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ARAŞTIRMA MAKALESİ / RESEARCH ARTICLE

INDUSTRY 4.0 AND SUSTAINABLE SUPPLY CHAIN

ENDÜSTRİ 4.0 VE SÜRDÜRÜLEBİLİR TEDARİK ZİNCİRİ

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Abstract

The integration of information technologies with industry has marked the beginning of the Fourth Industrial Revolution, which is called Industry 4.0 for short. The technologies of this era have been transforming not only the industry itself but also reshaping individuals and society. One cannot deny the very positive outcomes of Industry 4.0; however, it has also given rise to some environmental problems, including changes in climatic conditions, the running out of resources due to increasing amounts of production, industrial wastes, all of which pose irreversible threats to nature. These negative outcomes have mobilized individuals, non-governmental organizations and states requiring companies to reform the operation of supply chains in line with the sustainability principle of "meeting today's needs without compromising the ability of future generations to meet their own needs". The purpose of the current study is to present how Industry 4.0 might influence the functioning of the sustainable supply chain and the benefits it might bring. First, industrial revolutions, the concept of Industry 4.0 were introduced briefly. Then, the trends in supply chain management and with reference to sustainability and the possible contributions of Industry 4.0 to sustainability were discussed.

Keywords: Industry 4.0, Sustainable Supply Chain, Closed-loop Product Lifecycle, 6R
JEL Classification: L1, L2, M1, O33, Q31, Q56, Q57

Öz

Bilişim teknolojilerinin sanayi ile bütünleşmesi sonucu günümüzde 4. Sanayi Devriminin içinde olduğumuz kabul edilmektedir. Endüstri 4.0 olarak adlandırılan bu dönemde hayata geçirilen teknolojik faktörlerin sadece endüstriyi değil; bireyleri ve toplumu da önemli ölçüde etkilemektedir. Endüstrideki olumlu teknolojik gelişmelerin yanında çevresel etkiler de değişmekte fakat bu etki ne yazık ki olumsuz yönde olmaktadır. Değişen iklim koşulları, artan üretim ve buna bağlı artan kaynak tüketimi, endüstriyel atıklar vb. birçok faktör doğayı geri dönülemez ölçüde tehdit eder hale gelmiştir. Bu olumsuz gelişmeler bireyleri, sivil toplum örgütlerini ve devletleri harekete geçirmiştir. İşletmeler de dâhil oldukları tedarik zincirlerinin işleyişini 'günümüz ihtiyaçlarının, gelecek nesillerin kendi ihtiyaçlarını karşılama kabiliyetinden ödün vermeksizin karşılanması' şeklinde tanımlanan sürdürülebilirlik ilkesi doğrultusunda yeniden biçimlendirmektedirler. Bu çalışmanın amacı Endüstri 4.0'ın sürdürülebilir tedarik zincirinin işleyişinde nasıl bir etkisi olacağının ve getireceği faydaların sunulmasıdır. Çalışmada öncelikle sanayinin

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devrimleri, Endüstri 4.0 kavramı ve getirdiği yeniliklerden bahsedilmiştir. Ardından tedarik zincirinin yönetiminin gelişimi, sürdürülebilir tedarik zincirinin özelliklerine değinilmiştir. Son olarak Endüstri 4.0'ın sürdürülebilir tedarik zincirine nasıl katkı sunmasının beklendiği açıklanmıştır.
Anahtar Kelimeler: Endüstri 4.0, Sürdürülebilir Tedarik Zinciri, Kapalı Çevrim Ürün Yaşam Döngüsü, 6R
JEL Sınıflandırması: L1, L2, M1, O33, Q31, Q56, Q57

1. Introduction

The primary goal of companies since the beginning of the industrial revolution has always been to increase their profits. During the early years of industrialization, just increasing the amount of production was sufficient to increase the profitability thanks to the high demand and low competition. However, a lot has changed in the following years. First, companies that wanted to increase their profitability sought ways to reduce their costs due to increasing competition and the growing number of suppliers for the demand. Flexible production strategies were developed when cost reduction alone was insufficient to get ahead of competitors and reducing costs while increasing production flexibility and quality required new management approaches. Since then, companies on supply chains have tended to work cooperatively and have implemented technological and strategic plans for economic growth.

However, industrial development has brought about many threats to nature, such as climate change. Increasing consumption of natural resources and the resulting industrial waste has mobilized individuals, non-governmental organizations and governments as well as companies. The management of supply chain processes with only economic targets has lost its rationality because processes to meet unlimited consumption over the years. Meeting the needs of the modern world without compromising the ability of future generations to meet their own needs, the value of renewable resources and the issue of production using less harmful methods to nature have gained importance as the world cannot be a place to live without the sustainability of natural resources and the cooperation of all individuals, states and companies. Therefore, sustainability and its environmental dimension have become an important concept for companies.

The aim of Sustainable Supply Chain Management is to provide materials, information and capital flow to reach economic, environmental and social goals while meeting the expectations of all stakeholders in the supply chain network, from suppliers to customers. Supply chain involves processes from product design, raw material purchasing, logistics, production, sales, distribution, usage, end-of-life processes to waste management. In sustainable supply chains, new regulations are made compatible with the issues of using environmentally friendly materials, carbon emissions and ecological footprint to minimize pollution with waste management activities and promote recycling.

Industry 4.0 is a concept that basically aims the integration of production with Information Technologies. Beyond the automation of the value chains only within the enterprises, it is an industrial integration strategy in which all value chain steps are in real-time and continuous communication with each other, and thus, it is a smart and self-adapting strategy. Due to the technological factors summarized with the concept of Industry 4.0, it will be possible to practice sustainable management strategies in the entire supply chain.

2. Historical Evolution of Industry and Industry 4.0

There have been three major industrial changes in the past that fundamentally changed the factors of production and their relationships. The first and the most impressive influence of these was the transition from craft production to factory production in the late 18th century with the invention of mechanical looms that enabled more efficient use of water and steam power. The main development that led to this First Industrial Revolution was James Watt's invention of the steam-powered machine in Scotland in 1763 followed by Edmund Cartwright who invented the mechanical loom in 1784, which mechanized the weaving process and became the pioneer of the mechanization era. This revolution, which first appeared in the UK, spread to Western Europe, North America, Japan and then all around the world. While machines replaced manpower with the First Industrial Revolution, the use of minerals and metals increased, and transportation was greatly improved. Machines used in this period comprised of simple mechanical tools operating with the help of gears, pistons, belts and pulleys.[1] This great change in the industry and the great increase in the amount of production transformed economic relations and social structure as well.

The second major change in industrial production occurred with the assembly line technology developed in the US in the early 20th century and Taylor's management strategy. With the production facilities operating with electrical energy and the division of labor in manufacturing the mass production methods, such as the inexpensive steel production method developed by British inventor Henry Bessemer in 1860 and the first "assembly line" in a slaughterhouse in Cincinnati in 1870 began to spread all around the world. In the expansion of the Second Industrial Revolution, the developments in electricity and chemical science and the development of the transportation network, especially the railways, played a major role. The ease of transportation facilitated the supply of raw materials while the products manufactured could reach new and distant markets. The reforms in industry again spread to social and economic platforms. The US and Germany became world leaders thanks to their developed economies. Electrical machines were manufactured in the USA and Germany and they were exported to other countries. Productivity in manufacturing has significantly increased by means of the "mass production line" method that Henry Ford started to use in his automobile factory in 1913, which was then adopted by other sectors as well. This method enables mass production based on standardized goods. The motto of this industrial period, known as Fordism, has been called "mass production for the masses". When Fordism, which prevailed as the main manufacturing method until the end of the 1960s, was not able to respond to the increasing competition and the diversification in consumer demands anymore, new production strategies were developed in which flexibility and diversity came into prominence to reduce costs.

The third major change in the industry was the result of the combination of technological developments with increasing competition and the necessity to respond to diversity in consumer demands. In 1968, the development of PLC (programmable logic controller), a microprocessor-based device that processes the information received from the sensors according to the existing program and transfers it to other

1 Çeliktaş, M.S. et al. (2015). Endüstriyel Devrimin Son Sürümünde Mühendisliğin Yol Haritası, Mühendis ve Makine, 56(662): 25.

units, started a new era in the industry. The 'programmable machines' and 'industrial robots' using electronic and computer-based technologies enabled full automation in production, which made it possible to reduce the costs while providing flexibility, variety and speed in production.

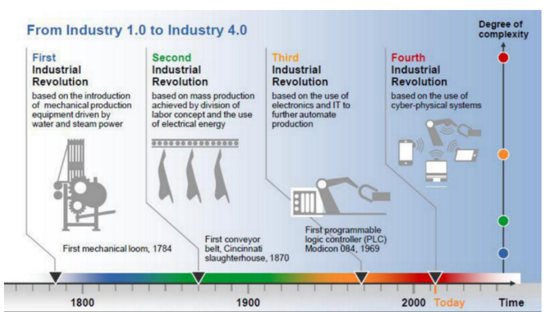
Today we are in the midst of the fourth phase of the industrial revolution, where value chains are connected end-to-end via dynamic data processing and cyber-physical systems that link the physical world and cyberspace via internet. Machines have begun to manage themselves and production processes in smart factories without the need for a labor force or involvement. The concept of Industry 4.0 was first introduced at the Hannover Trade Fair in 2011 as part of Germany's 2020 High Technology Strategy Action Plan. Industry 4.0 refers to the integration of technologies such as information, communication, internet, automation, data collection and analysis with new production and distribution functions.

Although technology has been the main contributor to the emergence of the Fourth Industrial Revolution, there are other factors that can be grouped under four main headings, which are regional trends (increase in social interaction and trade between countries), economic trends (emerging new powerful economies and increasing globalization via financial resource flows), technological trends (increasing connectivity and developing platform technologies) and commodity trends (increasing scarce resources, increasing concerns about environment and security)[2].

In addition to these, in his book *The Zero Marginal Cost Society: The Internet of Things, the Collaborative Commons, and the Eclipse of Capitalism*, Jeremy Rifkin (2014) posits that the capitalist era is closing, not quickly but inevitably. He calls this new age following the capitalist era "Collaborative Commons". With Industry 4.0, supply chain processes will be more flexible, efficient and apt for collaboration which helps to reduce costs and increase quality[3].

The stages of industrial revolutions and their distinctive features are summarized in Figure 1.

Figure 1: Stages of the Industrial Revolutions



Source: Liang, S. et al (2018). Intelligent Manufacturing Systems: A Review, International Journal of Mechanical Engineering and Robotics Research, 7(3): 325.

2 TÜSİAD, (2016). Türkiye'nin Küresel Rekabetçiliği İçin Bir Gereklilik Olarak Endüstri 4.0 Gelişmekte Olan Ekonomi Perspektifi, Rapor, http://www.tusiad.org/indir/2016/sanayi-40.pdf, (Accessed on: 21.02.2019).

3 Altuk Özden, V. E. (2018). Endüstri 4.0 ve Uluslararası Finansal Raporlama Standartlarına Etkileri, Süleyman Demirel Üniversitesi İktisadi ve İdari Bilimler Dergisi, 23: 1640.

2.1 Industry 4.0

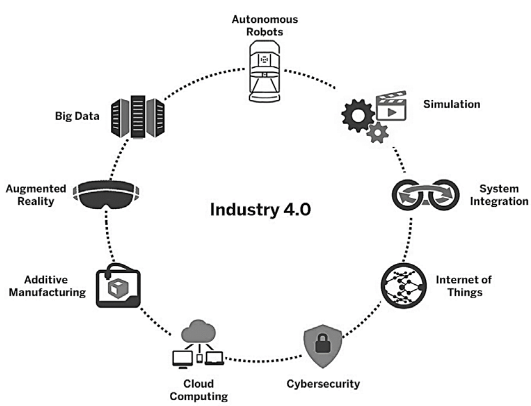
Industry 4.0 is a conception that basically aims the integration of production with Information Technologies[4]. Beyond the automation of the enterprises themselves, it is a smart and self-adapting industry integration strategy in which all value chain members are in real-time and continuous communication with each other.

In the new world promised by Industry 4.0, the machines, computers, sensors and integrated computer systems in the factories will simultaneously and continuously exchange information with each other, and they will be able to produce by managing themselves, with almost no need for people. This simultaneous information sharing and self-decision capability of the machinery and computer systems will reduce production time, energy, raw material and labor costs while increasing production quantity and quality. Each product will have its own serial number, or identity, which will provide information about the product's history (production location, raw material properties, usage-repair-maintenance specifications, etc.). These products will be continuously connected to the Internet just like the machines by which they are manufactured and will be able to physically react to the environment they are in with their sensors, and will be able to exchange information in real time with other devices connected to the Internet all over the world. Considering all these changes together, we might suggest that when Industry 4.0 is accomplished, not only factories and industry, but also all individuals and societies will be affected.[5]

2.2. Enabling Technologies of Industry 4.0

Technologies and applications that enable Industry 4.0 are summed up in Figure 2.

Figure 2: Industry 4.0 Technologies



Source: Örücü, E.O. (2016). Her Şey İnsan Yararına, TMMOB Elektrik Mühendisleri Odası Elektrik Mühendisliği Dergisi, 459: 21.

4 Manavalan, E., Jakakrishna, K., (2019). A Review of Internet of Things (IoT) Embedded Sustainable Supply Chain for Industry 4.0 Requirements, Computers Industrial Engineering. 127: 933.

5 Börteçin, E. (2014). 4. Endüstri Devrimi Kapıda mı?, Bilim ve Teknik, Mayıs, 27.

Internet of Things (IoT): 'Things' for Industry 4.0 refers to any physical substance, such as a system, device, product. For example, refrigerators, bus stops, vehicles, ventilation systems, production machines, etc. can make conclusions by use of "artificial intelligence" operated by the information hardware and software embedded and act accordingly. Since the communication medium in the Internet of Things is the Internet, the need to confine the objects to a certain limited area is eliminated. Through the Internet of Things, machines and cyber-physical systems can access databases of globally dispersed suppliers, manufacturers and distributors, thereby all processes on the supply chain can communicate with each other. For instance, thanks to the Internet of Things, it is possible to place an order with suppliers in different countries for the reduced raw material stock of a product produced in a country, without the need for human intervention, and it can be ensured that the desired amount of raw materials are included in production just in time and efficiently.[6] In addition to the concept of Internet of Things-IoT, the concept of Internet of Services-IoS has also begun to be used. Internet of Systems-IoS, is a concept that encompasses IoT and CPS (Cyber Physical Systems) together. It refers to the integration of web and service-based information technologies with the value chain that produces not only goods but also services.[7]

Big Data and Analytics: The term big data refers to data sets that are too large or too complex to be analyzed by traditional methods. Traditionally, companies tend to make business decisions based on the data obtained from various sources, such as production records, financial records and market research reports. However, the data used in decision making is now obtained from many different and new sources, such as the sensors of smart products (especially thanks to the Internet of Things), websites, search engines and social media sites (e.g., Google, Facebook, Twitter). Data collected and stored systematically from these new sources is called big data.[8] Distinguishing properties of big data are defined by 4V, Volume, Variety, Velocity and Veracity. Developments in information technologies and decrease in data storage costs have popularized the use and analysis of big data. With the analysis of big data, the trends in customer demands can be predicted, and strategic plans and evaluations can be made based on these predictions.

Smart Robotics: Robots are programmable, multi-purpose, stationary or mobile machines that can provide autonomous control. Robots can solve the problems they encounter within their own programs installed by humans. Smart robots, on the other hand, update their programs with their past experiences and develop different attitudes and solutions to new situations and problems without the need for human intervention.

Vertical and Horizontal Integration: In Industry 4.0, vertical integration is a digital system integration where entire in-house processes (starting from product design, procurement, production, marketing, distribution, etc.), machines, workstations, computers and all means of production are

6 Kaygın, E. et al. (2019). Endüstri 4.0'a Akademik Bakış, Atatürk Üniversitesi İktisadi ve İdari Bilimler Dergisi, 33(4): 1070.

7 Reis, J. Z., Gonçalves, R.F. (2018). The Role of Internet of Services (IoS) on Industry 4.0 through the Service Oriented Architecture (SOA). IFIP WG 5.7 International Conference, APMS 2018, Seoul, Korea, August 26-30, 2018, Proceedings, Part II. p.3.

8 Yıldırım, Y. (2019). Endüstri 4.0'a Kapsamlı Bir Bakış: 2011'den Bugüne, Bilgi Dünyası, 20(2): 232

connected and communicated through the Internet of Things.[9] Horizontal integration, on the other hand, is a digital system integration of each production and planning process of the enterprise with the equivalent production and planning processes of other members on the value chain in order to ensure the eliminate waste and maximize flow. For instance, product design, manufacturing and shipment processes of the companies on the supply chain can be integrated with each other through their digital systems. End-to-end engineering refers to the integration of the entire product life cycle from beginning to end. It is the integration of the same interfaces of systems and processes within the factory with the end-to-end digital engineering systems and the systems of all value chain members including customers. It can also be expressed as the incorporation of vertical and horizontal integration.

Cloud Computing: Cloud computing technologies ensure that all data owned by companies are stored on a virtual server, that is, in the cloud, and that the data is accessible when needed through internet-connected devices.[10]

Cyber Security: Every device using an Internet system is vulnerable to cyber-attacks. With cyber security technologies, only permitted computer systems can connect to the existing network and transactions are encrypted to prevent cyber-attacks. These cyber security risks that can be encountered in both horizontal and vertical integration processes can be in the form of theft or alteration of personal or corporate data and information as well as possible cyber interventions in production lines and machines, which may lead to life-threatening conditions, disruption or full stop of production.[11]

Additive Manufacturing (3D Printing): It is the construction of a physical 'three-dimensional' object by printing layer by layer from a digital three-dimensional model.

Augmented Reality (AR): Augmented reality is defined as the transformation of objects in the physical world into sound, video, graphic and GPS data with computer-based sensors.

Simulation: Simulation, which can be described in its simplest form, imitation of real life combining many of the Industry 4.0 technologies. For example, the data regarding demands and expectations of customers, which are collected and processed via big data and analytics, can be modeled by simulations to evaluate how it might change in the future or how different attitudes of companies might affect customers. Smart factories can pre-adapt their production to changing conditions thanks to simulation models. Along with augmented reality, simulation applications are particularly beneficial for repair-maintenance and training services.

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9 Duarte, S., Cruz-Machado, V. (2017). An Investigation of Lean and Green Supply Chain in the Industry 4.0, Proceedings of the 2017 International Conference on Industrial Engineering and Operations Management (IEOM). Bristol, UK. p.259.

10 Annaç Göv, S., Erdoğan, D. (2020). Dördüncü Endüstri Devriminin (Endüstri 4.0) Neresindeyiz?, İstanbul Gelişim Üniversitesi Sosyal Bilimler Dergisi, 7(2): 302.

11 Yoşumaz, İ., Özkara, B., (2019). Endüstri 4.0 Sürecinin Hazır Giyim İşletmeleri Üzerindeki Etkileri: Hugo Boss Türkiye Örneği, İşletme Araştırmaları Dergisi, 11(4): 2591.

Cyber-Physical-Systems (CPS): The systems that connect the physical world and the cyber space via the Internet are called cyber-physical systems. Virtual elements can be transferred to outputs that easy to understand and ideas can be transferred to machines to be implemented. It is possible for both elements to act together in a coordinated manner.[12]

Smart Factories: The application of Cyber-Physical Systems (CPS) in production systems is called Cyber-Physical Production Systems (CPPS) or Smart Factories.[13] Smart factories are flexible systems that can adapt their operations to new conditions in real or near-real time, learn from their experiences, and fulfill entire production processes autonomously.[14] The new generation smart factories where product-related data are stored and shared, production and planning are carried out by smart robots without the need for human intervention. Similarly, the reverse process from the customer to the raw material supply as well as from raw material to product phase and even to the recycling processes after the use of the product is planned using big data. In this way, labor costs might be reduced to almost zero, most of the human-induced errors might be prevented while speed and flexibility in production might be increased, and much more efficient output might be obtained with unmanned production in safety – or health-threatening sectors.

3. The Evolution of Supply Chain Management and Sustainable Supply Chain

The history of supply chain dates back to the 1960s. The pioneering discourse about the "physical distribution stage", which is considered the first stage of supply chain management, belongs to Donald J. Bowersox, who is the author of the book "Supply Chain Logistics Management". In his book published in 1969, Bowersox argued that fulfilling the distribution function outside the company with intra-channel integration would provide a competitive advantage, which emphasizes the logistics function of the management of supply chain.

In the 1970s, the effect of high inventory levels on total production costs as well as product quality and delivery time gained attention, and it was apparent that in coordination with suppliers and distributors negatively affected customer satisfaction and costs.[15] During this period, Material Requirements Planning (MRP) method, which combined production planning and purchasing, was developed. Companies established a central physical distribution department that carried out marketing, production and financing-related distribution activities within themselves and have adopted a management approach that combined the logistics management of the entire system instead of optimizing the logistics of each activity separately. As the supplier and materials management functions were integrated with physical distribution, a new paradigm called Supply

12 Alçın, S. (2016). Üretim İçin Yeni Bir İzlek: Sanayi 4.0, Journal of Life Economics, 3(8): 23.

13 Rudtsch, V., Gausemeier, J., Gesing, J., Mittag, T., Peter, S. (2014). Pattern-based Business Model Development for Cyber-Physical Production Systems, Procedia CIRP, 25: 314.

14 Coşkun Arslan, M., Demirkan, S. (2019). Endüstri 4.0 ve Muhasebe Sistemine Etkisi Üzerine Kuramsal Bir İnceleme, Enderun Dergisi, 3(1): 45.

15 Güleş, H.K., Paksoy, T., Bülbül, H., Özceylan, E. (2009). Tedarik Zinciri Yönetimi, Stratejik Planlama, Modelleme ve Optimizasyon, Gazi Kitabevi, p.2.

Chain Management (SCM) emerged.[16] In his book "International Supply Chain Management", J.B. Houlihan brought a new holistic perspective to the supply chain by combining the firm's strategic decisions with the physical distribution focus.[17]

The increasing global competition in the 1980s forced companies to reduce costs and increase product quality and diversity. At that time, the storage and transportations processes took %70 of the total production time starting from raw materials to the phase when the product is available to customers.[18] In his book 'Competing Through Supply Chain Management' published in 1998, David Frederick Ross describes this phase as the integration of logistics, which combines distribution, transportation and material management to shorten lead time and reduce costs.

The 1990s was a period when the agile supply chain concept was expressed by combining agile production systems with supply chain management. Quick response production and supply chain management, which emerged in response to rapidly changing customer expectations and needs under increasingly competitive conditions, enabled companies to adapt to changes with sufficient flexibility and reduced cycle time and costs by taking advantage of new strategies and new technologies.[19] Rapid innovations in technology and the density of competitive conditions triggered companies to change their understanding of supply chain management. The 1990s is the period when lean production and lean management philosophy became widespread following agile production. Lean manufacturing originated from the Toyota Production System (TPS) established by Taiichi Ohno and Shigeo Shingo. The lean supply chain was the evolution of the lean production philosophy pioneered by Toyota Motor Company, which highlighted the uninterrupted transfer of value throughout the value chain, starting from raw materials, and quickly arriving to end users.[20]

By the 2000s, some threats to nature, such as changes in climatic conditions, industrial wastes, and increasing energy consumption have been motivating individuals, non-governmental organizations and governments as well as companies. The increasing amount of production have led to the running out of scarce natural resources. Consequently, the value of renewable resources and the issue of production using less harmful methods have gained importance and green supply chain has inevitably come to the agenda of companies. Green supply chain aims to increase the profitability and market share by increasing the ecological efficiency of enterprises and all stakeholders on the chain, and prioritizing the reduction of environmental impacts and risks.[21]

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16 Çetin, O., Knouch, M. (2018). Sustainable Competitive Advantage in Green Supply Chain Management, in Çalıyurt, K.T., Said, R. (Eds.). Sustainability and Social Responsibility of Accountability Reporting Systems. Accounting, Finance, Sustainability, Governance & Fraud: Theory and Application. Springer Nature Singapore Pte Ltd. p.356.

17 Özdemir, A.İ. (2004). Tedarik Zinciri Yönetiminin Gelişimi, Süreçleri ve Yararları, Erciyes Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, 23: 90.

18 Güleş, H.K., Paksoy, T., Bülbül, H., Özceylan, E., 2009, .3.

19 Uçal Sarı İ., Çayır Ervural, B., Bozat, S. (2017). Sürdürülebilir Tedarik Zinciri Yönetiminde DEMATEL Yöntemiyle Tedarikçi Değerlendirme Kriterlerinin İncelenmesi ve Sağlık Sektöründe bir Uygulama, Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi, 23(4): 479.

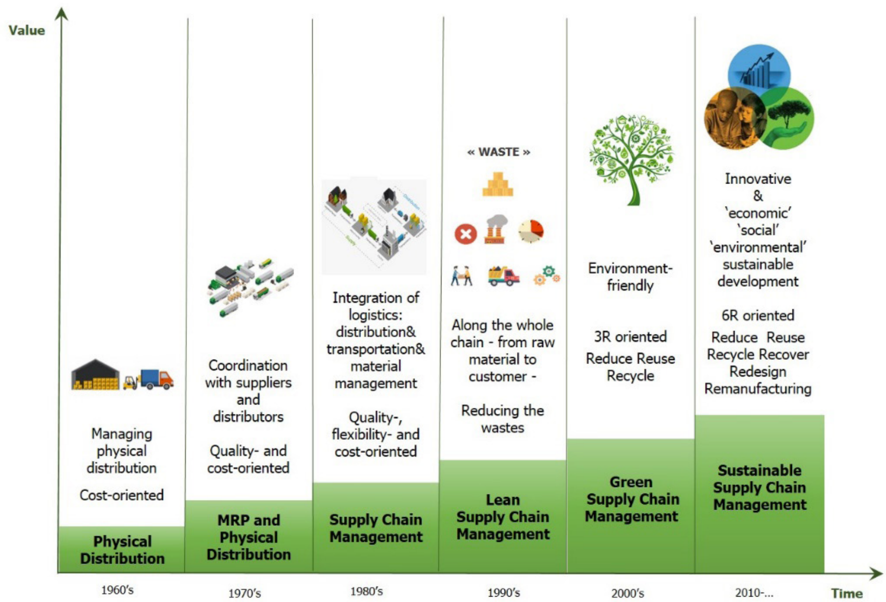
20 Akben, İ. Güngör, A. (2018). Tedarik Zinciri ve Yalın Tedarik Zinciri, Avrasya Sosyal ve Ekonomi Araştırmaları Dergisi (ASEAD), 5(7): 3.

21 Duarte, S., Cruz-Machado, V. (2018). Exploring Linkages Between Lean and Green Supply Chain and the Industry 4.0, Proceedings of the Eleventh International Conference on Management Science and Engineering Management, Lecture Notes on Multidisciplinary Industrial Engineering, p.1246.

Today, instead of the green supply chain approach, which focuses solely to protect the environment, sustainable supply chain approach has become more dominant because it functions in line with 'economic', 'environmental' and 'social' dimensions of sustainable development for managing materials, information and money flow to meet the expectations of customers and chain partners.[22]

The historical development of Supply Chain Management, beginning from the physical distribution approach in the 1960s until today, is summarized in Figure 3.

Figure 3: The Historical Development of Supply Chain Management



3.1 Sustainability and Sustainable Supply Chain

Sustainability was defined as 'meeting the needs of today without compromising the ability of future generations to meet their own needs' in the Common Future report published by the United Nations in 1987.[23] The value of renewable resources and the issue of production using less harmful methods to nature have gained importance as the world cannot be a place to live without the sustainability of natural resources and the cooperation of all individuals, states and companies. Therefore, sustainability and its environmental dimension have become an important concept for companies.

Sustainability is addressed in three categories, which are economic, social and environmental dimensions. Environmental sustainability is about taking care of the health of the ecosystems that provide resources while meeting the resource and service needs of current and future generations.

22 Seuring, S., Müller, M. (2008). From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management, Journal of Cleaner Production, 16: 1699.

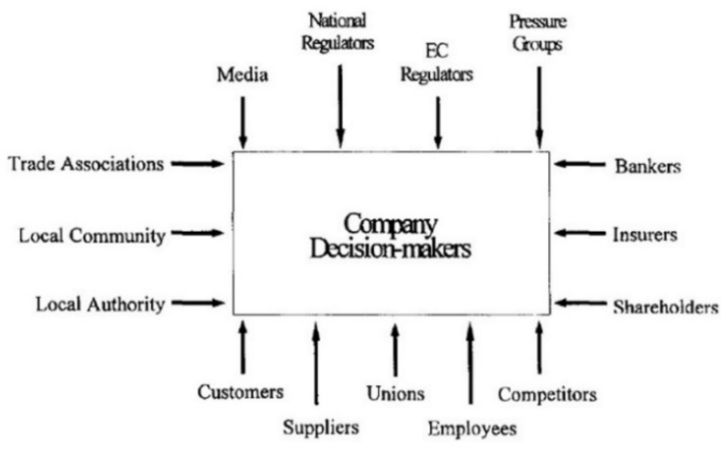
23 Özenir, İ., Nakıboğlu, G. (2019). Sürdürülebilir Üretimde Endüstri 4.0'ın Yeri, BMIJ, 7(5): 2257.

The environmental dimension focuses on the compatibility between the trend of use and renewal of resources in nature. Regarding the companies, this dimension also includes the manner of 'consuming just the natural resources that can be reproduced by nature, as well as producing emissions that can be absorbed naturally by the existing ecosystem'.[24] The economic dimension is related to the effect of cost and income distribution in relation to production and consumption activities on the economic welfare of the society. The social dimension is related to the effect of consumption on personal well-being; involves human rights, employee rights and corporate governance and refers to ensuring that future generations have access to social resources as much or more than the current generation.[25]

Sustainable Supply Chain Management is the provision of material, information and capital flow under economic, environmental and social objectives and it aims to meet the expectations of all stakeholders in the supply chain network ranging from suppliers to customers.[26] In Sustainable Supply Chain, from product design, raw material supply, production, distribution, use to end-of-life processes and waste, the entire process should be rearranged with environmentally friendly practices by using environmentally sensitive materials in all processes along the chain, reducing carbon emissions, minimizing pollution with waste management activities and recycling.

There are many factors that encourage companies to transform their supply chains into a sustainable supply chain (see fig. 4).

Figure 4: Factors Driving Businesses to Sustainability



Source: De Ron, A.J. (1998). Sustainable Production: The Ultimate Result of a Continuous Improvement, International Journal of Production Economics. 56-57: 101.

24 Braccini, A.M., Margherita, E.G. (2019). Exploring Organizational Sustainability of Industry 4.0 under the Triple Bottom Line: The Case of a Manufacturing Company. Sustainability 2019, 11(36): 2.

25 Bilgili, M.Y. (2017). Ekonomik, Ekolojik ve Sosyal Boyutlarıyla Sürdürülebilir Kalkınma, Uluslararası Sosyal Araştırmalar Dergisi, 10(49): 563.

26 Chelmata, R., Santos-de Leon, N.J. (2020). Sustainable Supply Chain in the Era of Industry 4.0 and Big Data: A Systematic Analysis of Literature and Research, Sustainability, 12(10): 3.

The main purpose of companies is to reduce costs and increase the flexibility and efficiency of production to gain a long-term competitive advantage. With the development of an environmentally friendly management approach, energy and resource efficiency, increasing productivity, shortening innovation and marketing cycle times, horizontal and vertical integration and end-to-end digital integration of engineering on the entire value chain have also been included in business objectives. Industry 4.0 has the potential to create positive sustainability impacts across the entire value chain by providing solutions to economic problems by increasing efficiency and customizing products for customers with a transparent and traceable supply chain. Due to these developments, it might be suggested that the Industry 4.0 paradigm is a step towards creating more sustainable industrial values.[27]

3.2 Closed Loop Product Life-cycle and 6R

The product life-cycle refers to all the processes that a product goes through, from the idea phase, material supply, production, sales, after-sales services to after use. Product life-cycle management, on the other hand, is the system that allows all companies on the chain to register and track information of all of these phases with a common software.

The implementation of a closed loop product life-cycle system in environmentally friendly supply chains is an important tool to ensure sustainability.[28] With the closed-loop product life cycle, the aim is to improve environmental and social impacts as well as the economic benefits in the traditional form in all processes in the chain, starting from the design of the product, purchasing, production, storage, distribution and after-sales services.[29] Traditional supply chains can be classified under two categories based on the stages of the product lifecycle, which are forward and reverse supply chains. Forward supply chains generally include a series of processes related to obtaining the final product from raw materials and activities related to the delivery of these products to customers. Reverse supply chains, on the other hand, include the collection of products from the end user and transporting them to the separation facilities, testing the product in order to determine the condition of the product and the most economically effective reuse option, classification and separation processes, economically the most suitable recovery (repair, re-production, reuse, recycling) or selection and practice of disposal methods, and remarketing and distribution activities for recovered products.[30] The closed loop product life cycle system, which enables sustainability in the supply chain, incorporates forward and reverse supply chain processes.

27 Toker, K. (2018). Endüstri 4.0. ve Sürdürülebilirliğe Etkileri, İstanbul Management Journal, 29(84): 56.

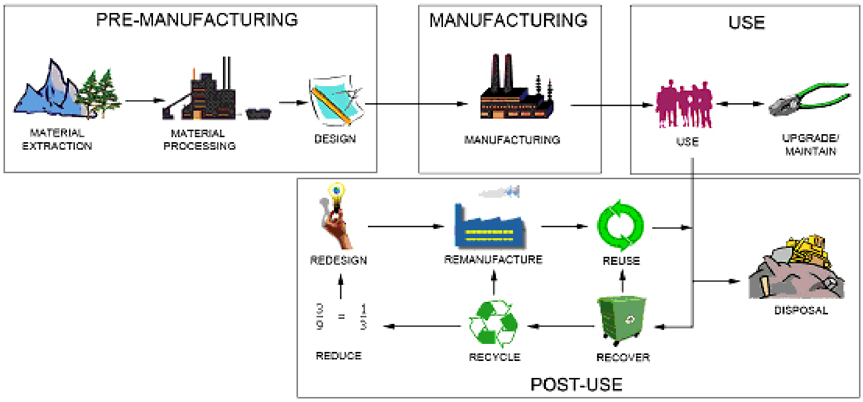
28 Yadav G., et al. (2020). A Framework to Overcome Sustainable Supply Chain Challenges through Solution Measures of Industry 4.0 and Circular Economy: An Automotive Case, Journal of Cleaner Production, p.4.

29 Badurdeen, F. (2015). Planning, Design and Management of Supply Chains for Sustainability, Proceedings of the Measurement Science for Sustainable Construction and Manufacturing Workshop Volume I, Position Papers and Findings, p.8.

30 Kaya, A., Alumur Alev, S. (2014). Kapalı Döngü Tedarik Zinciri Ağı Tasarımı. 14. Üretim Araştırmaları Sempozyumu (ÜAS 2014) İstanbul. Bildiri Kitabı. p.270.

Closed loop product life cycle system can be handled in four main stages, which are pre-production, production, use and post-use (See Fig.5).[31]

Figure 5: Closed Loop Product Life-cycle System Showing the "6Rs" for Perpetual Material Flow



Source: Jawahir et al., 2006, p.3.

Pre-manufacturing: The first step in the life cycle of a product is to obtain raw materials from nature. Raw material supply refers to the extraction of valuable raw materials from the layers of the earth's crust, and the collection of raw materials from sources, such as land, forests, water, etc. These extracted raw materials are then processed and consumed in the production processes of the end product. Pre-manufacturing also includes the packaging, storage and transportation of semi-finished products. The design of the product is also an important pre-manufacturing phase for the closed loop product life cycle system.

Manufacturing: It is the stage where raw materials and semi-finished products are transformed into finished products to meet consumer demands. Packaging, storage, distribution and promotion activities of finished products are also considered a part of the manufacturing stage.

Use: The use phase in the product life cycle is primarily related to the time the consumer owns and operates the product. During the use phase, the operation and the service-maintenance-repair of the product when necessary are required to be energy efficient and safe. It is important for sustainability because the product can be upgraded to compete with newer models and therefore, can last longer. Product use will end when one or more of the desired features of the product become insufficient to meet consumer's needs.

Post-use: It is the final processing stage for the disposal, recycling, reuse or other end-of-life processes of the product when the product reaches the end of its life, where it can no longer satisfy consumer needs. With the "6R" strategy, it is aimed to extend the product life cycle and ensure sustainability at this stage.

31 Jawahir, I.S., et al. (2006). Total Life-cycle Considerations in Product Design for Sustainability: A Framework for Comprehensive Evaluation. In Proceedings of the 10th International Research/Expert Conference, Barcelona, Spain, p.3.

In previous years, closed system product lifecycle management in green supply chains was traditionally defined with 3R 'reduce, reuse and recycle', while in sustainable supply chains 'recover, redesign, remanufacturing' strategies were added to these practices and the definition has been expanded to 6R strategy.

Reduce signifies designs that will reduce the need for resources during the design phase, techniques to reduce material and energy consumption and waste during the production phase, and practices for reducing waste for use and post-use phases.[32] With the reduce strategy, benefits such as cost reduction, gaining costumer's reputation and fulfillment of environmental regulations will also be achieved.

Reuse refers to the reuse of the parts of the product or the whole product itself, with little or no change.[33]

Recycle is the conversion of used and waste material into a new raw material or product.[34]

Recover is the process of collecting the product at the post-use phase and disassembling, classifying and cleaning the product for re-use in later life cycle stages.[35]

Redesign is improving next generate product through innovative techniques to facilitate recovery, reuse or reduce of products and materials.[36]

Remanufacturing involves the re-processing of used products or components without loss of functionality. It involves disassembling a used and returned product in its life cycle, repairing and reusing some parts after check, replacing some parts with new ones and producing a product that is "as good as new" in terms of quality, features and performance after reassembly.[37] The difference between manufacturing and remanufacturing is that the materials used in manufacturing are used for the first time whereas the sub-components of the product in remanufacturing consist of previously used raw materials and parts.

The practice of 6R in sustainable supply chain processes can make great contributions to the constant re-integration of products into the life cycle and thus minimize the ecological footprint.

4. Industry 4.0 and Sustainable Supply Chain

In order to be able to use closed-loop product life cycle management systems in sustainable supply chains and to implement 6R, which will minimize the damage caused by chain activities to the

32 Kuik, S.S., Nagalingam, S.V., Amer, Y. (2011). Sustainable Supply Chain for Collaborative Manufacturing, Journal of Manufacturing Technology Management, 22(8): 993.

33 Rosenthal, C., Fatimah, Y.A., Biswas, W.K. (2016). Application of 6R Principles in Sustainable Supply Chain Design of Western Australian White Goods, Procedia CIRP, 40:318.

34 Jawahir, I. S., Bradley, R. (2016). Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing, Procedia CIRP, 40:104.

35 Jawahir, I.S., et al (2006). Op cit. p.4.

36 Jawahir, I. S., Bradley, R. (2016). Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing, Procedia CIRP, 40: 104.

37 Reimann, M., Xiong, Y., Zhou, Y. (2019). Managing a Closed-loop Supply Chain with Process Innovation for Remanufacturing, European Journal of Operational Research, 276(2): 512.

environment, companies should pay attention to the issues covered by the three dimensions of sustainable development as well as having sufficient technological capability. The use of Industry 4.0 technologies in companies will enable sustainable supply chains to optimize their environmental, economic and social performance targets.

Industry 4.0 makes work processes more flexible, economical and environmentally friendly by transforming supply chain elements into a smart system based on cyber-physical interactions. Industry 4.0 contributes to the development of a global network of cyber-physical machines, equipment, sensors and facilities to improve data sharing, analysis and control of industrial systems. In addition, with the utilization of Industry 4.0 technologies, it is possible to monitor and control important production parameters such as production status, energy consumption, material flow, customer orders and supplier data in real time.[38]

The differences between sustainable supply chain functions and traditional supply chain functions and the contributions of Industry 4.0 technologies to these functions can be summarized as follows:

Product Design: In sustainable supply chains, the product design stage should be held with care so that the product components would not contain harmful contents to human health and nature. The durable design that will allow the product to be used for a long time will reduce the amount of waste after use. It is also important that these raw materials and supplies are compatible with 6R practices, especially with reuse and re-manufacturing. The reduction of materials used in product and packaging content is as important as the use of environmentally friendly materials in terms of sustainability. Contrary to a production manner that consumes nature by using new resources, redesign practices allow the reuse of resources for product designs.

Using the Internet of Things as an Industry 4.0 technology, it becomes possible to track the product throughout its life cycle will facilitate 6R practices.[39] In the design phase, attention should be paid to the design of smart products that will enable the Internet of Things. With the help of simulation, the compatibility of the materials to be used in the product with 6R practices and their impact on human health and on the environment can be tested. Thanks to the horizontal and vertical integration, 6R-compatible product design information can be shared with internal processes. In addition, the information of the design processes of other stakeholders in the supply chain can be shared and the efficiency of sustainability factors that can be achieved with the closed-cycle product life cycle, such as reduction and reuse might be ensured on the entire chain. Cloud technology, big data and analytics are important prerequisite technologies for data sharing in horizontal and vertical integration just as the cyber security is very important for the safety of the shared data throughout the supply chain.

Sourcing/Procurement and Purchasing: It is important to choose suppliers that use environmentally friendly production technologies and materials in the sourcing and purchasing stages in the sustainable supply chain. Environment-friendly materials should be selected in raw material and

38 Yıldız A. (2018). Endüstri 4.0 ile Bütünleştirilmiş Dijital Tedarik Zinciri. BMIJ, 6(4): 1217.

39 Ghobakloo, M. (2020). Industry 4.0, Digitization, and Opportunities for Sustainability, Journal of Cleaner Production, 252: 3.

supplies purchasing and environment-friendly technologies should be preferred in purchasing the production technologies as well. Priority should be given to machines and systems that will reduce carbon emissions, energy consumption and waste. 6R practices should also be prioritized in purchasing decisions. For example, by choosing recovered, recycled or reused raw materials and supplies in material purchases, the product life cycle will be extended and the use of resources and waste will be reduced throughout the supply chain. In terms of social sustainability, companies that meet the sustainability criteria for labor conditions should be selected and labor working conditions should be clearly defined in procurement contracts. It may also be preferable to work with suppliers from underdeveloped countries or regions to ensure economic sustainability since inequality of income distribution between countries or regions might be reduced to some extent.

Horizontal and vertical integration of Industry 4.0 technologies plays a major role in the performance of sustainability in the purchasing process. In addition to tracking whether the raw materials used and the products produced are harmless to the environment, regularly monitoring of the labor working conditions might force suppliers to improve their working conditions. Additive manufacturing technologies might make it possible to work with suppliers in much more distant regions and help backward regions with economic sustainability. Thanks to big data and analytics, it will be possible to compare many alternative suppliers and materials, which will increase economic sustainability efficiency by choosing lower cost alternatives. The Internet of Things, real-time tracking of raw material and supplies usage in production processes will be possible, which means that the time and amount of the material needed could be shared simultaneously with horizontally integrated suppliers, and that suppliers could work with less inventory and shorten delivery times.[40]

Production: With the design of production processes and technologies that will reduce waste generation, energy and raw material use, the efficiency of the environmental dimension of sustainability of the supply chain will be achieved. It will also contribute to economic sustainability as the costs will be reduced as a result of reducing the use of energy, raw materials and supplies. In traditional supply chains, production management focuses only on the increase of production or cost minimization where labor working conditions might go unnoticed. The social dimension of sustainability focuses on issues such as improving social opportunities including working conditions, wages, and health rights of the workforce utilized in production processes. Social sustainability requires fair employment of diverse groups within society with respect to gender, age, etc. Providing equal employment opportunities to diverse groups of society, being fair in remuneration and additional social rights while planning workforce in production processes is an issue that companies should pay attention to. Production in different regions and the fair allocation of employment to the regions is important for economic sustainability.

Thanks to the fast and transparent data sharing with horizontal and vertical integration of Industry 4.0 practices in production processes, wastes from defective production, overproduction, etc. might be greatly reduced. With the use of smart robotics and smart factories, production processes that

40 Luthra, S., Mangla, S. K (2018). Evaluating Challenges to Industry 4.0 Initiatives for Supply Chain Sustainability in Emerging Economies, Process Safety and Environmental Protection, 117: 170

pose a threat to human health or life can be practiced without human need. The Internet of Things and cyber-physical systems may simplify the monitoring of all stages of the product in real time and malfunction or unnecessary waiting could be immediately intervened. With the incorporation of technologies such as the Internet of Things, cyber-physical systems, big data and analytics, simulation, etc., it will be possible to track the increasing or decreasing trends in demands and production levels might be updated accordingly.[41] Thus, the damage to the environment will be minimized by reducing unnecessary resource consumption. It will be possible to significantly reduce inventory levels thanks to the real-time adaptation of production and predicted demand changes, which can be monitored in real time with smart factory applications. Since additive manufacturing technologies will eliminate the necessity of making all stages of production in the same place, part of the production can be shifted to underdeveloped regions or countries.[42]

Distribution: The distribution function in the supply chain includes distribution from the supplier to the production unit and from the production site to the distributor, retailer, customer and consumers. In sustainable supply chains, the distribution function is particularly effective in environmental sustainability. While cost minimization is the main target in traditional supply chains by deciding transportation type to be used in distribution; alternatives that will cause the least damage to the environment are preferred in sustainable supply chains. Especially in road transport, the type of fuel used in vehicles is important in terms of environmental sustainability. Since the number of trips in distribution will directly affect the fuel consumption of vehicles, mathematical models are used for careful planning to minimize the number of trips jointly by different stakeholders on the supply chain.

The Internet of Things enables simultaneous tracking of materials and products that will participate in distribution at all stages throughout the supply chain. Thanks to horizontal integration and cloud computing, the data is made accessible to all chain partners so that distribution vehicles could be used by different companies in product distribution. Since these technologies make the sharing of demand and production information at different stages of the chain simultaneously available to the whole chain, the future needs could be recognized in advance and added to the distribution planning. Equipping distribution vehicles with cyber-physical systems, such as navigation applications, will also reduce travel time.

Costumer-Use: The customer, who demanded that the product and the processes that the product goes through throughout the life cycle should comply with the sustainability dimensions, has been particularly effective in transforming the supply chain from traditional manner to sustainability. By preferring products that do not contain raw materials and materials that are harmless for human health and environment, by choosing brands that comply with the social sustainability conditions such as proper working conditions, by not buying products from brands that use harmful manufacturing technologies; customers could also act as an auditor of sustainability practices in the supply chain.

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41 Bag, S., Telukdarie, A., Pretorius, J.H.C., Gupta, S (2018). Industry 4.0 and Supply Chain Sustainability: Framework and Future Research Directions, Benchmarking: An International Journal, p.11.

42 Moktadir, Md. A., Mithun Ali. S., Kusi-Sarpong, S., Ali Shaikh, M.A. (2018). Assessing Challenges for Implementing Industry 4.0: Implications for Process Safety and Environmental Protection, Process Safety and Environmental Protection, 11: 732.

Big data and analytics play a major role in Industry 4.0 and are seen as key 'game changers' especially for the sustainable supply chain management.[43] With big data and analytics applications, customers can access great amount of data about supply chains. With the Internet of Things, it is possible to get access to information in which country the product to be purchased is manufactured, which country the materials used are from, and what the content of the product is. In addition, thanks to the augmented reality technology, customers who get the opportunity to experience the product before the actual purchase will be able to predict its benefits during use and will be able to choose the most suitable product for themselves. It will be possible to guide customers on issues such as next product preferences, re-purchases by processing the data related to the customer's current usage experiences through simulation and big data and analysis. In this case, cyber security is a very important prerequisite technology.

Post-use – Reverse Logistics: The most prominent point where the sustainable supply chain differs from traditional manner is the 6R strategies. With the closed-loop product life cycle, supply chain management does not end when the product reaches the customer, it is re-included in the value chain post-use with practices such as recycling, recovery, re-manufacturing, and reuse. In this way, first of all, the harm that will occur as a result of disposing the product or its components as garbage will be reduced. In addition, with the re-incorporation of this product or its components into the value chain as raw materials, the inputs required for producing these materials once again will be reduced. Maintenance and repair activities of the product also determine the environmental, economic and social dimensions in the sustainable supply chain in the post-use phase. Promoting consumption and re-purchasing in line with the growth target of economies causes consumption of natural resources at an irreversible level. Companies will support economic, social and environmental sustainability from a different perspective by offering maintenance and repair services to their customers that will ensure long-term use of their products and also increasing employment in these services. At this stage, just like the forward logistics operations in the distribution stage, the environmental harm of the distribution operations should be minimized in the reverse logistics stage. The fuel that will cause the least damage to the environment is preferred in the vehicles to be used, and the number of trips should be reduced as it directly affects the fuel consumption.

It will be possible to increase the quality of these services with the use of augmented reality technology in maintenance and repair services in the post-use phase. Increasing the quality of services such as repair and maintenance will prolong the life of the product and prevent waste generation.[44] Thanks to additive manufacturing, it will be possible to produce the materials required for these services at the place of use, so fuel consumption for transport will be reduced. In reverse logistics phase, with the horizontal integration and Internet of Things, it will be possible to gather products from their locations after use and send them to value chain levels where they can be re-utilized with 6R applications.[45] As in all other stages where Industry 4.0 technologies are utilized, in the reverse

43 Hahn, G.J. (2020). Industry 4.0: A Supply Chain Innovation Perspective, International Journal of Production Research, 58(5):1426.

44 De Man, J.C., Strandhagen, J.O. (2017). An Industry 4.0 Research Agenda for Sustainable Business Models, Procedia CIRP, 63:722.

45 Stock, T., Seiger, G. (2016). Opportunities of Sustainable Manufacturing in Industry 4.0, 13th Global Conference on Sustainable Manufacturing. Procedia CIRP, 40:5.

logistics stage, cyber-security technology is of utmost importance to the successful implementation of Industry 4.0 principles.

5. Conclusion

The developments in information technologies and their integration with industry have marked the beginning of the Fourth Industrial Revolution. It is apparent that the technological changes experienced in this period, which is also called Industry 4.0, will significantly affect not just industry but also individuals and society as a whole. However, technological and industrial developments bring about some harmful effects while making human life easier. The growing populations of countries and their changing consumption habits trigger an increase in production. The increase in production leads to an increase in industrial waste generation and consumption of natural resources. Changes in climatic conditions and industrial effects pose serious threats to future generations. The attempts of individuals who try to raise awareness have encouraged governments and enterprises to show some respect to nature. Companies have been reforming their supply chains in line with the 'sustainability' principle defined as 'meeting the needs of today without compromising the ability of future generations to meet their own needs' in the Common Future report published by the United Nations in 1987.

In the sustainable supply chain, in order for the world to continue to be a livable place, starting from product design, all processes along the chain such as raw material supply, production, distribution, use, end-of-life processes and waste must be rearranged in line with economic, social and environmental sustainability principles.

With the principle of environmental sustainability, environmental-friendly practices such as the use of environmental-friendly materials, reducing resource consumption and carbon emissions, minimizing pollution with waste management activities, and the potential of recycling come to the fore in the chain. The closed-loop product life cycle system is one of the most effective tools in ensuring environmental sustainability with reduce, reuse, recycle, recover, redesign and re-manufacturing practices expressed as 6R. Economical dimension of sustainability aims at fair share of costs and income related to production and consumption activities in society and the continuation of prosperity in the future. As a matter of social sustainability principle, the aim of supply chain activities is to comply with human rights, care about improving working conditions and fair distribution among social classes such as employment age, gender, etc., and that the consumption opportunities are equally shared among all individuals with diverse backgrounds.

Industry 4.0, whose technological components are summarized as the Internet of Things, big data and analytics, vertical-horizontal integration, cloud computing, additive manufacturing, augmented reality, simulation, cyber physical systems, smart robots, smart factories and cyber security, will enable supply chain functions to work in line with sustainable principles. Thanks to Industry 4.0 technologies, the Internet of Objects and horizontal integration especially, it will be possible to track the product along the entire life cycle beginning from production process as raw material to final product and until after use phase. In this way, systems that contribute to environmental sustainability such as using materials harmless for nature, reducing of resource and energy consumption, recycling, reuse, recovery, re-manufacturing can be utilized. Horizontal and vertical integration in supply chain, cloud computing, big data and analytics technologies are Industry 4.0 applications that support economic and social sustainability as well as environmental sustainability. Thanks to smart robots, smart factories and cyber-physical systems, decisions related to demand and production can be made simultaneously throughout the supply chain, thus reducing overproduction, the resulting resource consumption and waste generation.

Sustainable supply chain management has become a necessity for the world to continue to be a livable place with its environmental, social and economic dimensions. Industry 4.0 technologies are expected to provide convenience and opportunity for the transformation of supply chain functions into sustainable applications. However, there are also claims that it may have some negative outcomes, especially in social and economic dimensions. As the use of industry 4.0 technologies in supply chains becomes widespread, its effects might be evaluated closely by making comparative analyses in future studies.

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