vol. November, pp. 1–23, 2014.

[41] Y. Yoo, R. J. Boland, K. Lyytinen, and A. Majchrzak, "Organizing for Innovation in the Digitized World SPECIAL ISSUE," *Organ. Sci.*, vol. 23, no. 5, pp. 1398–1408, 2012.

[42] E. Lafuente, Y. Vaillant, and F. Vendrell-Herrero, "Territorial Servitization: Exploring the virtuous circle connecting knowledge-intensive services and new manufacturing businesses," pp. 19–28, 2017.

[43] F. Vendrell-Herrero, O. F. Bustinza, G. Parry, and N. Georgantzis, "Servitization, digitization and supply chain interdependency," *Ind. Mark. Manag.*, vol. 60, no. 1, pp. 69–81, 2016.

[44] C. Arnold, D. K. et Al., and K.-I. Voigt, "How the industrial internet of things changes business models in different manufacturing industries," *Int. J. Innov. Manag.*, vol. 20, no. 8, 2016.

[45] T. Lins, R. A. R. Oliveira, L. H. A. Correia, and J. S. Silva, "Industry 4.0 retrofitting," *Brazilian Symp. Comput. Syst. Eng. SBESC*, vol. 2018-Novem, pp. 8–15, 2018.