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ORIGINAL PAPER

INDUSTRY 4.0 AND 3D PRINT: A NEW HEURISTIC APPROACH FOR DECOUPLING POINT IN FUTURE SUPPLY CHAIN MANAGEMENT

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ABSTRACT. Background: The paper is devoted to the analysis of the trends and roles of decoupling point in the revolution of new technologies and Industry 4.0. Ever-growing demands and market requirements pressure to optimize the operations and be agile in every area of action. The crucial thing is to create a stable supply chain considering both the cost perspective and customer orientation. Fluctuations, congestion, and unexpected events may have a critical impact on operations and strategy, causing shortages and reducing efficiency. The objective of proper supply chain management is to optimize stocks and use technology to build synergy, which is a key point to increasing competitiveness throughout the entire stream and meeting customer demands. In our research, we offer a perspective on the growing field of 3D printing that may open a way to redefine a decoupling point and create more efficient networks.

Methods: This paper uses an analysis of literature related to the decoupling point, presenting the ground rules and their importance in supply chain management. A comparison of theory, current state, and trends is intended to heuristically identify bottlenecks and risks as a case study for continuous improvements in global logistics. Presented data aim to define a way how the supply chain can evolve and use 3D print to create a new perspective on the decoupling point.

Results: This study provides an overview of the trends in supply chain management and presents figures on the most common structures of current networks. Analysis of theory and technology development presents the possible changes in the definition of the decoupling point.

Conclusions: Surging market requirements and the necessity of cost competitiveness make supply chains more difficult to manage. Unexpected fluctuations, force majeure events, and limited infrastructure capacity are adventurous for ensuring continuous operations. The research provides the insight into the development of logistics to reduce uncertainty and may define a starting point for further analysis of advanced supply chain management based on new technologies.

Keywords: supply chain, decoupling point, agile management, 3D print, Industry 4.0

INTRODUCTION

Supply chain management is under constant pressure to provide high efficiency of operations and processes at all levels of the stream. Many people perceive the construction of a supply chain as a network, which is a correct perspective, but mainly they consider only its most explicit elements, like crucial suppliers, service providers, brands, and general exterior appearance: it may cause an underestimating the role of continuous improvement and present some semblance about the easiness of supply chain management.

Oliver and Webber used the term supply chain management for the first time in 1982 in the article *Supply Chain Management: Logistics Catches Up with Strategy*. The authors defined it as a material flow that starts with suppliers and goes through processes to the final customer. This simple consideration is the essence of this term, pointing out that the supply chain starts in a place where the very first raw material is mined [Oliver and Webber, M 1982]. Their concept was motivated by surveillance of the US economy suffering from decreasing competitiveness related to the expansion of Japanese corporations over the world. For considering, it was highly recommended to think about management as a separation of basic functions like purchasing, manufacturing, sales, and distribution.

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In the beginning, in the opinion of some experts, this proposal could pose issues to ensure the smooth operation. Then Webber and Oliver specified the concept idea of the fields integration of mentioned under the definition of supply chain management, which reflects corporate responsibility and provides a coherent strategy. The aim of this methodology was a constructive approach to the planning, distribution, and control of the supply chain, leading the company to excellence in ensuring the highest customer satisfaction in the most efficient way [Camman et al. 2017].

The continuous development of the global industry in the coming decades made supply chain management a crucial element of strategy as well as a field where companies can find significant savings, which could strengthen their position and reduce costs. The above-mentioned definition is now just a fundamental idea for any further changes in terminology and focus. However, continuous evolution opens the way to ask questions about the contribution of SCM in Industry 4.0 and overall profitability.

This paper will provide a multifaceted analysis of trends and ways in which supply chain management, is going to take place in the future, considering the current global situation related to bottlenecks occurring as a result of economical and infrastructure circumstances. It requires a further discussion on how the decoupling point should be redefined if we start to use modern solutions in manufacturing.

DECOUPLING POINT AS FUNDAMENTAL FACTOR OF SUPPLY CHAIN CONSTRUCTION – THEORETICAL BACKGROUND

The decoupling point, strictly speaking – is a place in the structure of the supply chain where the largest inventories should be stored. Its main role is to be a buffer for the needs resulting from independent demand. Some define a decoupling point as a place within the value stream that determines a separation of dependent and independent demand. For enterprises, an independent demand is a direct demand for the products they produce. Therefore, dependent demand means the needs related to requirements for another item, i.e., components, parts, semi-finished products, or raw material necessary to make a final product [Ivanov and Schönberger 2017].

In practice, orders received from the customer right away become an independent demand, defining the exact quantity of the product required to fulfill the order. Calculating the dependent demand is possible thanks to knowledge of the product structure and carryover stocks. This interrelation is reflected in the Bill of Materials (BOM).

The dependent demand is calculated by the MRP modules, which use planning parameters to maintain supply processes. Therefore, the decoupling point and its location are determined by the market and the supply chain in which companies exist – the concept of its definition is directly related to the reduction of inventories by producers and thus to the reduction of time differences during the execution of orders between the chain links [Wieczorek 2015].

According to Olhager, the decoupling point is considered in four ways, depending on the production model (or strategy) of a company:

- MTS (Make-to-stock) - products are stored in the finished goods warehouse, and customer orders are managed directly from stock. In this case, the products are located near the customer,
- ATO (Assemble-to-order) - components and subassemblies kept in stock by the manufacturer in a varying degree of complexity. An assembly process starts on customer’s demand,
- MTO (Make-to-order) - stock of material or parts is at a low level of complexity. A production process launched on customer’s demand,
- ETO (Engineer-to-order) - when the customer places an order, no inventory other than know-how (knowledge, technology, etc.) is available. Procurement and production processes are a consequence of the firm order.

Relation of a decoupling point to a production model

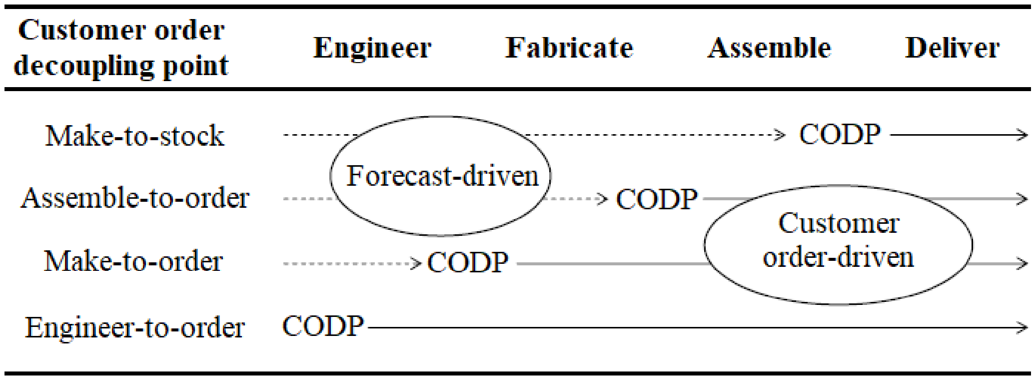

Fig. 1. Scheme of the the relation of decoupling point to a production model. Source: [Olhager 2012].

The findings of some studies suggested that companies should be more dynamic when considering their decoupling point strategy. According to available research, the further the information decoupling point is moved upstream, the better improvement in the dynamic behavior of the supply chain [Mason-Jones and Towill 1999]. It suggests that there is the best attainable performance when the operating mechanisms of stock management and production deployment are located at the factory.

At that time, it is also important to note that the product delivery strategy is inextricably linked to the type of goods produced by a particular manufacturer. Downstream of CODP production is related to specific customer orders (pull). On the upstream end, manufacturing processes are driven by forecasts (push). However, MTS allows providing maximally short delivery lead times and anonymity of customers, however, requiring the high accuracy of forecasting methods and increasing inventory costs for finished goods [Köber and Heinecke 2012].

In times of growing competitiveness, producers try to find the most profitable way to provide a reliable service and availability of the products to their customers. The research question of the present article is the prediction of how Industry 4.0 and new technologies can support the supply chain and manufacturing to meet the challenges of the market. We hypothesize that the next decades can redefine the CODP and eliminate wastes throughout the stream. In the following paragraphs, we will present the possible impact of 3D printing on the future shape of supply chains.

INDUSTRY 4.0 – MODERN VISION OF MANUFACTURING

Long-standing interest has been in the implementation of new technologies in manufacturing and customer service. Industry 4.0 as a term describing this vision was established in 2011 and since then we can find several definitions of its principles. For instance, from a supply chain perspective, the most important seem to be:

- Real-time Big Data algorithms and using them to improve OEE
- Service orientation offering online architecture
- Worldwide communication network supporting industrial & economic partnership

These principles can be achieved thanks to the implementation of state-of-the-art methods such as artificial intelligence (AI), robotics, or 3D printing [Vogel-Heuser and Hess 2016].

First, the findings of some studies focus on the horizontal structure of the network to create a flexible and effective chain being able to utilize a huge amount of information (Big Data) and reacting faster to changes [Tjahjono et al. 2017].

Second, from a manufacturing perspective it is important to integrate engineering disciplines and exist in an automated interdisciplinary production system toward the usage of integrated models [Feldmann et al. 2015].

Finally, equipment will be characterized by the application of high-end tools and machines. It leads to the creation of an environment where robots cooperate effectively with workers providing high flexibility and efficiency [Stock and Seliger 2016].

INDUSTRY 4.0 IN SUPPLY CHAIN MANAGEMENT

Although Industry 4.0 by many people is mainly related to manufacturing, the principles are crucial for effective cooperation of particular links within the supply chain. Research provides that functions of the supply chain may be distinct depending on the product or services. However, they are necessary to integrate and coordinate all processes to match the supply and demand throughout the 4 main levers: buy, storage, move and sell [Tjahjono et al. 2017].

Subsequently, further findings offer an opportunity to define the supply chain in Industry 4.0 as "smart logistics" considering a modern approach to products and services. This new paradigm is supported by the idea of digitalization that considers the coexistence of people and systems to manage information flows and improve operations [Barreto et al. 2017].

Therefore, the requirement was to define the structure of the modern supply chain and describe the basic relations between its elements. Another research proposed a definition that says about a set of resources interacting with their network and shifting physical activities into digital ones to reduce the consumption of resources, support productivity, and finally provide real-time feedback as well as full visibility of the process. Not only does it consider the internal supply chain, but also includes all external relations, supporting the digitalization of tools in all stages of the network [Queiroz et al. 2019].

Integration of resources within the Critical Digital Supply Chain

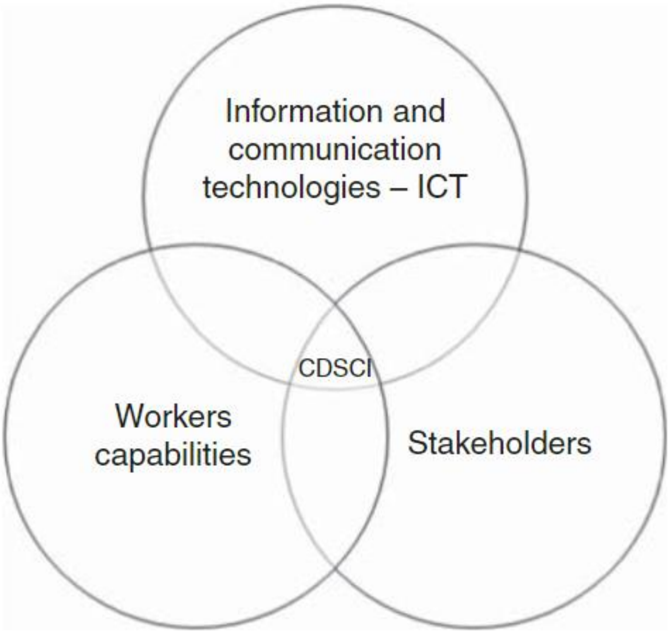

Fig. 2. Scheme of resource integration within Critical Digital Supply Chain: [Queiroz et al. 2019].

Specifically, according to the next study, to perform a digital supply chain, decentralization of the systems and cooperation based on the Internet of Things (IoT) are required, which independently manage the multiple-root data distributed in-network. Thanks to that, it is possible to create interoperable tools using the same IT standards to build synergy and provide the best performance [Weber and Weber 2010].

Modern tools and analytics allow one not only to improve the operations but also to implement statistical models and simulate future data. Thanks to it, there is possible a revolutionizing of the business spectrum and increasing competitiveness. It is important to mention that Industry 4.0 is not just a scientific approach to manufacturing and logistics, but conclusions from many types of research indicate this as a framework combining the solutions being implemented by real users. From this perspective, Industry 4.0 defines the business-applied solutions, supporting them with a scientific background, and analyzing results to guide how they should be developed in the future. Although there is the assumption that this idea is based on computer-aided tools, researchers' conclusions present the opinion that it is still largely based on the human decision-making process and efforts [Szymańska et al. 2017]

DUALISM OF DEVELOPMENT – NEW TECHNOLOGIES AND ENVIRONMENTAL RESPONSIBILITY

Increasing market requirements and globalism of manufacturing processes are strongly supported by tools related to Industry 4.0 and Logistics 4.0. Daily work and operations are possible thanks to solutions like RFID or sophisticated ERP systems that control all processes of companies. Research in this field provides that the Internet of Things, big data, and new technologies can increase productivity and enhance competitive edge in the supply chain. Modern solutions support end-to-end structures, adding value to material management, manufacturing, distribution, and customer service, which integrates even stronger the particular links and helps to save costs [Raman et al. 2018]

Technology and ever-growing demands caused regions to start to cooperate and finally globalized the market. With regard to Industry 4.0, globalization means the integration of international markets for commodities, labor, and capital. The benefits of this structure were significant from a cost perspective, geopolitical stability, and promotion of economic cooperation [O'Rourke 2019].

The companies wanted to achieve the best results and build their competitiveness on reduced costs. They realized then that production in Asia is much cheaper than domestic one. In 1978 the average wage in China was 3% of the average US wage at that time. Reforms in the 1990s caused an increase in these costs, but did not stop a rapid increase in demand for manufacturing in this country [Li et al. 2012]. This was possible because of the cheap energy available in China, as the country is the biggest producer of coal and its biggest consumer.

On the other hand, another finding provides that China is not ready to implement Industry 4.0 solutions because of problems like inefficient unit labor production, the imperfect standard system of industrialization, weak innovative capacity and lack of core talents, poor digital infrastructure, high energy consumption, high pollution, and low added value. China must improve its traditional manufacturing and implement modern solutions to meet the requirements of the future economy. There is need to say that idea of Industry 4.0 is considered to make countries more and more closely linked, so the Chinese manufacturing sector should start working on systematic development that involves government, universities, and research units [Feng et al. 2018].

However, in recent decades, the increase in production in Asia caused a huge demand for transportation from this region to other continents. This gap has been fulfilled by containerization, which significantly increased productivity in cargo handling. In 1984 the first container ships of around 4500 TEU were built. Companies that became the major container lines have understood that economy of scale will increase competitiveness and force agility to react. Second, they expected future growth in container volumes as a result of increased trade. And finally, there was a common understanding that there is a need for the development of port infrastructure to operate the larger ships [Cullinane and Khanna 2000].

According to United Nations and Clarksons Research, in recent years, we reported a significant increase in the proportion of mega-container ships in the global fleet. It shows that vessels with a capacity of more than 10.000 TEU constituted in 2021 almost 40% of the fleet, compared with 6% in 2011. Subsequently, there is a correlated decrease in the share of vessels less than 10.000 TEU. This trend is presented in Figure 2.

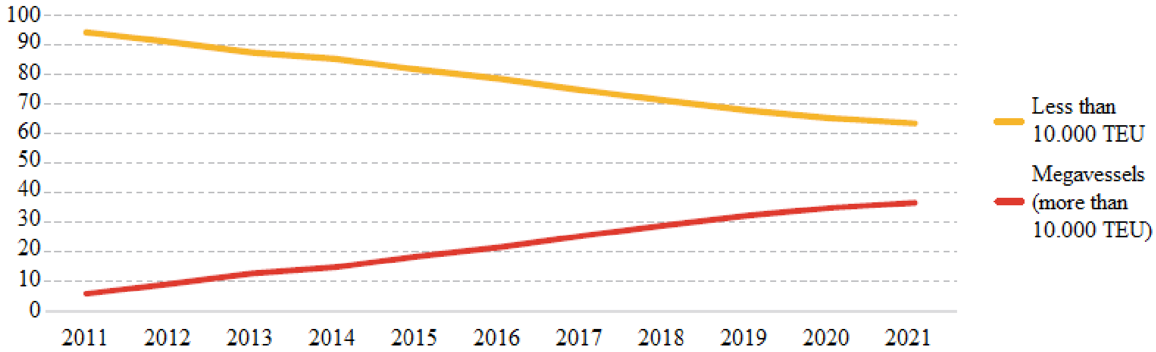

Fig. 3. Percentage share of mega-vessels in the global container ship fleet carrying capacity by TEU, 2011-2021: [LOGISTICS, D.O.T. AND. U.N.C.O.T.A. DEVELOPMENT 2021]

This presented change in fleet proportion is a natural consequence of the ever-growing containerized trade, which increased from about 40 million TEU in 1996 to 160 million TEU in 2021. Asia is a global leader as a hub for container port traffic with 2/3 of the the throughput and half of 20 largest ports located in China. It intensifies cost pressure or inefficiencies. Additional bottlenecks or force majeure events such as COVID-19 have shown that global trade and supply chains are prone to disruptions, which lead to increased production costs and consumer prices. From a geopolitical point of view, protectionism between China and its trading partners may also be concerning because it may affect not only affect international relations but also decelerate global trade. China, as a developing country, is increasingly consuming its products, creating a domestic supply chain. The semiconductor crisis has proved how the shortage of raw material in one region can be critical for global industry causing a stop of production in automotive manufacturing [LOGISTICS, D.O.T. AND. U.N.C.O.T.A. DEVELOPMENT, 2021].

What does dualism actually mean? According to the opinions of researchers, neoliberal globalization is focused on profit and market more than considering any environmental aspects [Lehman 2009]. In recent decades, we realized what is the impact on the environment caused by manufacturing and transportation. The threat of climate change makes pressure on global supply chains to improve not only the factors important for businesses (e.g., lead times or costs) but also to reduce pollution. It was clearly stated that reforms and business models have widened the inequality between developed and developing regions [Free and Hecimovic 2021].

The new circumstances and the global situation intensify the consideration of defining a new supply chain order. One of the solutions would be the diversification of operations across other geographical areas. In this case, China's role in global manufacturing would be diminished and operations could be moved to Vietnam, Indonesia, Mexico or Europe, which may strengthen regional networks and increase resilience against growing geopolitical uncertainty [Free and Hecimovic 2021]. Technologies like 3D printing, AI, or Big Data will be very important for supply chains because they can redefine the framework of supply chain operations, increase the potential of local manufacturing, and simplify the networks reducing the complexity of assembly. The available research provides that there is a required change in decision-making processes to adapt companies to the reality of Industry 4.0 reality and understand all challenges and barriers related to it [Tsolakis et al. 2021].

3D PRINTING AS A PART OF FUTURE SUPPLY CHAINS

3D printing is not a new idea. The first reference to the technical capabilities of additive manufacturing can be traced back to the 1980s. However, the discussion of this technology was brought up again when the process costs have become affordable [Chan et al. 2018]. Additive printing is still a developing field, but the current state offers the use of a wide range of materials and techniques, which allow producing some goods used in multiple areas [Longhitano et al. 2021].

This technology is crucial importance for R&D activities. It can be integrated with scanning and allow one to digitalize of the product. At the same time, 3D printing can minimize the risks in product design, because 3D samples can be prepared in many configurations. It allows the customer to review the models without an expensive investment in tooling. Subsequently, there are possible cost savings as well as lead-time reductions. Furthermore, an expected is expected evolution in structure and identification of companies that offer services in this field. Companies can move from Original Equipment Manufacturer (OEM) to Original Design Manufacturer (ODM). This supports an easier way to create a new brand and produce products in small quantities with relatively affordable capital [Chan et al. 2018].

Increased environmental responsibility is also one of the advantages of additive printing. Thanks to the simplification of the manufacturing processes, the stages of production are reduced. Consequently, it improves the number of wastes that could be generated during operations. Additionally, while traditional business models are concentrated in geographical locations to achieve economic of scale, 3D printing can eliminate the distance between the production and consumption point. This concept is strongly supported by IT which allows the transfer or exchange of data [Singh and Agrawal 2021].

However, the findings provide that the full potential of 3D printing has not yet been yet achieved. This technology is used mainly by small manufacturers, which can fill a gap in market demand on a local scale. From a functional perspective, its services can be separated into three categories: generative, facilitative, and selective. Therefore, the advantages of additive manufacturing can cause complementing, replacing, or even creating new supply configurations. This may be possible due to offering high flexibility in terms of volumes, product customization and complexity [Rogers et al. 2016].

REDEFINITION OF DECOUPLING POINT IN INDUSTRY 4.0 FRAMEWORK

The decoupling point known in the current shape and understanding is strictly related to the economy based on the wide networks within the supply chains. Globalism that we mentioned in the previous paragraphs caused a major increase in complications, and disruption being a result of the increased complexity of the processes whilst trying simultaneously reduce the costs of warehousing or transportation.

The dynamic development of technologies and the growth of living standards have created the need to produce more sophisticated and individualized products. It truly impacted supply chain and manufacturing operations because mass production (e.g. in automotive) has become even more complicated. From an economic standpoint, suppliers sourced to produce the components are located, in large part, in Asia, which is an important disadvantage if assembly plants are located in Europe or US.

Increased prices for goods, the deteriorating geopolitical situation, and the limited infrastructure capacity are the reason for high uncertainty within global supply chains. The current industry has many challenges to overcome these issues. Industry 4.0 in our opinion, will change the understanding of logistics processes, but should also redefine the business models in terms of decoupling point.

3D printing technology can allow implementation of the new stages of decoupling point:

1. PTO (Print-to-Order) – printing of standardized products based on the available projects. Usually simple or fast-moving goods, tools, and service parts.
2. PTA (Print-to-Assemble) – printing of product with adjustable parameters or available in several variants. The process is driven by production orders or purchase orders. The variable of product is specified in the BOM existing in pre-defined various options.
3. ETP (Engineer-to-Print) – product is designed, printed, and tested based on the individual demand of the customer. Defined for unique and/or advanced products with a high level of customization.

Our concept presents new insight into a gap in understanding of the decoupling point in Industry 4.0 considering its evolutionary context. This framework could be used by supply network designers to make a decision about the business model and build an efficient end-to-end supply chain. Proposals or potential adjustments to this concept may be a part of a later discussion.

DISCUSSION AND CONCLUSION

The main objective of this paper was to analyze how supply chain and manufacturing can evolve thanks to the implementation of tools that are part of the Industry 4.0 framework. We agree with researchers that digitalization and modern solutions have an enormous potential to become the game changers in the re-definition of the supply chain.

At the same time, we understand the changes in the global market, also considering geopolitical factors. In our opinion, extensive networks can be a reason for many disruptions and negatively affect continuity of operations. The limited capacity of ports, busy shipping lanes, and increasing individualization of products are challenging for companies these days. In our view, although modern IT solutions are widely used by users, bottlenecks and potential uncertainty are related to physical operations and transportation, which have their natural limitations.

Constantly developing the field of 3D printing will be crucial to overcome these constraints and strongly support the cost perspective of businesses. We can easily define the following advantages of this solution for future supply chains:

1. Reduction of components/links within the supply chain: a simplification of networks, eliminating the processes or suppliers which extend the supply chain unnecessarily.
2. Optimization of processes - 3D printing can narrow down a list of materials needed to produce the same products. It means that a particular company could manufacture different products made of the same raw material. Processes may be driven by firm order and support variability of production.
3. Cost reduction:
    a. Warehousing – significant reduction in stock narrowing them down to raw material needed to print the final goods. Possible optimizations in storage methods and better utilization of space
    b. Transportation - the moldable and loose nature of raw material can improve container utilization.
4. Increased agility of the processes and business models – availability of raw material can significantly improve the inhouse operations and allow to react quickly to changing demands. For Engineer-to-Print, it means a potential elimination of lead times for material and the possibility to focus on the development of the product.

Potential limitations are related to the technology of 3D printing and currently existing models of supply chains. The complexity of the goods and the shape of the networks require progressive development and analysis of business models. It is truly important to consider this evolution as a complex task that involves not only the supply chain, but also purchasing, engineering, product development, and manufacturing. We propose further discussion regarding the transitional stage between the current and future state.

At the moment, two global automotive companies, Renault and Stellantis – are considering developing the idea of refactoring used cars. Their future manufacturing facilities will be supposed to receive cars, proceed with a scanning procedure to detect all mechanical damages as well as hidden defects (e.g., within electric systems), and replace defective elements with new ones. To be effective, this concept must be supported by new technologies, because the advancement of construction and unpredictability of potential damages do not allow one to keep scenario of serial production of components.

FUTURE RESEARCH

Our findings have focused on the supply chain perspective and presented how the decoupling point can evolve in terms of the Industry 4.0 framework. Future research should consider the transitional stage to effectively use available technology, not impacting current businesses. The coming studies should also examine the influence of new approaches on decision-making. From a global perspective, it would also be required to analyze whether this concept may improve the sustainable growth of particular regions, also supporting also environmental responsibility.

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