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DEMIR, Sercan, GUNDUZ, Mehmet Akif, KAYIKCI, Yasanur <http://orcid.org/0000-0003-2406-3164> and PAKSOY, Turan

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READINESS AND MATURITY OF SMART AND SUSTAINABLE SUPPLY CHAINS: A MODEL PROPOSAL

Sercan Demir[1], Mehmet Akif Gunduz[2], Yasanur Kayikci[3], Turan Paksoy[4]

[1] Harran University, Faculty of Engineering, Department of Industrial Engineering, Sanliurfa, Turkey

[2] KTO Karatay University, Faculty of Economics and Administrative Sciences, Department of International Trade and Logistics, Konya, Turkey

[3] Turkish German University, Faculty of Engineering, Department of Industrial Engineering, Istanbul, Turkey

[4] Necmettin Erbakan University, Faculty of Aeronautics and Astronautics, Department of Aviation Management, Konya, Turkey / Director of KTO Karatay University Lean & Green SCM Lab, Konya, Turkey

Abstract

Many companies embrace Industry 4.0 technologies to enable operational sustainability against increasing climate change effects, decreasing natural resources, and raising consumer awareness of environmental issues. Even though readiness and maturity assessment of smartness and sustainability concepts are nested, no study simultaneously focuses on these concepts. As pioneering research, we propose a novel model titled "Smart and Sustainable Supply chain Readiness and Maturity model (S3RM)" and validate it by conducting a case study in the automotive industry. We design our model upon the triple-bottom-line (TBL) approach consisting of smartness and sustainability dimensions. Our study introduces the TBL of smartness covering availability, integrity, and adaptability sub-dimension. TBL of sustainability includes social, environmental, and economic sub-dimensions. The proposed model calculates the Smart and Sustainable Readiness and Maturity Index by averaging sustainability scores' summation and smartness scores' multiplication. Each sub-dimension consists of items measured by a readiness and maturity scale. The findings suggest how smartness and sustainability items create strengths, weaknesses, opportunities, and threats for the supply chain operations. Our model provides managerial implications in assessing the readiness and maturity of Industry 4.0 tools and sustainability indicators. This study offers a road map to managers on smart and sustainable supply chains' defined target areas.

Keywords: Industry 4.0, smart and sustainable supply chains, digitalization, sustainability, smartness, readiness and maturity model

Introduction

In recent years, globalization and increasing global competition, increasing technological growth rate, diversity in customer demands, and increasing complexity in supply chain processes have led companies to add smart and sustainable paradigms to their supply chain strategies. Real-time information sharing among the supply chain players and the effective coordination of each step in the chain plays an essential role in efficient supply chain management (Dev et al., 2020). This is possible by the transition from the traditional supply chain to the digital supply chain.

The Fourth Industrial Revolution, also known as Industry 4.0, was coined for the first time in Germany in 2011 (Kagermann et al., 2011). Industry 4.0 is an innovative paradigm that aims to integrate emerging technologies (e.g., the Internet of Things, artificial intelligence, cloud computing, autonomous vehicles, robotic systems, smart sensor and automation networks, virtual and augmented reality) into the production processes (Zhong et al., 2017). New technologies bring many innovations to our lives while converting the conventional supply chains into Industry 4.0 based digital supply chains.

Today, sustaining, monitoring, and real-time tracking of critical business operations are possible by adapting to the digital supply chains (Ghadimi et al., 2018; Sahay and Ranjan, 2008). Some of these operations are purchasing decisions, supplier selection, planning and coordination of production and distribution processes, receiving customer feedback and responding to their requests effectively, delivery and after-sales service. Rapidly increasing big data and global scale complex variables can be controlled and used to favor smart and sustainable supply chains (Jabbour et al., 2020). However, adaptation to Industry 4.0 and the sequent maturity period may cause many unexpected problems for many enterprises. The ineffective application of critical Industry 4.0 competencies to all operations simultaneously hinders setting up a smart factory and implementing digital transformation (Ghobakhloo and Fathi, 2019). Quantitative measurement and evaluation of firms' maturity levels after preparation and adaptation to Industry 4.0 are of great importance for senior management. By understanding the current maturity levels of firms and sectors, senior management and policymakers can see the whole picture, better focus on Industry 4.0 performance, and set a road map for the future. Besides, increasing environmental awareness, legal regulations, diminishing natural resources, and market competition lead to the emergence of sustainable supply chains (Demir et al., 2020). Hence smart and sustainable supply chain readiness and maturity assessment helps evaluate the current state and set a strategic roadmap.

Maturity models are business management tools that conceptualize and measure an organization's maturity or a process regarding a specific target state (Schumacher et al., 2016). Bierhold (2018) defines maturity models as "a tool that is used to measure, compare, describe or determine a path or roadmap." Maturity models are assessment tools used to interpret an organization's maturity in terms of a target state. These models are suitable for companies that aim to transform their technologies and business activities for the better applications of Industry 4.0 (Kumar and Nayyar, 2020) and are used as tools for methodical and continuous performance development (Langston and Ghanbaripour, 2016). Maturity models are designed to guide supply chains during their adaption process to Industry 4.0. The original aspects of maturity models are their structure and complicacy of the queries, and ease of access (Gajšek and Sternad, 2020). These models consist of consecutive steps that evaluate circumstances and lead to future improvements (Vivares et al., 2018).

In today's highly competitive markets, companies must integrate both smart and sustainable practices in their processes to maintain their competitive edges (Garcia-Muiña et al., 2018; Ghobakhloo and Fathi, 2019). To the best of our knowledge, our study is the first to propose a maturity model that assesses both the smartness and sustainability dimensions of supply chains. We propose a model that can measure supply chain readiness and maturity by simultaneously taking smart and sustainable dimensions into account and validating the model by conducting a case study in the automotive industry. This study is organized as follows: Section 2 reviews the existing Industry 4.0, sustainability, and readiness and maturity models literature. Section 3 presents the methodological framework of the proposed model. Section 4 discusses the results and implications for engineering managers. Finally, Section 5 summarizes the conclusions.

Literature Review

The Fourth Industrial Revolution, namely Industry 4.0, give rise to the digitalization of today's supply chains. This transformation in supply chains is the digitalization of all company operations, not just a production line's operations. This new concept is called the smart supply chain. Industry 4.0 maturity models are concerned with the compliance level of companies and sectors in this operational digitalization process. In today's world, where globalization and competition are rapidly increasing, the supply chain's sustainability is vital for businesses. Therefore, the smart supply chain that comes out with the digital transformation brought by Industry 4.0 becomes a concept that must be associated with sustainability. This study proposes a readiness and maturity assessment model to measure smart and sustainable supply chains'

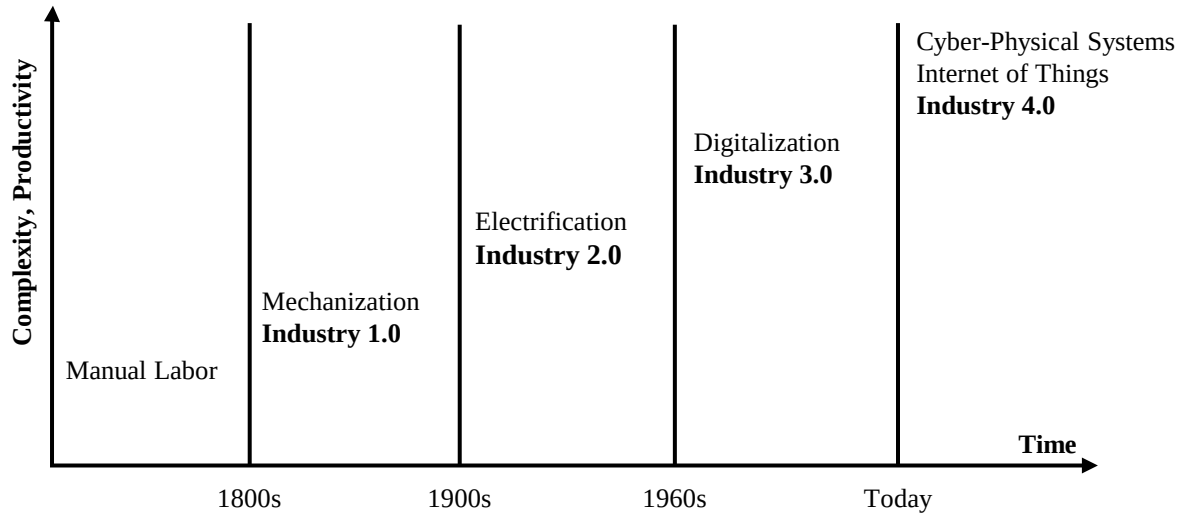
adaptation to digital transformation. In this context, Industry 4.0, maturity models, smart and sustainable supply chains will be briefly discussed in the following subsections.

Industry 4.0

The industry is an economic activity that is concerned with producing highly mechanized and automatized goods. Breakthrough technologies and technological advances have brought about many paradigm shifts since the beginning of industrialization. For instance, the First Industrial Revolution resulted from technological advancements in mechanization, while heavily electrical energy usage in industry initiated the Second Industrial Revolution. These were followed by the Third Industrial Revolution, triggered by the wide diffusion of digitalization in the industry (Lasi et al., 2014). Industrialization progressed through three stages named "Industrial Revolutions" each with its own characteristics (Carvalho et al., 2018). Although it is not considered a historical episode by itself, the industrial revolution was the most important single advancement in history over the past three centuries (Stearns, 2012). Today, we are at the beginning of the Fourth Industrial Revolution era, initiated by the advancements in Information and Communication Technologies (ICT). This transition is rendered by the integration of automation and cyber-physical systems (CPS) with decentralized control and advanced connectivity enabled by the Internet of Things (IoT) into the manufacturing systems (Rojko, 2017). IoT and CPS integrate modern production systems and network connectivity (Xu et al., 2018). A timeline of Industrial Revolutions is presented in Exhibit 1.

Exhibit 1. An overview of the four Industrial Revolutions

Source: Demir et al. (2020)



The term, Industry 4.0 was coined for the first time by German Economic Development Agency (GTAI) to publicize the idea that we are at the edge of the latest Industrial Revolution era that was initialized by the emergence, advancement, and convergence of new technologies. While the foundational technologies of Industry 4.0 enable a real-time connection between the physical and digital domains, these technologies hold the promise of minimizing cost, increasing flexibility and speed, enhancing quality, and, more importantly, striking the right balance between key operations (Olsen and Tomlin, 2020). In the near future, "digital enterprises" will enable the collaboration of customers and suppliers in a smart environment. However, the upcoming challenge is to raise awareness about the benefits of applying Industry 4.0 technologies in manufacturing systems. Another challenge is to guide companies through their transformation process and required digital transformation steps while letting them adopt the idea of being in the central part of digital transformation strategy (De Carolis et al., 2017a).

Industry 4.0 is a new profound paradigm shift in manufacturing systems, and it has started as a result of the integration of the Internet technologies and smart systems into the digitalized manufacturing environments, and it is considered as the vision of future production (Lasi et al., 2014). The integration of digitalization and the Internet into the manufacturing processes cause a worldwide transformation of industrial production. The future factories will employ CPS that connect machines and human beings. Coherent cooperation among technological tools and advancements will produce intelligent products in industrial processes, and it is considered the foundation of future smart factories (Tjahjono et al., 2017). The digital transformation in the Industry 4.0 era is led by connected systems such as sensors, machines, IT systems, and workpieces connected through the whole value chain (Rüßmann et al., 2015). Exhibit 2 elaborates twelve technologies reshaping industrial production.

Exhibit 2. Twelve technologies reshaping production

(Adapted from Brunelli et al., 2017; Mushtaq and Haq, 2019)

Technology	Impact and contribution to the system
Robotics and autonomous systems	Autonomous robots that collaborate in manufacturing systems (Bicho and Schöner, 1997; Wong et al., 2017)
Additive manufacturing	3D printers are used for rapid production (Gibson et al., 2021; Wong and Hernandez, 2012)
Augmented and virtual reality	Technology that allows using computer-generated data in logistics, display devices, such as glasses improve the productivity of employees (Olshannikova et al., 2015; Reif and Walch, 2008)
Simulation	Integration of the real time-data to the conventional simulation system generates precise outputs (Rodic, 2017; Wan et al., 2015)
Horizontal and vertical system integration	Connectivity through vertical integration from supplier to customer in the same supply chain and horizontal integration among competitors and business partners within different supply chains (Liu et al., 2015; Pérez-Lara et al., 2020)
The Internet of Things	The network of machines, products, items, services, and people in supply chains (Atzori et al., 2010; Li et al., 2015)
Cloud computing	Open systems for the management of the vast volume of data and synchronized communication systems throughout supply chains (Antonopoulos and Gillam 2010; Marston et al., 2011)
Cyber-security	Protection of networks, devices, data, and software programs from the cyber-attacks through the convergence of technologies, processes, and practices (Flatt et al., 2016; Von Solms and Van Niekerk, 2013)
Big data and analytics	The extensive utilization of the data collected from ERP, CRM, MES, SRM, and SCM systems to make an optimized real-time decision (Morabito, 2015; Sharma and Pandey, 2020)
Artificial intelligence	AI is the brain behind Industry 4.0. AI algorithms can optimize manufacturing operations and build resilient supply chains which can quickly respond and adapt to the changes in the market (Dopico et al., 2016; Lee et al., 2018)
Machine learning	ML algorithms discover the patterns in data and success factors of a supply chain network, while these algorithms are continuously learning from the process. Together with IoT sensors and data analytics, ML enables real-time optimization of supply chain networks (Candanedo et al., 2018; Diez-Olivan et al., 2019)
Blockchain technology	BCT establishes efficient and transparent supply chain networks and can be applied to supply chain networks in many ways, such as smart contracts, copyright protection, micropayments, tracking of devices, or identity management (Bodkhe et al., 2020; Yaga et al., 2019)

Smart and Sustainable Supply Chain Management

The growing attention in sustainable supply chain management (SSCM) in the literature provides remarkable insight into what kind of sustainable supply chain strategies are used by businesses. SSCM considers sustainability's environmental and social dimensions since it must address the issue from a broader perspective and focus on a wider range of performance goals (Seuring and Müller, 2008). Businesses aim to increase economic performance in the long run, thereby extending their economic life by integrating economic, social, and environmental perspectives in SCM (Carter and Rogers, 2008). According to Sisco et al. (2011), "supply chain sustainability is the management of environmental, social and economic impacts and the encouragement of good governance practices, throughout the lifecycles of goods and services." Besides, supply chain sustainability achieves organizational goals by utilizing innovative strategic and tactical technologies (Kim et al., 2014).

From this point of view, SSCM is the management of material, information, capital flows, and collaboration across companies throughout the supply chain while meeting customers' and stakeholders' requirements. The three dimensions of sustainable development, i.e., economic, environmental, and social, stems from customers' and stakeholders' needs and constitute the goal of the SSCM (Seuring and Müller, 2008). A set of barriers need to be removed to achieve a successful implementation of a sustainable supply chain. Managerial, organizational, and economic challenges are the most prominent barriers that hinder the successful adaptation of SSCM (Yadav and Singh, 2020). The internal barriers that prevent organizations from implementing SSCM are "cost and lack of legitimacy", while the external barriers are "regulation, poor supplier commitment, and industry-specific barriers" (Walker et al., 2008). Besides, lack of top management commitment and support, lack of training, resistance to adoption of advanced technology, and financial constraints are among the most challenging obstacles in the way of a successful SSCM implementation. (Tseng et al., 2019).

In the literature, SCM smartness and sustainability have been studied separately in recent years. However, scholars and practitioners have not yet reached a consensus on integrating SCM smartness and sustainability. For that reason, the literature on these two subjects is highly fragmented.

While the competition is getting more intense, customers are becoming more demanding. Therefore, companies must constantly adapt their supply chain to the global business environment, which becomes smarter, more transparent, and more flexible at all levels (Prinz

et al., 2016). The overall objective of the transformation from the conventional to smart SCM is to reduce costs and lead times while offering customized products and services which meet increasing requirements (Barreto et al., 2017).

The concept of Industry 4.0 is the modernization of industrial tools with digital technologies, e.g., the Internet of Things (IoT), big data, cyber-physical systems (CPS), and artificial intelligence (AI). These technologies are considered the elementary units of Industry 4.0 and the basic tools of industrial digitalization (Monostori, 2014). Industry 4.0 integrates business and technical systems via information and communication technologies (El Kadiri et al., 2016). Digital revolution affects the industrial ecosystem more widely and transforms the world of supply chain management, described as "smart supply chain management." According to Kagermann et al. (2013), the digital revolution is gradually erasing the boundaries between B2B (Business to Business) and B2C (Business to Customer) by directly interconnecting supply and demand. Information systems allow connections at all levels, from suppliers to customers, to optimize customized product flows, reinforce innovation, and improve resource management (Hermann et al., 2016). It is not enough for a company to switch to Industry 4.0 internally, but the entire supply chain must progress in this transition (Hofmann and Rusch, 2017). Thus, smartness is the focus of recent supply chain development operations. Few studies cover smart and sustainable production systems in the literature. For instance, Yin et al. (2020) study sustainable and smart product innovation ecosystems by conducting an integrative review. In another study, Mastos et al. (2020) investigate the impacts of supply chain smartness on SSCM.

The literature covers many different aspects of SSCM, and the studies are fragmented into various concepts. Essentially, these studies focus on the green purchase and integrated supply chain in a closed loop. Wu and Dunn (1995) mention that a sustainable supply chain differs from reverse logistics because it targets saving natural resources, reducing waste, and increasing productivity. Hart (1997) indicates that SSCM must have the smallest environmental footprint. Beamon (1999) suggests that SSCM is an upgrade of the conventional supply chains to include activities that aim to decrease the ecological damage of products throughout their life cycle, such as eco-design, saving natural resources, reducing hazardous materials, reusing and recycling products. Amjad et al. (2021) state that environmentally friendly manufacturing has been neglected due to economic concerns, and there is a need for responsible production and consumption methods due to the negative consequences of climate change. The authors propose a framework consisting of lean manufacturing, green manufacturing, and Industry 4.0

concepts. Krikke et al. (2001) propose various principles for the design of the closed-loop supply chain. The authors conclude that the integration of reverse logistics into the conventional supply chain is the most appropriate structure to conform to sustainable development principles. Wells and Seitz (2005) claim that green supply chains merge reverse logistics activities and traditional supply chains. Fleischmann and Minner (2004) examine the circular supply chain and introduce an extended supply chain. Krikke et al. (2004) suggest three key actions for optimal management of the sustainable supply chain: consistency between the purpose of returns and the shape of the supply chain network, modular reuse of products, and obtaining reliable information on reuse. According to Hervani et al. (2005), a sustainable supply chain includes green purchasing, green manufacturing, green distribution, green marketing, and reverse logistics. Guide and Van Wassenhove (2002) define the reverse supply chain as "a series of activities required to retrieve a used product from a customer and either dispose of it or reuse it." Silva and Figueiredo (2020) conclude that sustainable development goals substitute the triple-bottom-line perspective of supply chain sustainability. Wan et al. (2021) propose a model for assessing supply chain sustainability by adding new indicators to the existing triple-bottom-line dimensions. Exhibit 3 compares the studies that cover SSCM indicators.

Exhibit 3. SSCM indicators

Economic						Environmental					Social				Study
Logistics costs	**Delivery time & delay**	**Inventory reduction**	**Damage and loss**	**Frequency of service**	**Forecast accuracy**	**Reliability & flexibility**	**Green purchasing & green product**	**Resource efficiency & embodied energy**	**Emission, waste & pollution**	**Land use & environmental uncertainty**	**Development benefits & social impact**	**Job safety & health**	**Workforce pattern**	**Social acceptance**	
						X				X					Merschmann and Thonemann (2011)
X	X		X			X		X	X	X		X	X		Monnet and le Net (2011)
	X														Raab and Griffin-Cryan (2011)
X	X	X		X	X	X									Dougados et al. (2013)
							X								Hsu et al. (2013)
										X					Wu and Haasis (2013)
X						X		X	X		X		X	X	Gebler et al. (2014)
				X			X		X		X		X		Nowak et al. (2016)
X	X				X	X		X			X	X		X	Schrauf and Berttram (2016)
								X		X					Irani et al. (2017)
							X	X							Ghadimi et al. (2019)
X									X		X	X			Haag (2021)

Srivastava (2007) defines the main components of SSCM as "integrating environmental thinking into supply-chain management, including product design, material sourcing, and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life." Barker and Zabinsky (2008) state that there are two main challenges to strategic planning for a sustainable supply chain: (1) how to integrate recovery activities into the conventional supply chain, and (2) how to manage uncertainty about reverse logistics.

Srivastava (2008) presents a two-step multi-product model that maximizes the total profit from a closed-loop supply chain network. In the first stage, facility location is decided by taking strategic criteria and customer constraints into account, and in the second stage, layout and capacity expansions are determined. Pochampally et al. (2009) explain the strategic questions encountered by planners of closed-loop supply chains, which are a selection of used products, assessment of production facilities and future products, selection of new products and secondary markets, optimization of transport, synchronization of processes, and measurement of supply chain performance. Sarkis et al. (2011) study the integration of ecological considerations into inter-organizational SCM practices. Kumar et al. (2012) explore the benefits of SSCM in terms of cost reduction, efficiency, and innovation. Ahi and Searcy (2013) examine SSCM in the context of a company that collaborates with its suppliers to improve environmental performance. Govindan et al. (2014) introduce new performance measures of supply chain sustainability that provide information on the joint consideration of economic and environmental performance. Jabbour and de Sousa Jabbour (2016) propose a framework for the green human resource management and green SCM relationship. Li et al. (2016) compare the pricing and greening strategies of the single and dual-channel chain members. Teixeira et al. (2016) examine the relationship between green training and green supply chain practices such as green purchasing and collaboration with the consumers. Basiri and Heydari (2017) investigate the green channel coordination within a two-stage supply chain which markets a non-green product and plans to introduce a new green product. Rezaee et al. (2017) present a green supply chain model in a carbon trading environment. Zhao et al. (2017) present a green SCM model that minimizes the inherent risk of carbon emission and economic cost. Suryanto et al. (2018) explain the relationship between managerial support and organizational learning with the green SCM environment. Song and Gao (2018) establish a green supply chain model with two types of revenue-sharing contracts. Cousins et al. (2019) measure the moderating

effects of "ecocentricity and supply chain traceability on a firm's environmental and operating cost performance."

Recently, many scholars have focused on the technological aspects of Industry 4.0 and its implications in the SCM (Hermann et al., 2016; Tjahjono et al., 2017; Barreto et al., 2017; Vaidya et al., 2018). Butner (2010) asserts that smart supply chains can deal effectively with risks and meet business objectives by enabling cost containment and supply chain visibility. Valkokari et al. (2011) suggest that smart supply chains can only be achieved by understanding the strategic intents and corresponding roles of four main smart SCM actors: customer, manufacturer, supplier, and innovation partner. Faller and Feldmüller (2015) suggest that the technological aspects mainly concern the concept of a smart factory, i.e., creating an intelligent and learning environment in the production system. Seitz and Nyhuis (2015) inquire about the advantages of CPS in terms of production planning, control, and monitoring, which are logistics model performance and possible logistics cost reductions. Wu et al. (2016) examine the opportunities which smart supply chains offer for cost reduction and efficiency improvement. Yuvaraj and Sangeetha (2016) explore the traceability of goods in the internal and external environment by smart supply chains using low-power wireless communication systems. According to Strandhagen et al. (2016), the production environment significantly impacts the practicability of Industry 4.0 key elements related to production logistics. Prinz et al. (2016) claim that the real and virtual business world is being transformed into IoT through big data and faster, more efficient, and more flexible production. Sanders et al. (2016) assert that smart production is associated with the most modern ICT to create a digitally interconnected supply chain. This also implies an interconnection between the products, machines, ecosystem, customers, and each stage of the product life cycle. Thus, supply chains grow into increasingly complicated structures and become difficult to understand. Özlü (2017) suggests that adopting an Industry 4.0 model can increase the workforce efficiency, production, and competitive advantage. Schlüter and Henke (2017) claim that future supply chain risks can be mitigated at the beginning phase by proactive management of data along the supply chain. Strandhagen et al. (2017) argue that companies with a high degree of repetitive production find Industry 4.0 worthwhile to implement in inbound logistics, as manufacturers with a lowly repetitive production think the opposite. Abdel-Basset et al. (2018) highlight that smart SCM meets customer expectations by automating the identification process of products, monitoring the flow of goods globally, achieving transparency, and reducing time and cost. Authors also conclude that IoT helps set up an extensive digital infrastructure to combine data, items,

products, physical objects, and value chain operations to overcome traditional supply chain challenges. Gupta et al. (2019) claim that flexible supply chains can be succeeded by adapting smart SCM.

As summarized above, smart and sustainable SCM studies focus on organizational impacts of the digital transformation of supply chains; however, readiness and maturity of smart supply chains have not been taken enough attention from scholars and practitioners so far. In the following sections, we present the readiness and maturity models in the literature.

Readiness and Maturity Models

Maturity models are conceptual structures that define the maturity or the development state of a specific area of interest. In industry, maturity models are strategic tools used to define and measure a company's maturity level in a determined area or an operation associated with a business objective (Santos and Martinho, 2019). According to Kohlegger et al. (2009), a maturity model conceptually represents phases of increased quantitative or qualitative capability changes of a maturing element to assess its advances concerning defined focus areas. Hence maturity models are powerful tools to evaluate the capabilities of maturing elements and improve their maturity to a higher level by taking necessary actions. A progressive roadmap from the beginning to a target destination must be followed to reach a desired level of maturity. Maturity models help organizations recognize where they are, lead them during this transformation process, and help them acquire the required information to determine which areas need special attention (Hribar Rajterič, 2010; Lahrmann et al., 2011). Maturity models are usually composed of dimensions representing specific capabilities from an area of interest and levels that are ordinal labels that signify maturity stages. These models help companies analyze the current situation and classify capabilities of specific areas that are used for comparison and benchmarking (O'Donovan et al., 2016).

To become or remain competitive in the market, companies must evaluate where they stand in digital transformation and assess their utilization rate of Industry 4.0. That is why it is meaningful to measure Industry 4.0 penetration and perform required actions (Lichtblau et al., 2015). While maturity models are mostly used to conceptualize and measure an organization's maturity or a process based on a predefined target state, the goal of a readiness model is to set a starting point and launch the development process. Readiness assessment occurs before the initialization of maturing process, while maturity assessment measures the actual state during the maturing process (Schumacher et al., 2016). Companies should implement a detailed digital

maturity assessment to clarify their status of digital readiness for digital transformation. Undoubtedly, a deep understanding of the current state of digitalization is the first step for a successful digital transformation. Gaining a clear view of digital maturity will help companies explore and utilize the opportunities generated by digital technologies (De Carolis et al., 2017b). The digital transformation should start with a clear view of their current level and a strategic plan that guides the management through digitalization trends. Industry 4.0 readiness and maturity models guide decision-makers through benchmarking and strategic planning processes to achieve long-term goals for a company's digital transformation (Rajnai and Kocsis, 2018). According to Basl and Doucek (2019), maturity models "can help companies make easier and faster decisions concerning the question of in which areas they should build up Industry 4.0, and at what tempo".

Industry 4.0 readiness models

Roland Berger (2015) publishes one of the first studies on Industry 4.0 readiness comparison among countries. The author evaluates the European countries and China by clustering them into four sets to show the considerable differences in technological potential and percentage of manufacturing activities in GDP. Goetzpartners (2015) compares the US and German companies' digital competency based on their IoT expertise by investigating digital vision and strategy, IoT products and services, and the value chain transformation. As the results show in the studies mentioned above, Germany and the US are the pioneer countries in Industry 4.0 transformation. Basl and Doucek (2019) analyze various Industry 4.0 readiness and maturity models in the literature and propose a metamodel based on the individual layers organized using available indexes and maturity models applied in pioneer countries where Industry 4.0 is under continuous development.

Even though the need for digitization is recognized by many, the efforts for organizational transformation are still at the early stages. However, the manufacturing industry is characterized by relatively low readiness in terms of digital transformation compared to other sectors (Bechtold and Lauenstein, 2014). Botha (2018) proposes a conceptual model for future readiness measurement along with future readiness levels and a future readiness index. The proposed approach measures an enterprise's future readiness for Industry 4.0 and assesses the current technology level, company behavior, and events as future-shaping factors. De Carolis et al. (2017b) suggest a maturity assessment method based on the Capability Maturity Model Integration (CMMI) framework to investigate the manufacturing firms' digital maturity and

help them develop a transformation roadmap. Roland Berger (2015) presents a generic model to calculate the company-specific Industry 4.0 maturity index by investigating four essential factors: infrastructure, processes, data traffic, and work models.

De Carolis et al. (2017a) introduce a Digital Readiness Assessment Maturity Model (DREAMY) based on their previous CMMI model's principles to guide companies towards their digital transformation process. Ernst and Frische (2015) investigate the status of Industry 4.0 regarding the Industrial Internet of Things (IIoT) development by analyzing current technologies, the requirements, and the strategic approaches for successful digital transformation. Lin et al. (2020) examine the smart manufacturing readiness of Taiwanese companies by adopting a maturity model that uses cluster analysis and addresses the problems regarding the maturity evaluation of technologies, processes, and organizations. Lucato et al. (2019) propose a model that measures the Industry 4.0 readiness of companies and helps managers to identify strategic actions to improve the readiness level for Industry 4.0. Machado et al. (2019) study many Swedish and German companies' digital readiness by implementing a self-check tool to identify their readiness level and technical challenges during the transformation process. Basl (2017), Kopp and Basl (2017) analyze Czech companies' Industry 4.0 readiness level by applying a questionnaire survey. Basl (2018) presents different methods for measuring and evaluating the Industry 4.0 readiness of companies. Stentoft et al. (2019) investigate the main drivers for the increased Industry 4.0 readiness level and barriers against a successful implementation for small and medium-sized enterprises (SMEs) by conducting a questionnaire survey.

Samaranayake et al. (2017) investigate the key enabling factors of Industry 4.0 implementation in six technological readiness dimensions. Nagy et al. (2018) carry out a qualitative research study to test the Industry 4.0 readiness of firms by conducting several interviews. Mittal et al. (2018) review the existing smart manufacturing and Industry 4.0 maturity models and analyze whether these models meet the specific requirements for Industry 4.0 implementation of the small and medium-sized enterprises.

Nausch et al. (2019) propose a model that can assess the readiness level of an organization's capability to utilize data in the Industry 4.0 context and help managers evaluate an organization's status and identify strategies to increase data usage. Nick et al. (2019) introduce a survey to assess the Industry 4.0 readiness of companies in Hungary. Pacchini et al. (2019) introduce a model that can evaluate the degree of Industry 4.0 readiness of a manufacturing company and help managers to identify required actions to improve the degree of readiness.

Rajnai and Kocsis (2018) discuss an overview of Industry 4.0 readiness assessment models and provide related methods in the literature. Sony and Naik (2019) discuss the key ingredients for assessing Industry 4.0 readiness for organizations and analyze these key ingredients and interrelationship between these factors in detail through a thematic analysis. Vrchota and Pech (2019) analyze the Industry 4.0 readiness of enterprises through questionnaires and create an Industry 4.0 index by using explorative factor analysis, which allows companies to determine their current level of Industry 4.0.

Industry 4.0 maturity models

The digital transformation describes the future trends that initiate the Fourth Industrial Revolution. The utilization of digital data, connectivity, traceability, autonomous and real-time decision-making capabilities are the main features of smart factories, which are the core elements of the next industrial revolution. Lasi et al. (2014); Alcácer and Cruz-Machado (2019) present a review of the enabling technologies behind Industry 4.0. Drath and Horch (2014) discuss the background of the Fourth Industrial Revolution, its technical drivers, and its future in manufacturing. Rüßmann et al. (2015) study nine technology trends considered as the basic elements of Industry 4.0. Hermann et al. (2016) discuss the design principles of Industry 4.0 to clarify the basic concept and identify the potential use of the key technologies during Industry 4.0 implementation. Brunelli et al. (2017) present managerial insights regarding the Industry 4.0 implementation collected from the companies which are frontrunners in implementing Industry 4.0 and captured the benefits of digital transformation in their business. The authors study the impact of Industry 4.0 key technologies on company performance and provide managerial insights from leading companies that implement Industry 4.0.

Gökalp et al. (2017) present a systematic literature review on the existing maturity models and suggest a new one. Akdil et al. (2018) review the current maturity models for Industry 4.0 adaptation process and propose a novel maturity model that includes three dimensions: smart products and services, smart business processes, and strategy and organization. Aguiar et al. (2019) introduce a maturity model framework that helps companies assess their current digital capability and build a roadmap to reach higher capability. Veza et al. (2015) analyze the current maturity level of Industry 4.0 in the Croatian manufacturing industry by conducting questionnaires to gather data from many enterprises.

Lichtblau et al. (2015) propose a six-staged Industry 4.0 readiness model that includes six dimensions and eighteen associated fields (sub-dimensions) identified by conducting

workshops with company representatives. Geissbauer et al. (2016) propose a four-staged Industry 4.0 maturity model that consists of seven dimensions. This model enables companies to evaluate their Industry 4.0 maturity level and delineate the results using an online self-assessment tool while providing an action plan for a higher level of maturity. Exhibit 4 presents readiness and maturity studies in the literature.

Rockwell Automation (2016) introduces a five-staged maturity assessment model called "The Connected Enterprise Maturity Model," consisting of four technology-focused dimensions. Schumacher et al. (2016) propose an empirically designed Industry 4.0 maturity assessment model for industrial enterprises operating in the field of intermittent production. Exhibit 5 presents the scope of the dimensions and sub-dimensions of readiness and maturity models in the literature.

Exhibit 4. Readiness and maturity literature

Type of study	Model type	Methodology	Dimensions	Study
Research report	Maturity	N/A	N/A	Bechtold and Lauenstein (2014)
Research report	Readiness	N/A	N/A	Goetzpartners (2015)
Research report	Readiness and maturity	Generic model	Infrastructure, processes, data traffic, work models	Roland Berger (2015)
Qualitative research	Maturity	Conceptual model	N/A	De Carolis et al. (2017b)
Qualitative research	Readiness and maturity	Conceptual model	Process, monitoring & control, technology, organization	De Carolis et al. (2017a)
Qualitative research	Readiness	Questionnaire	Motivation and strategy, investment, technology, data & smart products, employees	Kopp and Basl (2017)
Literature review	Readiness	Conceptual model	N/A	Botha (2018)
Literature review	Readiness and maturity	N/A	N/A	Mittal et al. (2018)
Literature review	Readiness	N/A	N/A	Rajnai and Kocsis (2018)
Literature review	Readiness and maturity	Metamodel	Leadership, corporate culture, human resources, technology	Basl and Doucek (2019)
Qualitative research	Readiness	Case study	Strategy and organization; smart factory, smart operations, smart products, data-driven services, employees	Machado et al. (2019)
Qualitative research	Readiness	N/A	Strategy, governance, operations, objects	Nausch et al. (2019)
Qualitative research	Readiness	Questionnaire	Strategy and organization, smart factory, intelligent processes, smart products, services based on product data, employees	Nick et al. (2019)
Quantitative research	Readiness	New model proposal	The Internet of Things, big data, cloud, cyber-physical systems, robots, additive manufacturing, augmented reality, artificial intelligence	Pacchini et al. (2019)
Literature review	Readiness	Thematic analysis	N/A	Sony and Naik (2019)

Exhibit 5. Dimensions and sub-dimensions of existing readiness and maturity models

Study	Type of model*	Number of dimensions	Number of sub-dimensions	Number of levels	Empirical method**	Area of focus						
						Products & services	Customers	Processes & operations	Strategy & organization	Information technology	Employees/ leadership & culture	Cyber-security
Roland Berger (2015)	M	4	11	1 to 3				+	+	+		
Lichtblau et al. (2015)	R	6	18	0 to 5	Q	+		+	+	+	+	+
Bogner et al. (2016)	M	3	14	1 to 4	I, Q	+	+	+				
Ganzarain and Errasti (2016)	M	3	N/A	1 to 5			+		+	+	+	
Geissbauer et al. (2016)	M	7	N/A	1 to 4	S	+	+	+	+	+	+	+
Gill and VanBoskirk (2016)	M	4	N/A	1 to 4	S, W	+	+	+	+	+	+	
Leyh et al. (2016)	M	4	N/A	1 to 5		+		+		+		+
Rockwell Automation (2016)	M	4	N/A	1 to 5			+	+		+		
Schumacher et al. (2016)	M	9	62	1 to 5	C	+	+	+	+	+	+	
De Carolis et al. (2017a)	M	4	5	1 to 5	I, Q	+		+	+	+		
Dennis et al. (2017)	M	6	N/A	0 to 4		+		+	+	+	+	
Gökalp et al. (2017)	M	5	N/A	0 to 5				+	+	+		+
Kopp and Basl (2017)	R	5	N/A	0 to 5	S			+	+	+	+	+
Pessl et al. (2017)	M	13	N/A	1 to 5		+		+	+	+	+	
Samaranayake et al. (2017)	R	6	20	N/A	Q	+			+	+	+	+
Schuh et al. (2017)	M	4	N/A	1 to 6					+	+	+	+
Weber et al. (2017)	M	3	N/A	0 to 5		+		+	+	+		
Agca et al. (2018)	R	6	37	1 to 4		+	+	+	+	+	+	+
Akdil et al. (2018)	M	3	13	0 to 3	Q	+		+	+	+	+	

Study	Type of model*	Number of dimensions	Number of sub-dimensions	Number of levels	Empirical method**	Area of focus						
						Products & services	Customers	Processes & operations	Strategy & organization	Information technology	Employees/ leadership & culture	Cyber-security
Bibby and Dehe (2018)	M	3	13	1 to 4	I, W, C	+		+	+		+	
Bittighofer et al. (2018)	R	6	N/A	0 to 5	S	+	+	+	+	+	+	
Botha (2018)	R	4	40	0 to 3	S		+		+	+	+	
Brozzi et al. (2018)	R	3	23	1 to 5		+		+	+	+	+	+
Keskin et al. (2018)	R	6	43	N/A	C	+	+	+	+	+	+	+
Singapore EDB (2018)	R	16	N/A	N/A			+	+	+	+	+	
Aguiar et al. (2019)	M	2	N/A	0 to 5			+	+	+	+	+	+
Castro et al. (2019)	R	6	26	0 to 5	Q, C	+		+	+	+	+	
Machado et al. (2019)	R	5	N/A	0 to 5	I, Q, C	+		+	+	+	+	
Nausch et al. (2019)	R	23	N/A	0 to 5	I, S, Q	+		+	+	+		
Nick et al. (2019)	R	12	N/A	N/A		+	+	+	+	+	+	+
Pacchini et al. (2019)	R	8 (items)	N/A	1 to 6	I, C			+		+		
Wagire et al. (2021)	M	7	38	1 to 4	Q, C	+	+	+	+	+	+	+

* M: Maturity, R: Readiness

** C: Case study, I: Interview, Q: Questionnaire, S: Survey, W: Workshop

Research Gap

In recent years, globalization, increasing competition, diminishing resources, demographic changes, environmental problems, legal regulations, and climate change have forced companies to develop sustainable business models. The digital transformation movement bestows companies a great vision of mass adaption to newly developed smart technologies and applications. In this sense, companies need to mature in smart systems and sustainability strategies in the digital transformation process to increase their competitiveness and adaptability to a constantly changing business environment. The need arises to develop a readiness and maturity model that can measure sustainability and digital transformation results to evaluate enterprises' current capabilities.

The literature review so far reveals that no readiness and maturity model covers sustainability and smart systems together. In this respect, we propose a novel model, "S3RM", an acronym for "smart and sustainable supply chain readiness and maturity", to fill up this research gap. Our model will contribute to the literature by providing an assessment tool that enables enterprises to measure the readiness and maturity level of digital supply chains by simultaneously taking smart and sustainable dimensions into account.

Methods

In this study, we purpose to model measurement of readiness and maturity in terms of smartness indicators representing Industry 4.0 tools and sustainability indicators representing social, environmental, and economic dimensions for ten SCM processes, which are (Croxton, 2003; Croxton et al., 2001; Croxton et al., 2002; Lambert, 2008; Lambert and Cooper, 2000; Lambert et al., 2005; Rogers et al., 2002; Tan, 2001): (1) supplier management (supplier selection and evaluation), (2) purchasing management, (3) order management, (4) customer relationship management and sales management, (5) warehouse/inventory management, (6) handling, (7) transshipment, (8) packaging, (9) insurance, and (10) inspection and customs clearance.

The methodology of the study covers a scale development process. From this aspect, The Smart and Sustainable Readiness and Maturity Index is the main output of the S3RM model, and it will be developed and transformed into a measurement tool. Scale items were operationalized with the thematic analysis of the qualitative data obtained through the literature review. Typically, the thematic analysis aims to identify patterns in the text, and it can be more useful for identifying and characterizing the main ideas and themes of the text documents (Trochim

et al., 2016, p.66). This method is particularly useful in studying concepts that have a broad area of research. Thematic analysis is employed based on the conceptual framework proposed by Tate et al. (2010). To understand how similar concepts are categorized, a series of match merging is performed to obtain subcategories. Each subcategory is assessed for SCM-specific terminologies, such as ecolabels and cyber security. Then subcategories are assigned to relevant smart or sustainable dimensions. The next step is to operationalize and convert these items into measurable metrics by assigning a five-point Likert scale rating system. Operationalization, the first step of conceptualization, transforms concepts and structures into various measurement tools, and it starts with making abstract concepts measurable (Burnette, 2007). Accordingly, we transform the conceptual expressions of smartness and sustainability into measurable variables and create a survey for the field study.

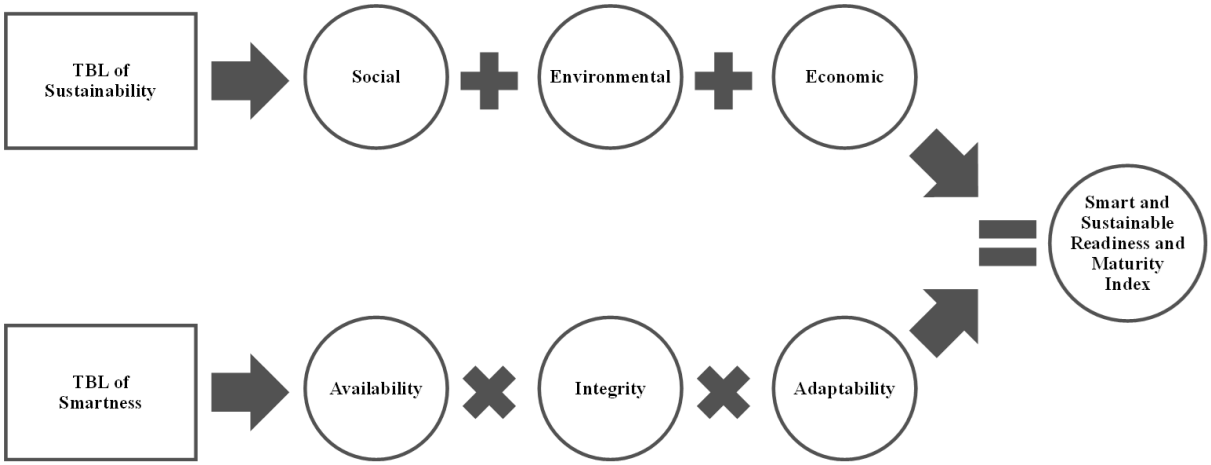
We validate the survey by ensuring face validity and content validity to assess the questionnaire items' dependability. Face validity denotes how a measurement tool appears to measure the concept it is intended to measure, while content validity indicates how adequately a measurement tool represents the concept (Sekaran and Bougie, 2016, pp.221-223). A two-step validation process is performed by adapting the procedure used by Mason et al. (2020). At the first step, we have the questionnaire reviewed by two different evaluators to establish face validity, ensuring that our survey does not contain common mistakes such as loaded, confusing, leading, or double-barreled questions. Then we ran a pilot test with ten supply chain experts to sort out controversial or irrelevant questions and attest to the instrument's content validity. We made several modifications, such as collecting two items under the "mobbing free work environment" item at this final step of survey validation.

This study's original aspect is to propose a conceptual model and measurement tool that integrates TBL of sustainability with TBL of smartness introduced here for the first time as a concept that measures readiness and maturity of a smart and sustainable supply chain. The model has two dimensions: TBL of sustainability and TBL of smartness. On a holistic framework, the two dimensions of the model have different ontological characters. While smartness has a hierarchical structure, sustainability is heterarchical. We design the smartness sub-dimensions in a ranking order to represent their hierarchical formation. TBL of sustainability consists of three sub-dimensions: social, environmental, and economic. TBL of smartness defines the digitalization of SCM, and its sub-dimensions are availability, adaptability, and integrity. Availability defines the existence of Industry 4.0 tools in enterprises at an ontological base. Adaptability is the measure of how effectively these Industry 4.0 tools

are used in businesses. Integrity is an indicator of the extent to which the organization embraces the Industry 4.0 tools. This sub-dimension represents employee participation as well as managerial support. In other words, it is an indicator of how much support is provided to Industry 4.0 technologies at all levels of the organization.

The conceptual model of S3RM is presented in Exhibit 6 and Equation (1). The sustainability index represents the arithmetic mean of its three sub-dimensions. The smartness index denotes the geometric mean of its three sub-dimensions. The Smart and Sustainable Readiness and Maturity Index equals the average of sustainability and smartness indexes. We assign equal weights to the dimensions to avoid bias in the decision-making process.

Exhibit 6. S3RM model



$$\Psi_i = \frac{1}{2}\left(\sum \upsilon_{ij}/3\right) + \frac{1}{2}\left(\sqrt[3]{\prod \mu_{ik}}\right) \quad (1)$$

υ_{ij}: TBL of Sustainability sub-dimension j score of company i

μ_{ij}: TBL of Smartness sub-dimension k score of company i

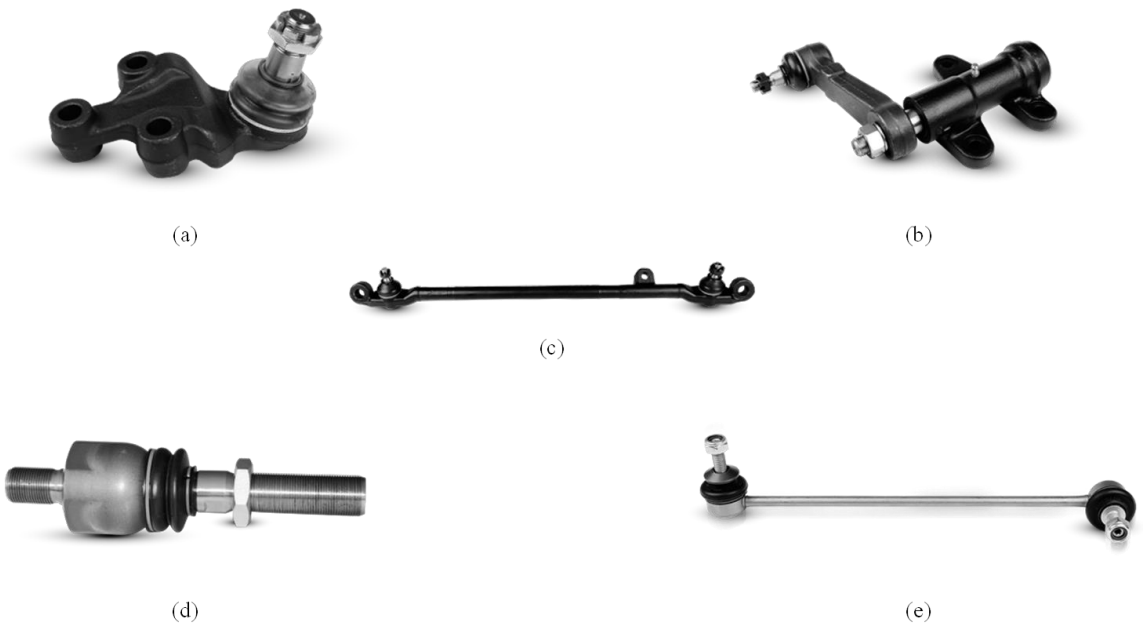
Ψ_i: Smart and Sustainable Readiness and Maturity Index Score of company i

A Case Study

We test the proposed model within a company that operates in the automotive sector to show its applicability. The company ABC was founded in 1975 and is one of the largest automobile parts suppliers in Turkey. The company name is disguised and renamed as ABC, and the provided data are distorted due to the company's confidentiality policy. ABC produces various products such as ball joints, rods, draglinks, wishbones, stabilizers, axial joints, and bushings

for passenger, commercial, and heavy commercial vehicles (see Exhibit 7). The product range of the company is 15 thousand, and they introduce 1000 new items per year. The facilities are located on a 90 thousand square meters area. The company exports its products to more than 60 countries and employs more than 1200 personnel. The main machinery and processes of the company are aluminum forging, steel forging, more than 250 CNC's, cataphoretic coating, 3D printers, robotic arms, CAD/CAM/CAE methods, electrostatic painting, ERP, Simulation, AGV's, conveyor systems, automated storage and retrieval systems, and CRM. The company follows lean production principles, uses TQM tools, and possesses IATF 16949-2016 certification, a technical specification of the automotive industry's quality management system. They acknowledge the importance of sustainability applications such as environmentally friendly filter systems for painting and coating processes. The company tries to minimize its negative effects on the environment by applying ISO 14005:2019 standards and secures occupational health and safety by pursuing OHSAS 18001 standards.

Exhibit 7. Samples of products (a: ball joint, b: s-rod; c: draglink, d: axial joint, e: link stabilizer)



The company wants to measure smart and sustainable supply chain readiness and maturity to determine the digital transformation strategy. The model developed in this study is suggested to the company and implemented with the top management's permission.

The data is collected by conducting interviews with operational managers in the facility of ABC company. We measure readiness and maturity scores by using five-point Likert scales.

Availability scores represent the extensiveness of utilizing smart tools in SCM operations on a scale of 5 (completely wide), 4 (wide), 3 (moderate), 2 (rare), and 1 (none). Integrity scores denote how effectively smart tools are used in SCM operations on a scale of 5 (completely effective), 4 (effective), 3 (moderate), 2 (rare), and 1 (idle). Adaptability scores signify how compatible the smart tools are for achieving the goals of SCM operations on a scale of 5 (completely compatible), 4 (compatible), 3 (fair), 2 (poor), and 1 (very poor). Finally, the three sustainability sub-dimensions show how considerable the sustainability indicators are for SCM decision-making on a scale of 5 (severe), 4 (moderate), 3 (mild), 2 (very mild), and 1 (none).

Each sub-dimension of the smartness dimension and the sustainability dimension consists of questionnaire items. The smartness items are all the same for three sub-dimensions which are the contemporary smart technologies ready for SCM operations: additive manufacturing, artificial intelligence, augmented and virtual reality, big data and analytics, blockchain technology, cloud computing, cyber-security, machine learning, robotics and autonomous systems, simulation, the Internet of Things. Contrariwise, the sustainability items differ by each sub-dimension. The social sub-dimension covers thirteen items: occupational health and safety, liberal business environment, mobbing-free work environment, long-term employment, access to training, career development, social benefits and perks, work schedules, employee loyalty, job satisfaction, union rights, corporate social responsibility, and stakeholder relations. The environmental sub-dimension comprises eleven items: recycling, reusing resources, reducing resource usage, ecolabels, ISO-14000 certification, waste disposal, minimizing energy usage, maximizing renewable energy usage, minimizing emission, avoiding hazardous material, and minimizing pollution. Lastly, the economic sub-dimension holds nine items: cost reduction, manufacturing lead time and order cycle time reduction, inventory turnover, loss and damage reduction, minimizing land and area use, quality cost reduction, CRM performance, total revenue, and shareholder value.

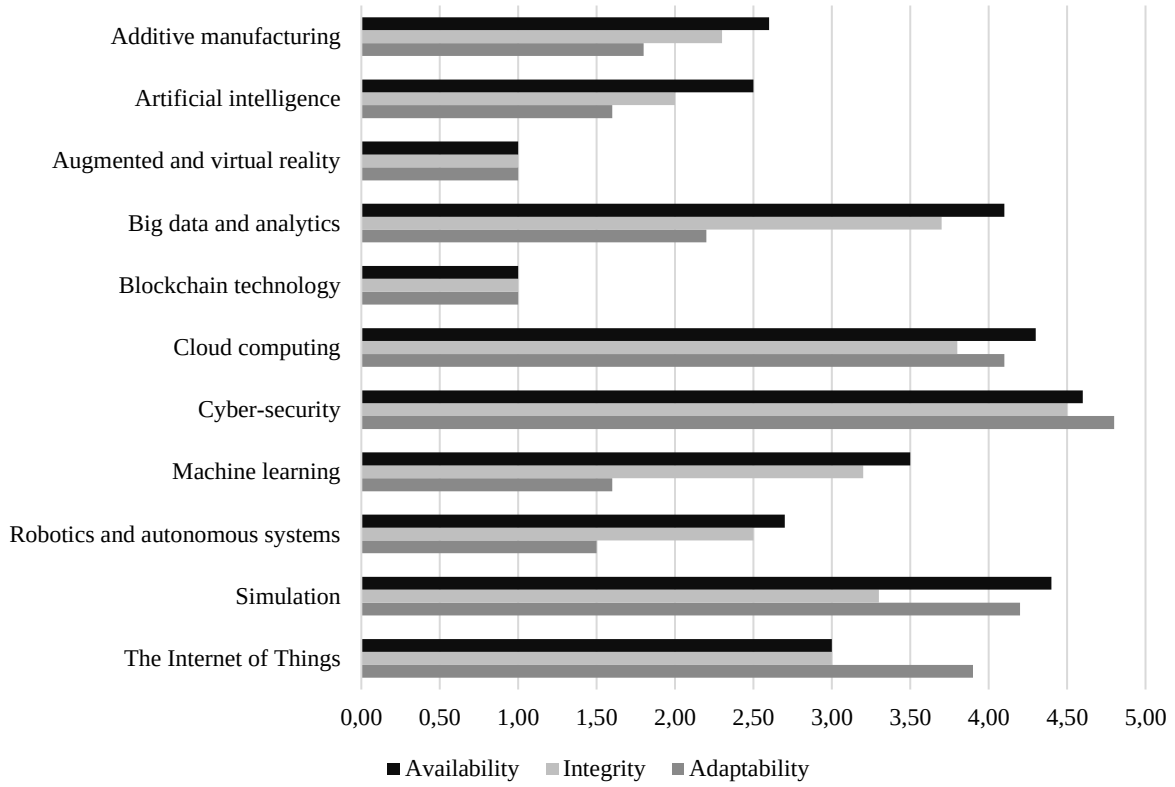
Implications for Engineering Managers

Our research primarily contributes to the engineering management body of knowledge's operations and supply chain management field by offering an assessment tool that helps engineering managers simultaneously evaluate the readiness and maturity of a supply chain in terms of smart and sustainable dimensions. Furthermore, we include the TBL of smartness as a new terminology for the first time. This approach will help engineering managers evaluate the supply chain regarding availability, integrity, and adaptability sub-dimensions. The

generated Smart and Sustainable Readiness and Maturity Index allow managers to compare smart and sustainable supply chains' current and targeted performance level. In this sense, the index works as a strategic road map for contemporary supply chain management.

Each item's readiness and maturity scores are obtained from the interviews with the operations and production managers. We present the dimension scores that are obtained from the questionnaire through Appendix I to VI. The appendix tables reflect the average score of SCM's ten processes for each questionnaire item. Exhibit 8 illustrates the readiness and maturity scores for each smartness item. Cyber-security has the highest score for the three sub-dimensions of smartness. Contrarywise blockchain technology and augmented and virtual reality are inefficient for the manufacturing process. A possible reason for this inefficiency is the lack of infrastructure; thus, the availability sub-dimension will influence others unfavorably. As the availability sub-dimension stands out, the other sub-dimensions are impacted positively. A smart supply chain's readiness and maturity are hierarchical by nature; thus, availability, the prior element of the system, predicts the posteriors' existence.

Exhibit 8. Scores of smartness sub-dimensions



Sustainability scores are presented in separate radar charts for each sub-dimension. Exhibit 9, Exhibit 10, and Exhibit 11 illustrate social, environmental, and economic sub-dimension scores, respectively. The radar charts illustrate sustainability sub-dimensions and guide managers through the enterprises' sustainability status and show the relative position of the items for all sustainability sub-dimensions. Among the social sub-dimension items, occupational health and safety, corporate social responsibility, stakeholder relations, and union rights top the score chart, however mobbing-free work environment, social benefits and perks, career development, and access to training has the lowest score. Relatively, the company has the lowest average scores on the environmental sustainability sub-dimension. Ecolabels, maximizing renewable energy usage, reusing resources, and reducing resource usage are prominent environmental sustainability weaknesses. Nevertheless, ISO-14000 certification, minimizing pollution, minimizing energy usage, and avoiding hazardous material are outstanding strengths. Finally, shareholder value, CRM performance, manufacturing lead time, and order cycle time reduction are the superior items of economic sustainability, conversely minimizing land and area use, and quality cost reduction items need to be developed. Accordingly, to achieve a desirable state of sustainability, the company must improve its underperformed sustainability items.

Exhibit 9. Scores of the social sub-dimension

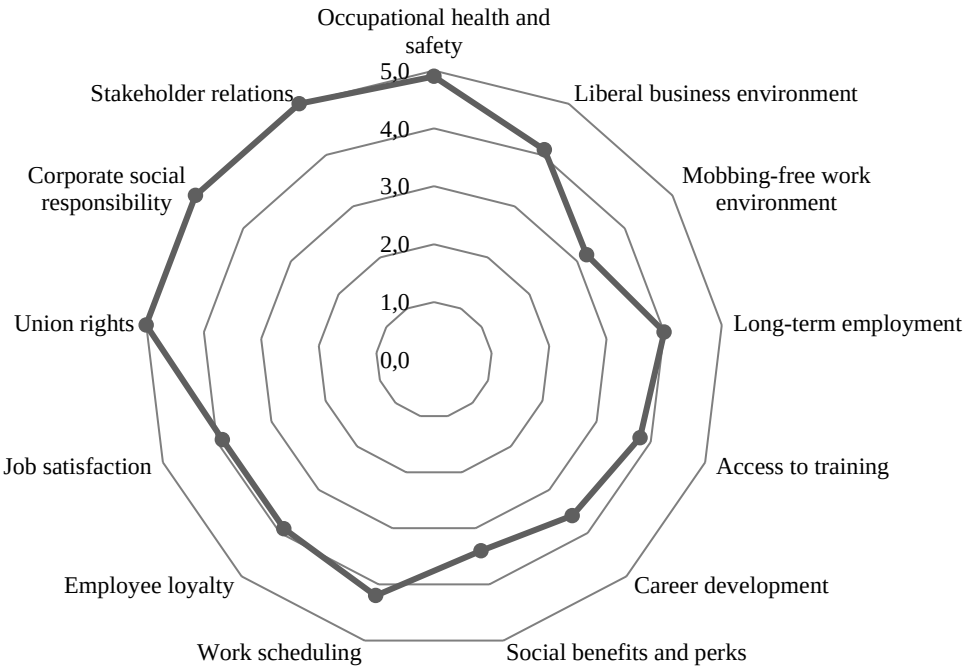


Exhibit 10. Scores of the environmental sub-dimension

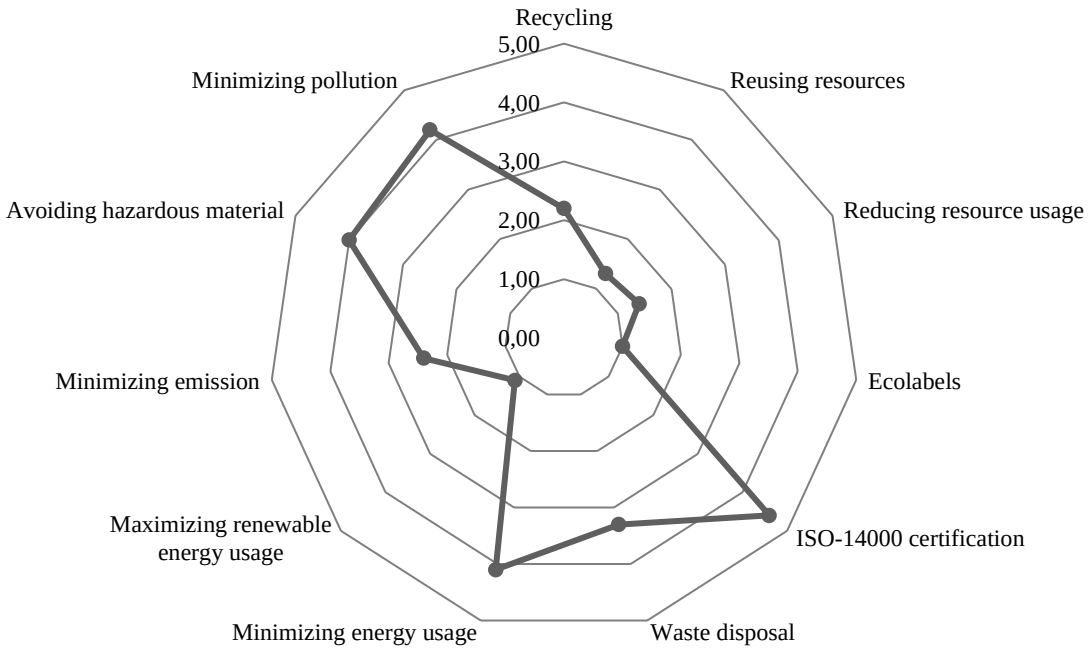
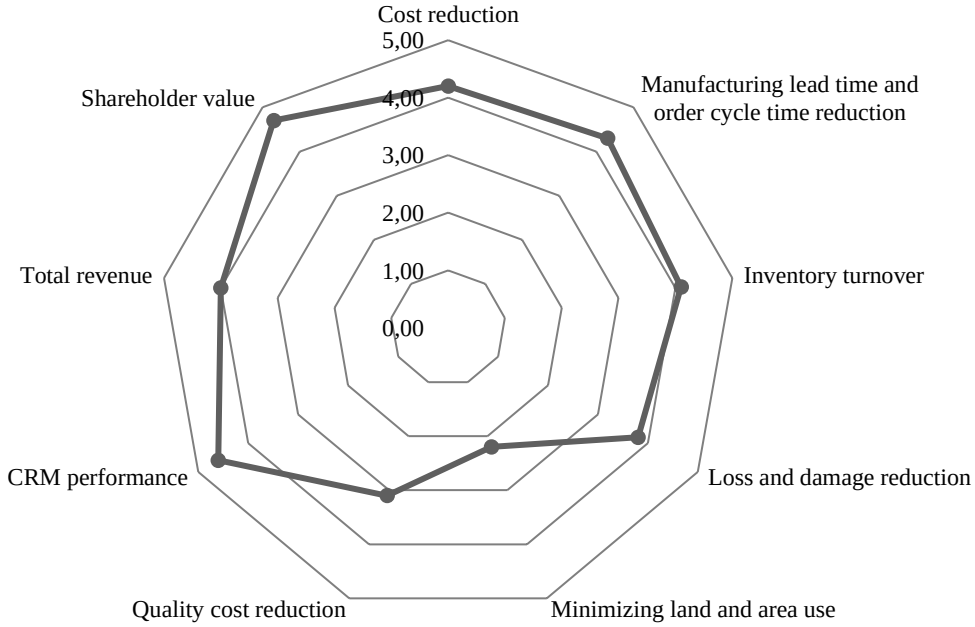


Exhibit 11. Scores of the economic sub-dimension



The S3RM score is calculated for ABC company by using the proposed model as follows in Exhibit 12.

Exhibit 12. Model scores

Dimension/sub-dimension	**Readiness and maturity score**
Social (υ_1)	4.15
Environmental (υ_2)	2.69
Economic (υ_3)	3.89
Sustainability($\bar{\upsilon}_j$)	*3.58*
Availability (μ_1)	3.06
Integrity (μ_2)	2.75
Adaptability (μ_3)	2.52
Smartness ($\bar{\mu}_k$)	*2.77*
S3RM (Ψ)	**3.18**

The ABC Company scores 3.18 out of 5.00 in terms of supply chain smartness and sustainability. Adaptability and environmental are the weakest sub-dimensions within the smartness and sustainability dimensions, respectively. These scores give details about the company's strengths, weaknesses, opportunities, and threats regarding smart and sustainable supply chain dimensions. For instance, the environmental sub-dimension is the most significant threat to sustainability since its readiness and maturity score is lower than the Likert scale's imaginary origin (mild = 3.00). More specifically, the lack of ecolabels and insufficient

renewable energy usage are the impediments to sustain environmentally. Mobbing-free work environment and social benefits and perks will grant an opportunity to be more socially sustainable when elevated to other social items since these are the two items that lower the average score of social sub-dimension.

When comparing the sustainability and smartness dimensions, available evidence indicates that the smartness readiness and maturity average score is lower than the sustainability score, considering smart technologies require more maturity of overall supply chain operations. Moreover, we observe that smartness readiness and maturity scores gradually decrease, confirming the smartness dimension's hierarchical structure. This finding is understandable since companies have a harder time investing in Industry 4.0 technologies and integrating and adapting them. These results provide managerial insights to develop a smart and sustainable supply chain strategy. Hence, the model helps the managers to assess the company's position in terms desired target state.

Conclusions

Readiness and maturity models are indispensable tools to assess an organization's smart manufacturing capabilities. These models help an organization explore digital readiness and maturity, recognize their deficiencies, and comprehensively adjust their processes with smart manufacturing. Industry 4.0 is a paradigm shift that merges new technologies such as the Internet of Things, artificial intelligence, cloud computing technology, autonomous vehicles, robotic systems, sensor and automation networks, virtual and augmented reality, and so forth into supply chain operations. The paradigm shift brought about by Industry 4.0 raises the question of its possible effects on the sustainability of a supply chain. Therefore, the digital transformation impact we have observed throughout all the supply chain activities cannot be separated from its social, environmental, and economic sustainability attributes. However, scholars and practitioners have not yet given enough attention to the need for a holistic theory that brings smartness and sustainability together. Such an approach must assess supply chains' smartness and sustainability via a model that represents the readiness and maturity level. The need for a model that measures the readiness and maturity of a supply chain by simultaneously taking smart and sustainable dimensions into account is inevitable.

Our research work aims to develop a model to assess smart and sustainable supply chain readiness and maturity. We propose the S3RM model as a conceptual framework and a measurement tool that merges TBL of sustainability with TBL of smartness. TBL of

sustainability consists of social, environmental, and economic sub-dimensions. TBL of smartness identifies the digitalization of SCM. This dimension includes availability, adaptability, and integrity sub-dimensions. Together with these sub-dimensions, TBL of smartness terminology is the originality of our study.

Nara et al. (2021) propose a sustainability-oriented model to investigate the impact of Industry 4.0 technologies on the economic, environmental, and social metrics of TBL for sustainable development. The author's model reflects the "expected average impact of digital technologies on three dimensions of sustainability." Ghobakhloo (2020) identifies the sustainability functions of Industry 4.0 technologies by conducting a systematic literature review. Bai et al. (2020) examine Industry 4.0 technologies in terms of implications on sustainability. Our study differs from these previous studies by combining smart technologies and sustainability indicators, individually weighted components of a readiness and maturity model. Thus, our model separately measures smartness and sustainability indexes, determines a combined readiness and maturity score, and gives the decision-makers insights into the company's current state.

This study makes a two-fold contribution to the literature. First, the S3RM model is the first assessment tool that measures the readiness and maturity of a supply chain in terms of smart and sustainable dimensions at the same time. Besides, TBL of smartness is the novel terminology that we add up to the literature.

The Smart and Sustainable Readiness and Maturity Index, the numeric outcome of our model, is found by computing the sustainability and smartness scores. This index score helps enterprises pinpoint, evaluate their current state of smart and sustainable supply chain readiness and maturity and guides managers to identify strategic decisions for the future direction. The model assesses company-wide sustainability and a comprehensive technological capability by simultaneously evaluating smartness and sustainability dimensions. Our study presents a detailed literature review on smart manufacturing technologies, sustainable supply chains, and the existing readiness and maturity models in the literature. Besides, the S3RM model is a user-friendly tool to identify an enterprise's current state of smart and sustainable supply chain readiness and maturity, and it is a suitable model for self-assessment.

Limitations and Opportunities for Further Research

Despite its contributions, our model has some limitations to be addressed for future research. In this research work, we implement the S3RM model in an automotive parts manufacturer.

Future research activities will extend the case studies to several companies and propose new smartness and sustainability assessment models reflecting industry-specific dimensions. Future studies might include opinions of multiple decision-makers giving unequal importance to SCM smartness and sustainability by weighting these dimensions with different coefficients. Further research is also needed to incorporate competitors' current states as a benchmarking tool to define target positions.

Notes.

Acronyms. AGV: Automated guided vehicle, AI: Artificial intelligence, BCT: Blockchain technology, CAD: Computer-aided design, CAE: Computer-aided engineering, CAM: Computer-aided manufacturing, CPS: Cyber-physical systems, CMMI: Capability Maturity Model Integration, CNC: Computer numerical control, CRM: Customer relationship management, DREAMY: Digital Readiness Assessment Maturity Model, ERP: Enterprise resource planning, ICT: Information and communication technology, IIoT: Industrial Internet of Things, IoT: Internet of Things, IT: Information technology, MES: Manufacturing execution systems, ML: Machine learning, S3RM: Smart and Sustainable Readiness and Maturity Model, SCM: Supply chain management, SRM: Supplier relationship management, SSCM: Sustainable supply chain management, TBL: Triple bottom-line, TQM: Total quality management

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Appendix I. Availability scores

Items	Availability scores				
	None	**Rare**	**Moderate**	**Wide**	**Completely wide**
Robotics and autonomous systems			2.70		
Additive manufacturing			2.60		
Augmented and virtual reality	1.00				
Simulation				4.40	
The Internet of Things			3.00		
Cloud computing				4.30	
Cyber-security					4.60
Big data and analytics				4.10	
Artificial intelligence			2.50		
Machine learning				3.50	
Blockchain technology	1.00				
Average availability score (μ_1)			**3.06**		

Appendix II. Integrity scores

Items	Integrity scores				
	Idle	**Rare**	**Moderate**	**Effective**	**Completely effective**
Robotics and autonomous systems			2.50		
Additive manufacturing		2.30			
Augmented and virtual reality	1.00				
Simulation			3.30		
The Internet of Things			3.00		
Cloud computing				3.80	
Cyber-security					4.50
Big data and analytics			3.70		
Artificial intelligence		2.00			
Machine learning			3.20		
Blockchain technology	1.00				
Average integrity score (μ_2)			**2.75**		

Appendix III. Adaptability scores

Items	Adaptability scores				
	Very Poor	**Poor**	**Fair**	**Compatible**	**Completely compatible**
Robotics and autonomous systems		1.50			
Additive manufacturing		1.80			
Augmented and virtual reality	1.00				
Simulation				4.20	
The Internet of Things				3.90	
Cloud computing				4.10	
Cyber-security					4.80
Big data and analytics		2.20			
Artificial intelligence	1.60				
Machine learning		1.60			
Blockchain technology	1.00				
Average adaptability score (μ_3)			**2.52**		

Appendix IV. Social scores

Items	Social scores				
	None	Very mild	Mild	Moderate	Severe
Occupational health and safety					4.90
Liberal business environment				4.10	
Mobbing-free work environment			3.20		
Long-term employment				4.00	
Access to training				3.80	
Career development				3.60	
Social benefits and perks (e.g., leave rights, kindergarten, food service, transportation, pension rights)			3.40		
Work schedules (e.g., work-life balance, flexible work hours, remote work, job sharing)				4.20	
Employee loyalty				3.90	
Job satisfaction				3.90	
Union rights					5.00
Corporate social responsibility					5.00
Stakeholder relations					5.00
Average social score (υ_1)			**4.15**		

Appendix V. Environmental scores

Items	Environmental score				
	None	Very mild	Mild	Moderate	Severe
Recycling		2.20			
Reusing resources	1.30				
Reducing resource usage	1.40				
Ecolabels	1.00				
ISO-14000 certification					4.60
Waste disposal			3.30		
Minimizing energy usage				4.10	
Maximizing renewable energy usage	1.10				
Minimizing emission		2.40			
Avoiding hazardous material				4.00	
Minimizing pollution				4.20	
Average environmental score (υ_2)			**2.69**		

Appendix VI. Economic scores

Items	Economic score				
	None	Very mild	Mild	Moderate	Severe
Cost reduction				4.20	
Manufacturing lead time and order cycle time reduction				4.30	
Inventory turnover				4.10	
Loss and damage reduction				3.80	
Minimizing land and area use		2.20			
Quality cost reduction			3.10		
CRM performance					4.60
Total revenue				4.00	
Shareholder value					4.70
Average economic score (υ_3)			**3.89**		

Short Biographies of Authors

Dr. Sercan Demir completed his M.Sc. degree in Industrial and Systems Engineering at the University of Southern California, Los Angeles, in 2012. He was awarded his Ph.D. degree in Industrial and Systems Engineering from the University of Miami in 2017. His current research focuses on Industry 4.0 and digital transformation, disaster risk management and humanitarian SCM, and game theory applications on supply chain management. He teaches courses such as operations management and computer simulation systems.

Dr. Mehmet Akif Gunduz obtained his B.Sc. degree in management engineering at the Istanbul Technical University in 2008. He received his M.Sc. in business administration at the Selcuk University in 2012 and Ph.D. degree in business administration at the Hacettepe University in 2017. He is presently an assistant professor at the Department of International Trade and Logistics of KTO Karatay University. His research interests are international business management, competitive strategies, marketing research, and logistics.

Dr. Yasanur Kayikci is an associate professor of Logistics and Supply Chain Management and works for the Department of Industrial Engineering, Engineering Faculty at the Turkish-German University. She received her Ph.D. in Information Business and Logistics Management from Vienna University of Economics and Business (WU Wien) and obtained M.Sc. and B.Sc. degrees in Industrial Engineering from Graz University of Technology (TU Graz) and Yildiz Technical University.

Dr. Turan Paksoy is presently a full professor and dean in the Faculty of Aeronautics and Astronautics at the Necmettin Erbakan University. His papers frequently appear at reputable and internationally recognized journals such as Computers and Industrial Engineering, European Journal of Operational Research, Transportation Research. His academic studies have been cited about 500 times in SCI journals. Dr. Paksoy's current academic interest includes lean manufacturing, logistics, supply chain management, and fuzzy decision making.