RESEARCH ARTICLE

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Analysis of Product Sustainability by Using a Risk-Oriented System Dynamics Model

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Measuring product sustainability plays a significant role to gain competitive advantage. Nevertheless, while achieving sustainable products, all related risks associated with sustainability should be considered. Previous studies are limited by the lack of the dynamic and multidimensional approaches. However, as the decision-making environment is constantly changing in the real world, a dynamic decision-making approach is required. The aim of this study is to develop a dynamic and risk-driven approach to investigate the product sustainability risks. The proposed approach considers all the related risks and interactions with a holistic view covering environmental, economic, and social sustainability. To deal with the dynamic and multidimensional nature of product sustainability, system dynamics is proposed. The results show that increasing the production capacity of the company and maintaining the production emphasizing innovation have led to improvements on both product sustainability and the main dimensions of sustainability. The realization of Industry I4.0 applications can be an effective strategy for the business to increase product sustainability. This study is supported with a case study implemented in the manufacturing industry to confirm the applicability of the model. This paper is useful for industry and policy makers to observe the potentials impacts of products sustainability risks.

1. Introduction

Sustainability has become a significant issue for businesses to gain competitive advantages. Sustainability aims to achieve effective utilization of natural resources and environmental effects, economic growth, and social awareness.[1] Therefore, companies have acquired a responsible point of view in financial, environmental, and social issues.

Nowadays, sustainable product development is a highly important issue because of the rapid depletion of raw materials, increasing social and environmental impacts of products, governmental regulations, and the awareness of social and environmental issues.[2] Besides, this concept, which is rapidly gaining importance, causes several risks while creating various opportunities to the organizations. Businesses that redesign their production processes and reorganize their products by assessing the risks and taking measures against them are to gain a competitive advantage. For this reason, they aim to develop a new market demand by diversifying their products in order to produce more sustainable and greener products.

Moreover, various methods exist to measure and evaluate the effects of product sustainability. However, most of them do not consider and evaluate three main sustainability aspects, which are environmental, social, and economic aspects. Several methods have been suggested to obtain a more extensive evaluation, which can take interrelations in three dimensions to fulfill the need of such a method, and it is suggested to do research covering social and economic impacts and the environmental effects as well. As a result, life cycle sustainability assessment (LCSA) appears as a new study field. However, LCSA does not cover the analysis of feedback mechanisms and interrelations between system components and requires systems notion applications. Besides, most of the presented methods related to measuring product sustainability have remained static when analyzing the behavior models of variables changing over time. However, system dynamics (SD) models can handle uncertainties via scenario-based analysis. Besides, SD models are effective in making future decisions as it uses cause-effect relationships.[3]

Rebs et al.[1] conducted a comprehensive literature review on the SD for sustainable supply chain management based on the systems thinking approach. The results show that risk management studies did not mention or formalize economic, environmental, or social sustainability. Among 62 papers, 8 papers used SD models that cover a formalized risk construct and 13 papers included risk by sensitivity and scenario analyses, and 19 papers mentioned managing risks. However, SD models mainly consider economic risks, but do not evaluate environmental and social risks. Besides, SD models are beneficial to evaluate uncertainties and deal with risks. At least, scenario analyses are performed to analyze the model behavior based on parameter changes.[1]

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This study aimed to explain the following research objective:

- To assess product sustainability risks with a holistic view that tackle with environmental, economic, and social sustainability

To achieve these objectives, an SD model is developed to analyze the interactions of product sustainability risk indicators related to the main dimensions of sustainability over time.

The remainder of this study is organized as follows: section two presents product sustainability, product sustainability risks, SD approach, and the literature review about sustainability. Section three presents research methodology. Section four includes the application of the proposed approach and the results of the study are discussed. In the section five includes discussion and implications. Finally, section six discussed concluding remarks and several ideas for future research, respectively.

2. Theoretical Background and Related Literature

This section first focuses on the concept of sustainability, product sustainability and product sustainability risks and then related studies are presented.

2.1. Product Sustainability Risks and TBL Approach

Sustainability has been widely adopted in various industrial fields. Therefore, many definitions exist for this concept. The first known definition of sustainability is “meeting the needs of the present without compromising the ability of future generations to meet their own needs”.[4] According to this definition, accurately analyzing the needs of future generations and the consumption of resources are vital to provide with an efficient way.

Sustainability can only be achieved considering both economic benefits and the environment and society. Therefore, sustainability is a framework that incorporates economic, environmental, and social dimensions holistically.[1] Fiksel et al.[5] provided the first framework to measure the sustainability performance and suggested that three dimensions of sustainability should be considered as a whole. Thus, various approaches are used to assess sustainability. Triple bottom line (TBL), a well-known approach, considers sustainability in a framework encompassing three different dimensions as economic, social, and environmental. Similarly, these three pillars of sustainability are defined as planet, profit, and people in various studies.[6]

The economic aspect has been regarded crucial in production processes since the beginning of the 20th century. Recently the social and the environmental aspects have gained significance. However, to reach the ultimate sustainability goal, an assessment should consider the economic dimension, and also the social and environmental aspects. These three main dimensions are strongly interrelated and should be considered simultaneously and evaluated systematically. Organizations should integrate their process into employees, customers, and shareholders to provide a sustainable manner. Nowadays, as industry and technology develop and the population increases, resources need to be managed efficiently.[7]

Besides, organizations should also integrate sustainability into their new product development cycles, their current products, and decision-making processes. The notion of sustainable systems and sustainable products are created based on this assumption. Business should create values for shareholders such as customers, employees, investors, and the society by producing sustainable products. Establishments, which can produce sustainable products, increase customer satisfaction by producing environmentally friendly products and create a positive effect on its employees and the society through social changes they accomplish, besides acquiring economic advantages. Therefore, businesses are trying to produce more sustainable products by developing and reorganizing their production processes.[8]

Sustainable products are those which provide environmental, societal, and economic benefits while protecting public health, welfare, and environment from raw materials to dispose.[9] Dinh et al.[10] defines a sustainable product as a concept that reduces resource consumption, minimizes waste, and creates customer satisfaction by meeting the customer’s needs. Sustainable products intend to minimize environmental impacts and provide the highest possible customer satisfaction. Besides, these products give companies various advantages like on-time delivery, lower raw material costs, betterment of occupational health and safety, the provision of high demand and customer satisfaction, and environmental regulations.

Moreover, sustainable society is only possible through sustainable products. Therefore, various methods are necessary to evaluate product sustainability. In product sustainability, the TBL approach, one of these methods, can be applied to each phase in a product’s life cycle. Because of the encouragement of producing sustainable products and the demand of sustainable products by shareholders, businesses should integrate sustainability into their production cycles.[11] In order to be successful in this approach, it is necessary to redesign product life cycles and adopt an eco-design approach. In the “Eco-design” or “Design for Environment” approach, while the environmental aspect is considered, the social and health aspects are mostly ignored. A multidimensional approach is needed which includes various components like environmental risk management, product reliability, waste management, and conservation of resources.[12]

The EU 2017 states that creating framework is necessary for action to consider people, planet, prosperity, and peace.[13] Thus, the industrial transformation process should adapt to provide economic development, social equality based on ecological consideration. Industrial organizations also change their conventional manufacturing to new production process that provide sustainable value creation. I4.0 concept, which emerged as a paradigm, provides companies with various advantages in order to create sustainable value. I4.0 has a significant effect on the interrelationships of industrial value creation for entire the life cycle of a product.[7,14] The fourth industrial revolution has the ability to achieve social and ecological boundaries as well as focusing on the economic dimension, such as increasing production capacity to ensure a more sustainable future. With I4.0, you will contribute to sustainable development by providing more flexible production and benefiting from renewable energy sources.[15]

Besides, though I4.0, the resources in the process are used more efficiently by monitoring the entire supply chain and obtaining data, which supports the implementation of the circular economy. Nara et al.[16] analyzed TBL approach for sustainable development. They investigated the impact of digital technologies on key performance indicators on sustainable development with fuzzy TOPSIS multi-criteria method. In order to create a balance between three aspects of sustainability, business need to emphasis on sustainable development. When making capital investment decisions by applications I4.0 technologies, it is significant to analyze the relationship between society and sustainability.[17,18] The potentials of I4.0 technologies make significant contributions to social sustainable development.[16]

Besides, businesses should develop a risk-oriented approach in an ever-changing dynamic decision-making environment. Risk is the presence of a possibility which can prevent any of an establishment's strategic, financial, and operational goals. Within a product cycle, there exist both environmental and production-related risks. Environmental risks should be investigated from the point of sustainability, which is only possible through risk management approaches. Ghobakhloo[7] stated that business have difficulty for conducting their strategies since they only focus on economic dimensions of TBL perspective. Therefore, sustainable development can achieve when environmental and social dimensions are considered. Digital technologies should also be realized by focusing not only on economic sustainability, but also on three dimensions to balance in TBL for sustainable development.[19,20]

As the TBL approach argues, in the context of sustainability risks, the environmental, social, and economic risks and the interactions between these risks are determined. For instance, while a late delivery, which results in customer complaints, causes a loss of reputation for the company, an increase in such complaints will create a non-value adding cost, and leading to a risk of a higher cost in production. In studies about sustainability, it is necessary to predict and categorize the environmental impact of possible risks.[21] Risk management approaches are useful in providing the creation of more sustainable systems to consider in a holistic way, which can be effectively applied. Hence, to achieve sustainability, three major dimensions that are substantial in the TBL- economic, environmental, and social-should be integrated to risk approaches.

Related studies are discussed in the next section.

2.2. Literature Review on Product Sustainability

Studies on sustainability have increased in recent years. Sarkar et al.[6] discussed three dimensions to evaluate product sustainability during the design stage. The LCSA method is applied as a sustainable measurement method to classify these bottles into three groups as disposable bottles produced for recycling, reusable metal bottles, and plastic repackaging bottles, and investigated the effects of these different bottles in social, economic, and environmental dimensions. Shuaib et al.[22] suggested the use of product sustainability index to measure product sustainability for the whole life product life cycle. Feng and Mai[23] used the fuzzy multi-criteria decision-making method to assess functionality, manufacturability, and reusability to deal with three main dimensions of sustainability.

Studies related to the integration of sustainability to risk management and product sustainability have gained prominence in recent years. Various approaches have been adopted and several studies have been conducted to measure product sustainability. Yılmaz and Flouris[24] present a conceptual framework for sustainability risk management. This study considers the combination of financial, environmental, and social justice performance based on the TBL. With the use of the TBL approaches, product value should be maximum while risks encountered in environmental and social dimensions are minimized. Sabaghi et al.[25] applied fuzzy technique for product sustainability assessment based on environmental, economic, and social effects of product life cycle. To tackle with uncertainty and fuzziness associated with sustainability problems, Giannakis and Papadopoulos[26] considered the sustainability risks encountered in supply chain in their study and intended to designate which risks are more important to devise effective sustainability strategies. Göçer et al.[27] argued that the risks are interrelated and these risks should be considered in a holistic way through a dynamic process.

Based on the reviews related to sustainability concept, socio-ecological structures are mostly ignored. However, sustainability is closely connected with industry, society, and government.[28] There are limited studies that use the SD modeling approach. For instances, Lee et al.[29] suggested the need for a multidimensional and dynamic structure to measure sustainability. They developed an SD model on a public bicycle system, and observed the behavior of five different components through time and provide improvements in the system through scenario analysis. Marvuglia et al.[30] presented a study emphasizing the need to create an SD model. Onat et al.[31] developed an SD model to analyze the impact of alternative vehicle technologies on sustainability. They composed a causal loop diagram to show the economic, social, and environmental impacts on a transportation system. In an attempt to evaluate the sustainability of Brazilian ethanol production, Guevara et al.[32] developed causal loop diagrams to exhibit the relationships in the system and proposed a SD model. Liu and Zeng[33] developed an SD model to investigate the risks in renewable energy investment projects. Elsawah et al.[34] contributed to the more effective conducting of SD models by using five different case studies. Onat et al.[3] made an extensive literature review to reveal the current difficulties and latest developments in LCSA applications. Alamerew and Brissaud[35] created an SD model in waste electrical and electronic equipment for product recovery management system to observe the interrelations of economic, social, and environmental aspects in addition to considering administrative and regulatory factors by using feedback loops. Yao et al.[36] proposed a method integrated especially for waste cell phone management and recycling. Initially, the indicators were determined through the LCSA approach and then an SD model was developed to analyze different scenarios. Williams et al.[37] carried out a comprehensive literature review which encompassed systems thinking and the concept of sustainability.

As mentioned above, numerous risk management approaches such as enterprise risk management, multi-criteria decision-making techniques, and simulation tools have been used to measure sustainability. However, the structural complexity of sustainability and the interrelations of social, environmental, and economic dimensions necessitate a systematic multi-dimensional approach.[1] However, only a limited number of researchers study this concept holistically through the concept of system approaches, especially considering social dimensions.

In order to fill the gap, this study uses the SD modeling among system simulation tools to analyze the risks, dynamic relations between the risks, and the effects of the long-term decisions. The future impacts are investigated through scenario analysis.

3. Research Methodology

In order to analyze the system, determine product sustainability risks in the company and identify relationships between them first in-depth case-study approach is used. Then, to success mentioned research objective of this paper, the SD approach is proposed by considering three aspects of product sustainability in the paper. Thus, the SD approach is employed to measure product sustainability in this study.

Sterman[38] defines a network containing feedback loops, problem cause and effect relationships in the SD approach. The structure of a system is explained through feedback loops, which are positive feedback loops and negative feedback loops. While positive feedback loops reinforce the system, negative ones balance it. The SD was initially defined by Jay Forrester in the 1950's as "industrial dynamics".[39] Forrester explained the SD as "a way of studying the behavior of industrial systems to show how policies, decisions, structure, and delays are interrelated to influence growth and stability".[39] The approach of "Limits to growth" by Meadows et al.[40] were suggested in 2013, aiming to tackle complex socio-ecological problems. This approach is still commonly used in sustainability measures. The structure of the system is analyzed by expressing the interrelations of all the variables in the system through feedback loops. The SD is beneficial for decision makers by providing possible future conditions in changing decision-making environments with policy and scenario analysis.[41]

Figure 1 illustrates the steps for the SD modeling process. In the first step, system boundaries are determined. The structure of the system is designed by creating the feedback loops and the variables regarding the problem. In the second step, a causal loop diagram illustrating the defined variables and feedback loops is formed. Interacting variables are determined and how they influence each other is investigated. A diagram systematically illustrates these relationships. In the third step, a SD simulation model is created by giving values to the variables. The system is operated to observe the behaviors of the variables in time. In the fourth step, the system structure is tested. In this phase, the model is improved through alternative scenarios. The accuracy of the model is tested in the fifth step.

The SD indicates the structure of the system by addressing issues such as feedback, stock, and delay, and enables the analysis of the system through simulation. The SD approach is the process of effectively understanding and managing the interrelations of the system and its nonlinear complex nature.

The matters of sustainability also have a dynamic process due to changing environmental conditions. A structural model must be established that is adaptable to changing conditions. Größler and Strohhecker[42] imply that the SD approach is suitable for sustainability studies and can be applied to many issues in sustainability. By analyzing scenarios, companies have the option to take the necessary precautions against them in a proactive approach or decide to adopt that particular policy or not by means of the prepared analysis. Via SD simulation modeling tools, it is possible to effectively realize decision making in a real-world environment.

Moreover, risk management is a difficult process due to the complex and dynamic structure of the risks. In the risk assessment process, using static evaluation models leads to an ineffective assessment of the process. The dynamic structure of the risks can be illustrated with the SD approach, one of the methods used to observe and analyze the change of risks in time. The difference of SD as opposed to other approaches in the analysis of the structure of complex systems is the usage of feedback, stock, and flow, which makes it possible to analyze the structure effectively.[33] The interrelations of three major dimensions of sustainability can be seen through systems thinking approach. SD models are used to help better understand and have a better decision-making process.[34,43] Therefore, the SD model is developed to measure product sustainability by considering all the risk interrelations in this study.

4. Implementation: A Case Study in Manufacturing Industry

This section presents information about the firm where the application is conducted. Then, the implementation steps of the proposed SD model are presented.

4.1. Company Profile

The company was established in 1945 and was renamed as a manufacturing and trading company in 1976. Its production

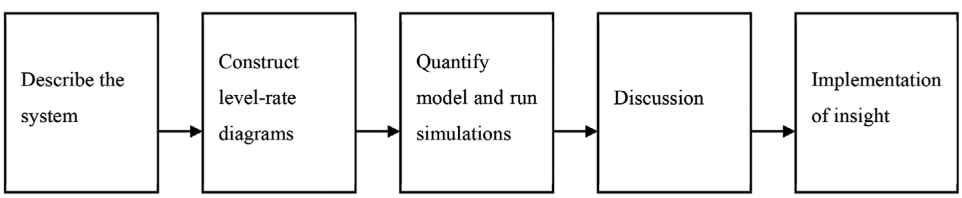

Figure 1. SD methodology. Reproduced with permission.[42] Copyright 2012, World Scientific Publishing.

range includes all types of suspension springs for light, medium, and heavy commercial vehicles. It was recognized as a research and development center in 2010. Being a global brand, the company accepts working through awareness of social responsibility in all activities, which is a fundamental aspect of work ethics and respect for people and the environment. Besides, employees strive to fulfill their social responsibilities as individuals. The company creates innovative design solutions to meet customers′ demands for optimum performance, durability, and efficiency in various commercial vehicle applications, to develop the most advanced design, production, and management technologies, to create a healthy work environment, and to maintain sustainable relationships with stakeholders by working for humanity, environment, and nature.

Besides, the company, which is an automotive supplier industry, aims to integrate digital technologies in all of its production processes. The company aims to improve its knowledge in this regard by taking part in projects involving digital transformation endeavors. Striving for the achievement of Sustainable Digitalization, the company provides much training and participates in digital fairs. It aims to bring its digital applications to the field completely in the digital transformation process. In 2020, the case company was awarded the Digital Transformation Project Award for their projects on digital transformation fields. The company is still constantly exploring the impact of digital transformation on production processes and products.

4.2. Application of the Proposed Approach

This section presents the stages of the SD model application process for measuring product sustainability.

4.2.1. Description of the System

Due to increasing legal regulations, customers' preference of environmentally friendly products, establishments' tendency to lower waste amount through recycling, and the need to improve working conditions, companies place a great emphasis on product sustainability to gain competitive advantage. It should be emphasized that while measuring product sustainability the risks should be evaluated extensively. Considering these facts, this study proposes an SD model for measuring product sustainability. To confirm the applicability of the proposed model, an implementation is conducted in an international manufacturing company. Product sustainability is measured by analyzing the risks, which the company confronts. The risks in economic, environmental, and social dimensions and their interrelations are considered. By considering the environmental, social, and economic dimensions, the risks affecting product sustainability and the indicators used in the analysis of these risks are identified. A total of 31 risks and indicators are designated, 16 of which are about economic dimension, while 9 risks are related to the social and 6 risks to the environmental aspect. Definitions of these risks and indicators about three dimensions of sustainability are elaborated in **Table 1**.

4.2.2. Causal-Loop Diagram of the Model

To analyze the interrelations of risks, it is necessary to observe how the risks in the system influence each other by using positive and negative feedback loops after defining the interrelations of the system's variables. Interrelationships of the variables are illustrated using a causal loop diagram in **Figure 2**. These relationships are developed by using expert opinions that are worked with different department such as general manager, supply chain manager, production department, information technology manager, sustainability engineering, information technology manager, sustainability engineering, sustainability environmental engineer, quality department team leader, production department in the case company. Risks affecting product sustainability have been discussed considering environmental, social, and economic dimensions.

First, the interrelationships of risks considered in the environmental dimension of sustainability are explained in detail. As the compliance of governmental laws increase, working environment risk level effect and environmental accidents decrease. Thus, companies reduce their risks through improvements on occupational health and safety and environmental applications they put into action by conforming to governmental regulations. The more a company invests in governmental regulations, the more it complies with governmental laws by creating positive feedback loops. Besides, environmental accident cause pollution in the system, and the pollution caused by an organization has a positive relationship with working environment risk level. As the pollution caused by an organization decrease, working environment risk level drops also. For example; pollution and disorder in the work environment leads to many risks in occupational health and safety. There is a negative relationship between pollution caused by organization and environmental sustainability. It can be seen negative feedback loop B1 in Figure 2. Sustainable products are designed to minimize the negative effects on environment. Environmental pollution has negatively affected the production of sustainable goods. In addition, governmental laws have positive effects on working environment risk level. This type of risk, which is considered in environmental dimension, is also related to the employee turnover ratio in social dimension. Working environment risk level and employee turnover ratio have direct positive relationships. As employees do not want to work under unsuitable conditions, termination of employment and the number of inexperienced personnel increases. It can also be stated that there is a positive relationship between recycling and level of innovation. As companies give more importance to new products, they can produce more sustainable products. Product and energy waste have a negative relationship with recycling. When a company increases its capacity to produce recyclable products, product and energy waste decreases. As product and energy waste decreases, environmental sustainability increases which results in a positive feedback loop by raising the level of compliance with the law. Improvements in environmental dimension contribute to the company's goal of producing sustainable products.

When it comes to social risks and the relationships between them, if employee turnover ratio increases, physical load also increases. The rate of employees leaving their company has

Table 1. Definitions of sustainability risk indicators.

Sustainability Risk Indicators	Definition
Environmental Dimension	
Environmental accidents	All types of unintentional explosions, fires, and hazardous material emissions which negatively affect environment or human health.[26]
Product and energy waste	All types of used, unwanted, or hazardous materials.[26]
Compliance of governmental laws	Defined as the corporate decisions being in accordance with the law in environmental aspect and employee health.[44]
Pollution caused by organization	The results of any application, which causes damage to the environment or harms any living thing in the nature during the production process.[12]
Recycling	Returning of the materials, which could be used again, to the production cycle after undergoing various processes.[45]
Working environment risk level effect	Any kind of risk level that employees face in their working environment during the production process.[46]
Social Dimension	
Worker competency	Employees' fulfillment of their responsibilities and tasks in providing value.[47]
Employee turnover ratio	An indicator of how long the employees will work in the company.[48]
Stakeholder engagement	Considering the interests of all parties by including customers, shareholders, and employees into all phases of production.[49]
Human resources management performance	All efforts toward the purposes of the organization such as recruitment, administration, and supervision of employees.[50]
Physical load	A measurable representation of the resources spent on the accomplishment of any task.[51]
Capability of human resources personnel	The role of human resources personnel in designating the right person for the right job.[52]
Effective training hours per employee	Providing necessary and sufficient training for the employees about their functions in the company.[53]
Company reputation	Positive and negative opinions of people about the company.[54]
Information infrastructure	Structures supporting the information technologies used by the company.[55]
Economic Dimension	
No-value added cost	Expenditure that adds to the total cost of a product but does not enhance its value from a consumer perspective.[56]
Order fulfillment errors	Any errors occurring in the reception, transportation or delivery of an order.[57]
Unit cost	Company's cost to build or create one unit of product.[58]
Product obsolescence	When a product ceases to be useful and fail to meet the needs of the customers.[59]
Customers claims	The condition of dissatisfaction with a product by a customer.[60]
Flexibility	Amount of production which is regulated by the needs of customers.[61]
Quality level	Defined as the condition of being fit for purpose or use, meeting the needs of a customer in a timely manner, and being conformant to the standards.[62]
Efficiency	Achieving higher output in terms of volume and quality from the same input.[63]
Level of innovation	The level of the company in creating a new product, idea, or method.[64]
Investment availability	Capability of a company to find suitable investment opportunities in topics such as production, innovation, information infrastructure and conformity with the law.[65]
Production capacity	Volume of products that can be generated out of available resources.[66]
Production cost	The total costs incurred by a business when manufacturing a product.[67]
Late delivery	The situation when the delivery of a product does not meet the deadline.[68]
Price	An amount of money paid for a product.[69]
Profitability	Company's ratio of yielding profit.[29]
Sales	The number of products the company sells in a particular time period.[29]

negatively affects working competency of staff. As worker competency increases, physical load is decreases. Thus, this negative feedback loop B2 can be seen in the Figure 2. As human resources performance surges, the ratio of employees continuing to work with the company also rises. In addition, there is a positive relationship between working environmental risk which we consider in environmental dimension and employee turnover ratio. Considering all these relationships, it can be stated that employee turnover rate and social sustainability have negative relationship. As worker competency rises, employee workload goes down, and it results in an elevated level of social sustainability. Furthermore, worker competency and effective training hours per employee index scale up accordingly.

When effective training is given, working competency of employees increases. An increase in the human resources management performance also leads to an increase in this index. Improvements in information infrastructure and capability of human resources personnel augment human resources management performance. This increase leads to an upward movement in stakeholder engagement, which is also related to company reputation. As a company gains reputation, confidence in that company is assured and stakeholders' engagement increases. An advance in stakeholder engagement and company reputation also increases social sustainability. As customer claims decrease, company reputation rises. This negative feedback loop can be seen in the balancing loop B3 in the Figure 2.

Information infrastructure and physical load directly affect two main dimensions. Improving information infrastructure influences economic dimension by lowering order fulfillment errors. Companies augment their information infrastructure through investments. As a result, through positive and negative feedback loops, worker competency, stakeholder engagement, company reputation and employee turnover ratio influence the social dimension. As order fulfillment errors, which is one of the risks considered in economic dimension, rise up, deliveries experience delays.

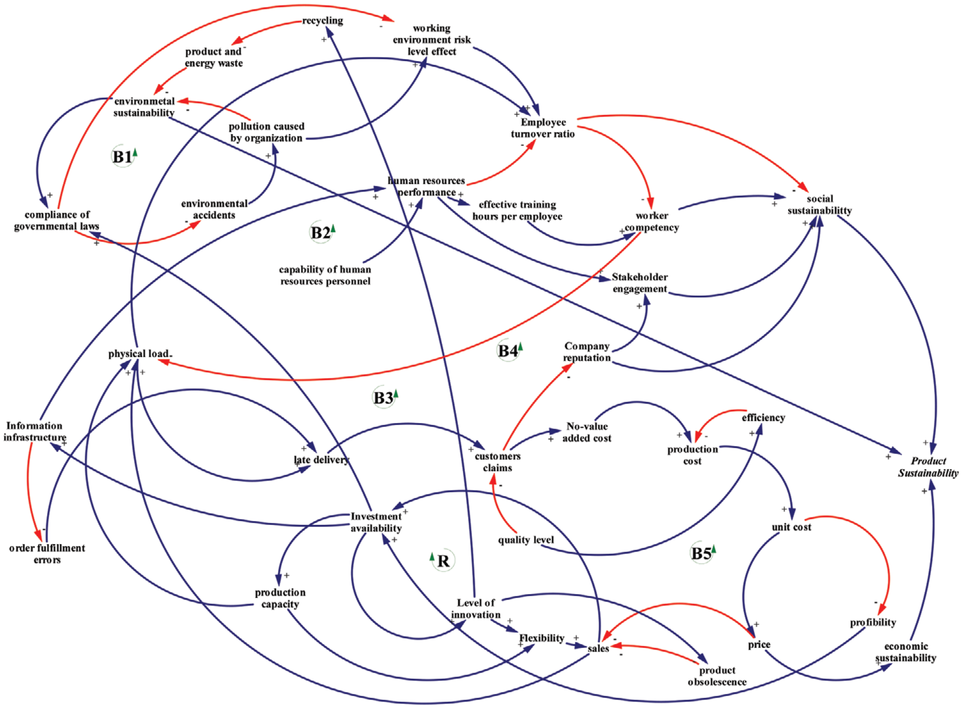

Figure 2. Causal Loop Diagram.

Flexibility is positively affected by the level of innovation. Advances in innovation decreases product obsolescence. As sales increase, the workload in social dimension goes up as well, however the sales continue to increase as the company manufactures innovative products that meet the needs of the customers. An increase in price causes sales to drop. The price, which is influenced by many factors as a result of feedback loops, affects sustainability in economic dimension. Moreover, an increase in workload in social dimension will also raise late deliveries. When late deliveries multiply, customer claims are to surge. As a result of customer claims, which cause reputation loss, returned products rise in number and it increases no-value added cost. If the company produces high quality products, the amount of customer claims decreases and it results in a higher level of productivity. The increase in no-value added cost and lower levels of productivity influences production cost both positively and negatively. As production costs rise, unit costs also surge. As unit cost rises, the price increases and results in a lower profitability. As the profitability and sales of the company mount, its capacity to invest increases accordingly. The company directs its investments toward increasing its production capacity, legal regulations, and information infrastructure. This balancing B4 and B5 loop can be seen in the Figure 2.

As the company's sales increase, the firm makes new investments and the level of adaptation to innovations increases with new investments. Therefore, with innovations, the firm increases its flexibility and this has a positive effect on sales. It can be seen in the reinforcing loop R in the Figure 2. Through positive and negative feedback loops, the effects of interrelations of risks in three major dimensions on sustainability are shown in a causal loop diagram in Figure 2.

4.2.3. Quantification of the Simulation Model

Stock, flow, and converters, whose interrelations are defined by using feedback loops, are explained and the equations and parameters, which are designated for the quantification of the model, are presented in this phase of the model. In order to simulate the model, causal loop diagram is quantified. Stella Architect software is used to create the SD model via stock and flow diagram.

Stock-and-flow diagram is presented in **Figure 3**.

Stock, flow, and converters are mainly used in the model. Stocks explain the status of the system increasing and decreasing variables in the system are shown with stocks. The stocks considered in the model are specified as level of innovation, compliance of governmental laws, information infrastructure, production capacity, employee turnover, and sales. Flows are utilized to display an action or activity. Thus, in the model, the flows are specified as capacity change, compliance of governmental laws change, employee turnover change, information infrastructure change, innovation change, and sales change. Besides, while converters transform inputs into outputs, connectors are used to show the relationships and interactions in the system. Converters in the model are specified as; average sale, capability of human resource personnel, company reputation, compliance of governmental laws effect, compliance of governmental laws rate, compliance of governmental laws ratio, customers claims, desired profitability, economic dimensions, effective training hours per employee index, employee turnover normal, employee turnover target, environmental accidents, environmental sustainability, flexibility, human resource management performance, information infrastructure rate, information infrastructure ratio, investment availability, late delivery, level of innovation rate, level of innovation ratio, max price, no-value added cost, order

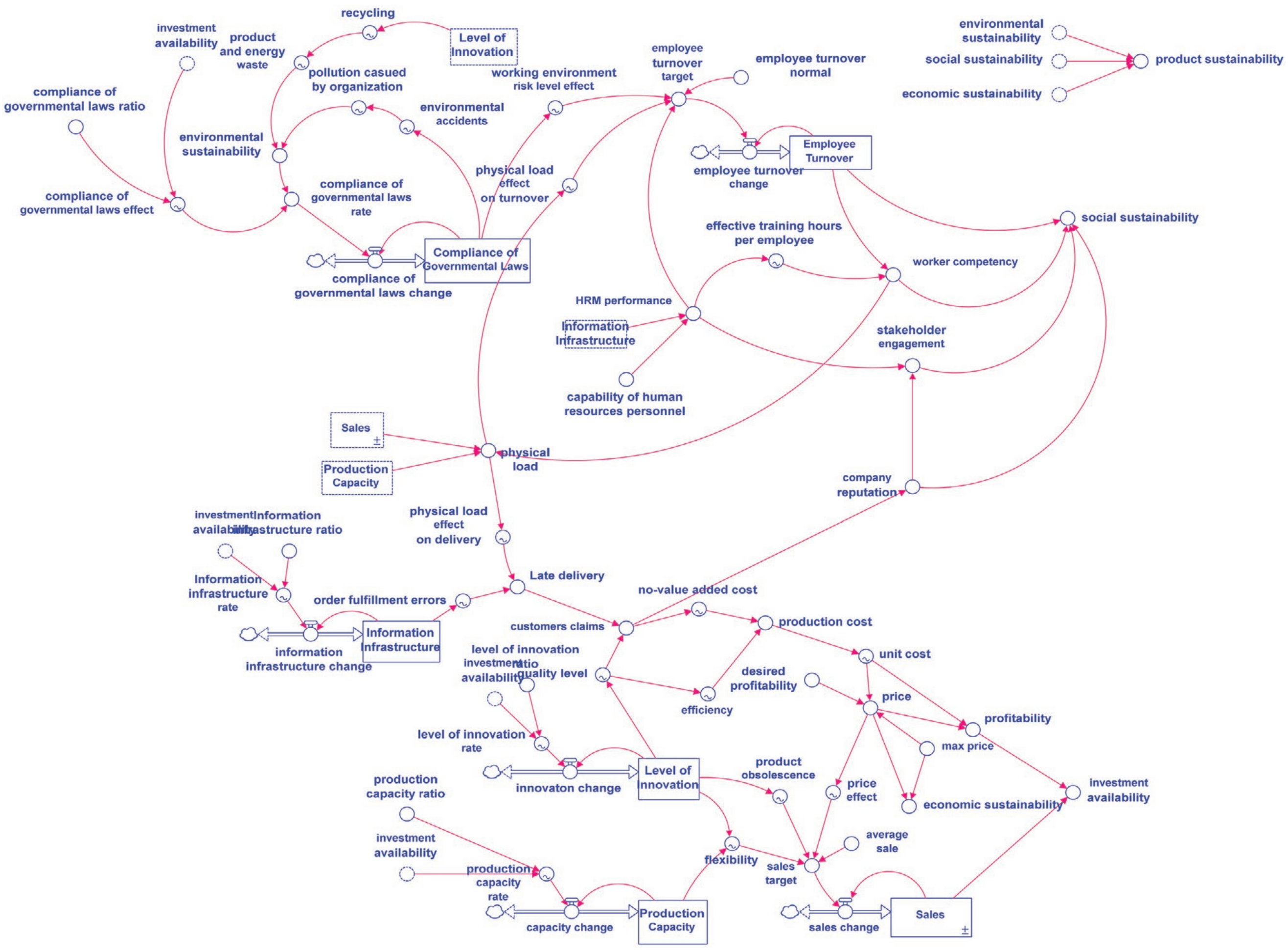

Figure 3. Stock and Flow Diagram.

fulfillment errors, physical load, physical load effect on delivery, physical load effect on turnover, pollution caused by organization, price, price effect, product and energy waste, product obsolescence, product sustainability, production capacity rate, production capacity ratio, production cost, productivity, profitability quality level, recycling, sales target, social dimensions, stakeholder engagement, unit cost, worker competency, and working environment risk level effect.

After developing stock and flow diagram, quantification of the model is provided by the participation of ten experts from the case company using semi-structured interviews. In the model, the related information is gathered from one General Manager, one Supply Chain Manager, two engineers from the Production Department, two from Sustainability Engineering, two Information Technology Manager, one Sustainability Environmental Engineer, and one Quality Department Team Leader who have more than 5 years' experience in their area of expertise. These experts are indicated in **Table 2**.

These participants were asked to assess the risk parameters weighing between 0–1 and the parameters were quantified by taking the average of the opinions taken from each expert. The average of each parameters value is indicated which are the initial values for the simulation in **Table 3**.

4.3. Results

The model is run using the equations and the initial values, and the run time of the model is 12 months. This study focuses on observing product sustainability risks with a holistic view considering environmental, economic, and social sustainability aspects. Thus, it is aimed to analyze product sustainability and

Table 2. Details of Experts.

Experts	Position	Experience
1	General Manager	29
2	Supply Chain Manager	26
3	Production Department	15
4	Information Technology Manager	8
5	Sustainability Engineering	9
6	Information Technology Manager	8
7	Sustainability Engineering	7
8	Sustainability Environmental Engineer	6
9	Quality Department Team Leader	13
10	Production Department	19

Table 3. Parameters of the model.

Parameters	Values
Compliance of Governmental Laws Ratio	0.29
Compliance of Governmental Laws	0.50
Employee Turnover Normal	0.25
Information Infrastructure	0.50
Capability of Human Resources Personnel	0.50
Employee Turnover	0.25
Information Infrastructure Ratio	0.23
Desired Profitability	0.15
Max Price	1.00
Average Sale	0.50
Level of Innovation Ratio	0.23
Level of Innovation Ratio on Flexibility	0.47
Production Capacity Ratio	0.26
Production Capacity Ratio on Flexibility	0.53
Sales	0.50
Level of Innovation	0.50

behavior model in three dimensions with the proposed model. Thus, the results of the simulation indicate first product sustainability and then the impact of sustainability on environmental, economic, and social dimensions. Simulation results are presented in **Table 4**.

Product Sustainability and three main dimensions: Considering the TBL approach, the 12-month behavior pattern of the environmental, economic, social, and product sustainability is illustrated in Table 4.

Product sustainability indicates the same behavior pattern in the same direction with the social and economic dimensions, whereas the parameters in the environmental dimension have a linear relationship with product sustainability. It can be seen in **Figure 4**.

Improvements in the performance of human resources decrease the employee turnover rate and thus, social sustainability value is positively affected by these variables in **Figure 5**.

Table 4. Results of the model based on current situation.

Dimensions/Months	0	3	6	9	12
Product Sustainability	0.536276	0.524709	0.540920	0.559629	0.579216
Economic Sustainability	0.766406	0.746381	0.755538	0.755996	0.776946
Social Sustainability	0.342422	0.307192	0.324886	0.347904	0.372249
Environmental Sustainability	0.500000	0.520555	0.542334	0.564988	0.588453

In the system, the variable of customer claims is associated with both the social and economic dimensions. In this respect, the behavior pattern of customer claims over time is analyzed on these two dimensions. A decrease in customer claims positively affects both the social and economic dimensions. **Figure 6** illustrates the effect of customer claims on product sustainability.

The company invests in four different branches. It directs its investments to keep up with the developments, reinforce its information infrastructure, increase its production capacity, and finally to improve the systems necessary for regulatory laws. Consequently, as the amount of investment has increased, the values related to the variables of social, environmental and economic sustainability have made progress in the 12-month period due to improvements in three main dimensions in **Figure 7**. Adapting for sustainable and digital technologies require significant investment. Therefore, in the first three months, investment availability is decreasing but after these months, investments are increasing dramatically when recover the cost of an investment.

The company's reputation affects the social and economic dimensions. As the company gains reputation, shareholders' respect toward the company builds up, positively affecting the sustainability variable in the social dimension. As the quality level rises, fewer customer claims occur, which results in a higher reputation

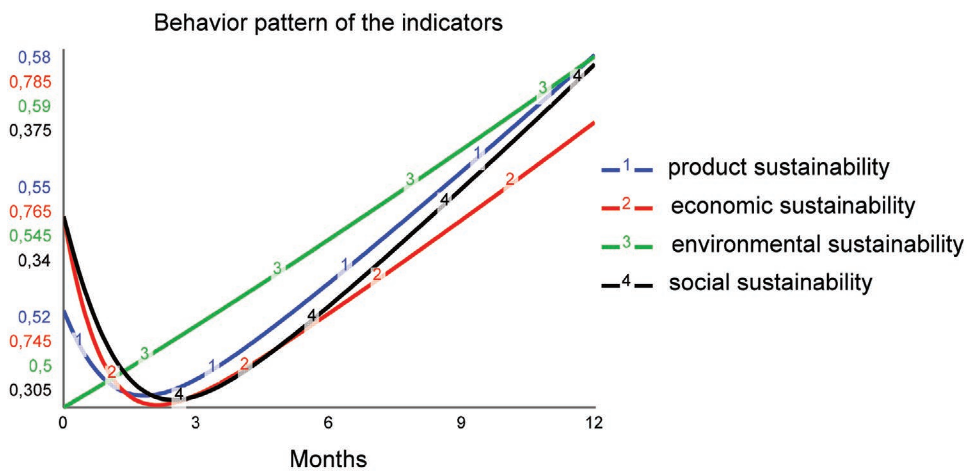

Figure 4. Behavior pattern of the indicators.

Figure 5. Behavior pattern of indicators regarding social sustainability.

level for the company. **Figure 8** indicates the behavior pattern of company reputation on economic and social sustainability.

When the behavior graph of the physical load variable is considered, a sharp increase in physical load can be observed until t = 2 (**Figure 9**). In the time periods after the second month, a decreasing growth is observed. Accordingly, economic and social sustainability, which decreased until t = 2, followed an upward trend subsequently. The graph shows that an increase in physical load affected the social and economic dimensions considerably at the beginning of simulation. Because of a gradual increase in the effects of other model variables on social and economic dimensions over time, a drop in the effect of physical load on these two major dimensions can be seen. Physical load variable is affected by different variables in the economic and social sustainability such as production capacity, sales, and worker competences, and also it has effects on employee turnover and late delivery. As the physical load is increases, employee turnover ratio is ascended. Employee turnover has a direct negative affect on social sustainability in the company. From an economic point of view, as sales and production capacity increase, the workload variable increases, while late deliveries due to increased workload cause loss of customers. Therefore, changes in the system caused a dramatic change in physical load due to its multiple relationships with many variables.

Two different scenarios have been analyzed to test the alternative policies and structures in the next section.

4.3.1. Scenario I

As all competitive firms do, the firm in this application intends to measure product sustainability. The firm decided to substantially minimize the risks faced in three major dimensions of sustainability. Thus, it needs to observe the behavior of product sustainability variable when the levels of innovation and production capacity are increased.

Improvements in the level of innovation make recycling more possible, improving the quality level of the product. When the company increases its recycling activities, which reduces waste, it also reinforces environmental sustainability due to the feedback loops. Moreover, the company decreases the number of customer claims by increasing the quality level, which prevents returned products, indirectly decreasing no-value added cost and allowing the company to gain reputation. As the reduction of no-value added cost influences the economic dimension of sustainability through feedback loops, a higher reputation for the company affects the social aspect. Improvements in production capacity increases flexibility, which increases sales and reinforce the economic dimension by using feedback loops. An

Figure 6. Behavior pattern of customer claims.

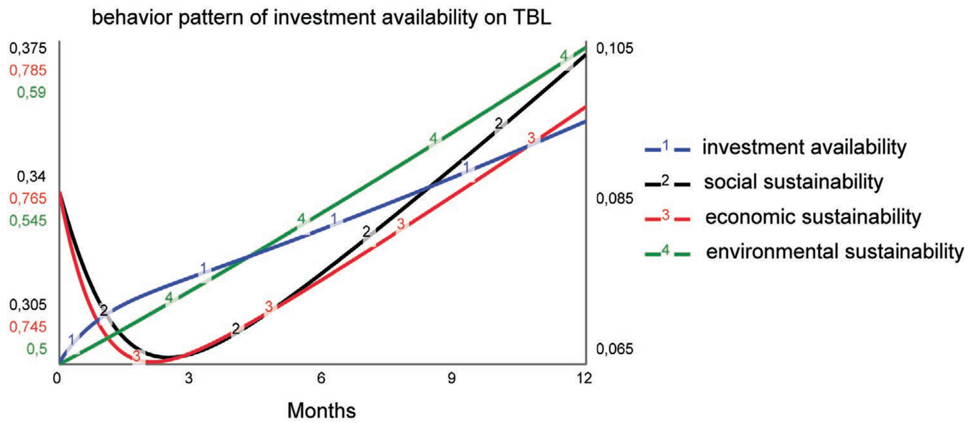

Figure 7. Behavior pattern of investment availability on the TBL.

increase in the production capacity influences the social dimension due to another loop. Current values in the SD model are 0.5 for production capacity and 0.5 for the level of innovation. The company designated the production capacity as 0.7 and the level of innovation as 0.8, and wanted to observe the effects of these values on product sustainability and three main dimensions.

Thanks to the improvements, product sustainability followed a change as presented in **Figure 10**. Figure 10 displays the effects of improvements on economic, social, and environmental dimensions, respectively. Additionally, **Table 5** presents three-month change rates of the twelve-month simulation results.

The initial value of product sustainability before improvements was 0.54. At the end of the simulation, the value reached 0.58 in 12 months. While the initial product sustainability value was 0.63 in Scenario I, it reached 0.66 in 12 months thanks to the improvements. If the company accomplishes the suggested improvements, the improvement rate will approximately reach 8%.

Economic sustainability decreased from 0.83 down to 0.70 in the first months of Scenario I. However, at the end of the 12-month period, it approached its initial level by reaching 0.76 and started an upward trend from then on. It is possible to predict that a more meaningful improvement could be achieved when the simulation model is run for periods longer than 12 months. This fall was an expected result, because the company has to invest to make progress in these values and this result in a decrease in economic sustainability in the short-term. Because of the effects of feedback loops in the simulation model, the company is to make profits out of its investments within a particular time period. As we have mentioned previously, the accomplishment of this improvement will have a positive effect on long-term economic sustainability of the company.

In the simulation model run, according to the suggested improvements, environmental sustainability increased its initial value of 0.68 up to 0.77 at the end of 12 months. As a result of the suggested scenario analysis, an improvement of 9% is accomplished in environmental sustainability.

4.3.2. Scenario II

In this scenario, according to the company's agenda, an application related to I4.0 is implemented.

The subject of this application, I4.0, also referred to as the fourth industrial revolution, involves automation systems, data exchange, and production technologies. This structure also plays an important role in smart factory applications. Since this revolution will allow the collection of all data in the production environment and make it possible to observe

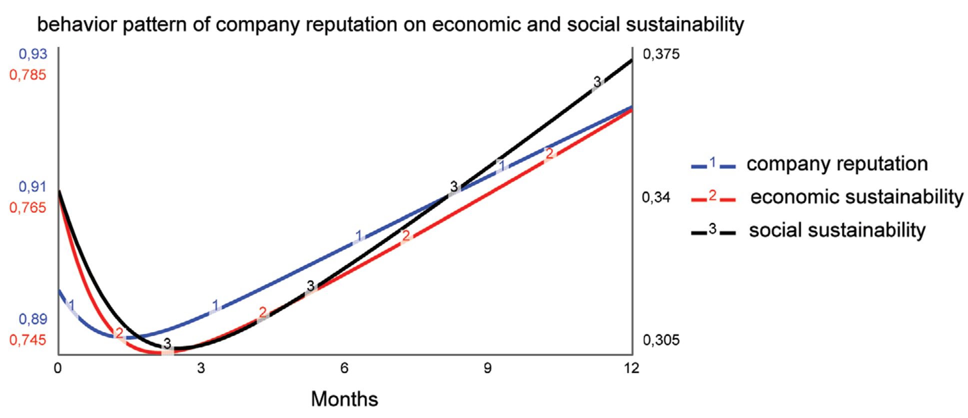

Figure 8. Behavior pattern of company reputation on economic and social sustainability.

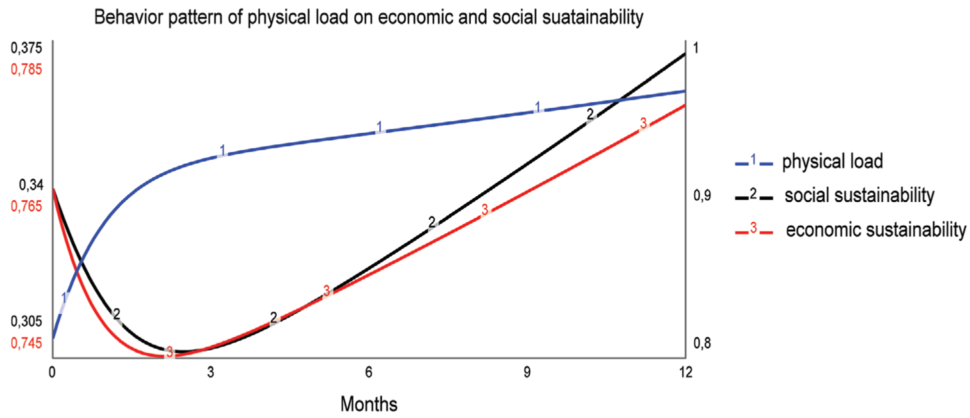

Figure 9. Behavior pattern of physical load on economic and social sustainability.

and analyze this information, it will lead to the emergence of more productive business models. The aim of I4.0 is to produce higher quality, cheaper, and faster products while generating less waste.

Due to I4.0, increasing production speed or a higher level of quality will not be sufficient to gain competitiveness, so not the most productive businesses but the ones which best meet the needs of customers will prevail. Therefore, we considered

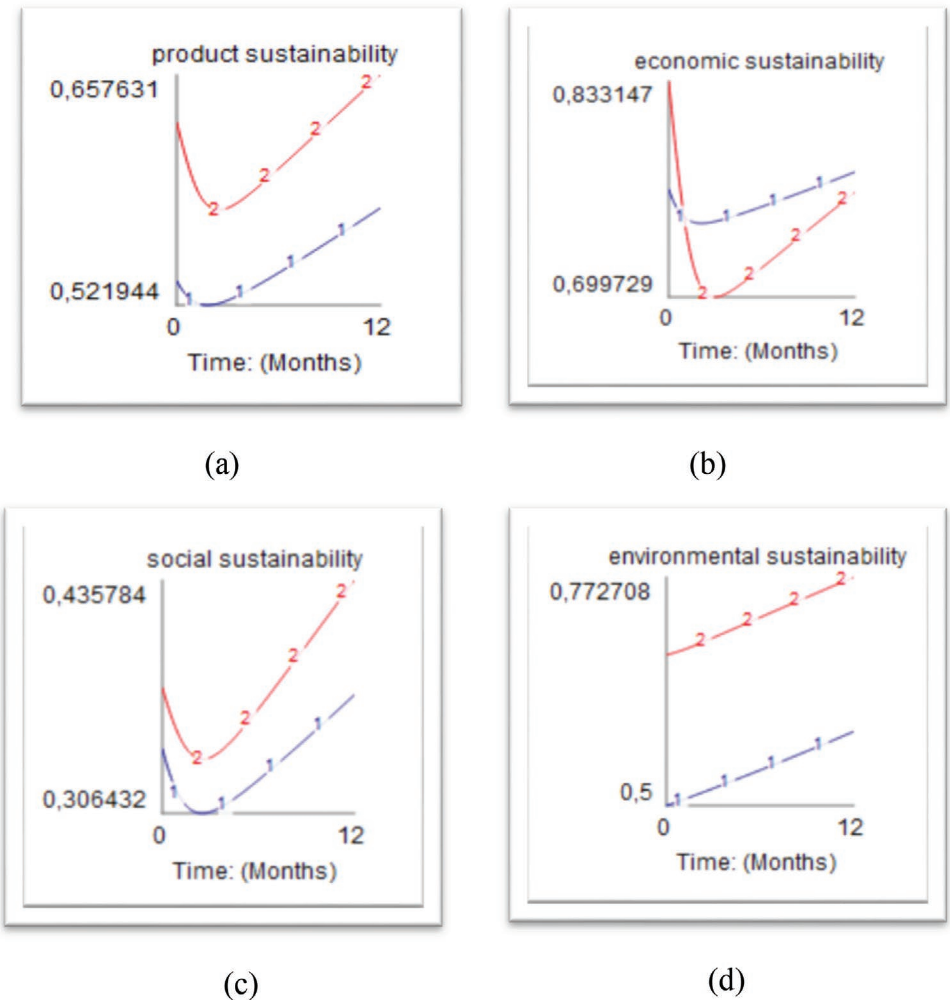

Figure 10. Behavior pattern of sustainability a) product, b) economic, c) social, d) environmental. The blue curve (1) shows the current situation, the red curve (2) shows the scenario I in the above graphs.

Table 5. Results of the model for Scenario I.

Dimensions/Months		0	3	6	9	12
Product Sustainability	Current Situation	0.536276	0.524709	0.540920	0.559629	0.579216
	Scenario I	0.629825	0.579200	0.602270	0.629955	0.657631
Economic Sustainability	Current Situation	0.766406	0.746381	0.755538	0.765996	0.776946
	Scenario I	0.833147	0.699729	0.717792	0.741212	0.764400
Social Sustainability	Current Situation	0.342422	0.307192	0.324886	0.347904	0.372249
	Scenario I	0.376327	0.337338	0.364286	0.399763	0.435784
Environmental Sustainability	Current Situation	0.500000	0.520555	0.542334	0.564988	0.588453
	Scenario I	0.680000	0.700532	0.724731	0.748889	0.772708

flexibility as the most important factor in the scenario we designed for the company. Moreover, as it is necessary in this scenario to deploy a capable work force and to increase the amount of investments for the application of I4.0, the variables of "capability of human resources personnel" and "investment availability" are considered the main factors that influence the system. In Scenario II, the default values of 0.5 for these variables were modified as 0.8 for "flexibility" and "investment availability", and 0.7 for "capability of the human resources personnel". The simulation model is run with these changes for a period of 12 months. **Figure 11** presents the results and simulation graphs.

The company observed the effects of the increased values of flexibility, the capability of human resources personnel, and investment availability on product sustainability and three main dimensions before applying I4.0.

The value of product sustainability level increased from 0.47 to 0.61 at the end of the 12-month period. In addition, the economic sustainability value increased from 0.54 to 0.62, social sustainability from 0.28 to 0.56, and finally environmental sustainability from 0.58 to 0.66. Furthermore, of the other variables affected in the system, the employee turnover rate initially increased and then started to decline. It was observed that the information infrastructure developed and the innovation level of the company increased. Production capacity and efficiency also improved in **Table 6**.

In line with the analysis of the second scenario, possible consequences that will emerge when I4.0 is applied in the company are presented for product sustainability, its three main dimensions, and the other affected variables in the system.

5. Discussions and Implications

The literature review shows that traditional risk analysis methods are used in studies dealing with product sustainability. These methods often conduct qualitative evaluations, and they do not analyze changing conditions dynamically. In addition, these methods do not debate the sustainability risks within three main dimensions related to product sustainability and the interrelations between risks dynamically. Besides, these

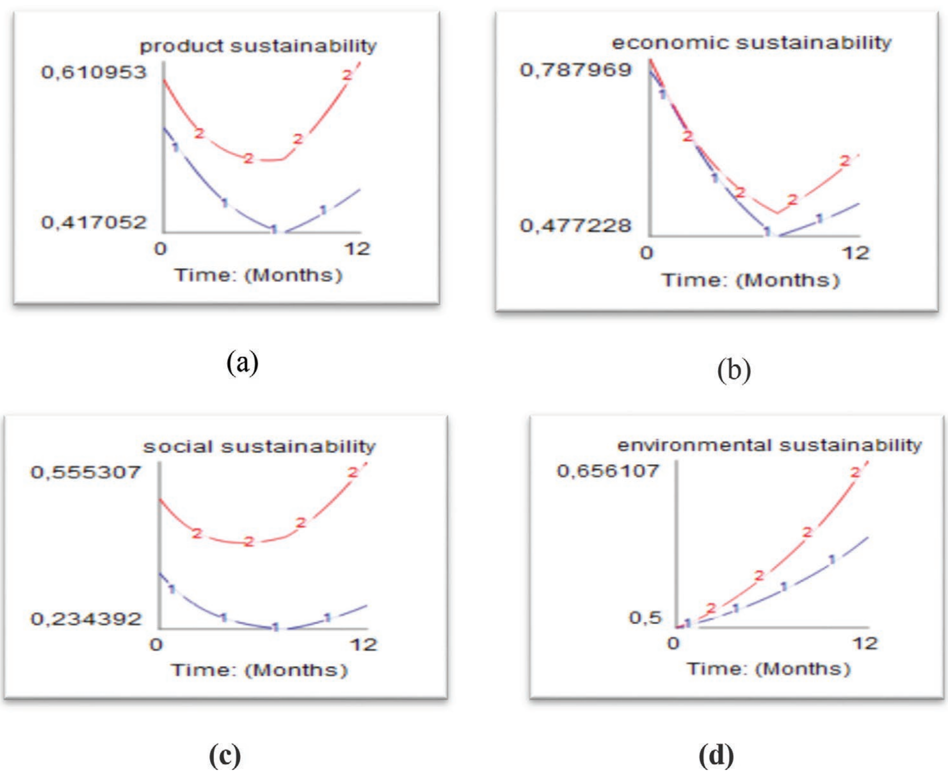

Figure 11. Behavior pattern of sustainability a) product, b) economic, c) social, d) environmental. The blue curve (1) shows current situation, the red curve (2) shows Scenario II in the above graphs.

Table 6. Results of the model for Scenario II.

Dimensions/Months		0	3	6	9	12
Product Sustainability	Current Situation	0.536276	0.465155	0.426001	0.431611	0.466696
	Scenario II	0.591096	0.519150	0.499299	0.532578	0.610953
Economic Sustainability	Current Situation	0.766406	0.618300	0.509109	0.495384	0.535088
	Scenario II	0.787969	0.627139	0.540857	0.550049	0.621445
Social Sustainability	Current Situation	0.342422	0.264899	0.238489	0.245817	0.280011
	Scenario II	0.485318	0.408752	0.402862	0.450665	0.555307
Environmental Sustainability	Current Situation	0.500000	0.512267	0.530405	0.553631	0.584988
	Scenario II	0.500000	0.521559	0.554178	0.597019	0.656107

methods remain static and mostly ignore indirect effects taking place in the system. As a result, several methods have been suggested to obtain a more extensive evaluation, which can take interrelations in three dimensions, to fulfill the need of such a method, it is suggested to perform research covering social and economic impacts in addition to environmental effects.[3]

With the digital transformation, the company is planning to produce faster, flexible, and low-cost production. The company will speed up its production processes through digital transformation and ensure an efficient use of resources simultaneously.[70] I4.0 provides the company with more flexibility in production systems and processes to cope with the increasing product variety and supply chain complexities.[71] Because with this transformation, the company will experience an increase in productivity by providing real-time data. Moreover, the company makes a significant initial investment for I4.0, but it will increase its sustainable performance with the increase in the need for employed workforce and more importantly, with a qualified workforce.[72] With this transformation, the company achieves long-term sustainable competition by offering a customer-oriented approach with increased productivity and flexibility in production. In addition, digital transformation increases the innovation capability of the company and ensures a sustainable policy with continuous improvement. Thus, I4.0 provides sustainable impacts throughout the firm and enabled the firm to develop sustainable policies.

It is one of the unique contributions of this study is to analyze three aspects of sustainability with the proposed model. This study is highlighted the sustainable infrastructure by digitalization and resource efficiency can be achieved. Enhance social sustainability, creating better life by increasing environmental sustainability and strengthen economic for providing competitiveness advantages can be achieved considering holistic view of sustainability. Companies and also society have responsibility to develop a quality, reliable, sustainable, and flexible infrastructure that supports economic development and social welfare. Thus, the company aims to achieve these goals by providing innovations and digitalization. Therefore, the implementation is in alignment with those sustainable goals (SDG 9 and SDG 12) which are build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation, and ensure sustainable consumption and production patterns.[73]

Based on our findings, employee turnover is directly linkage between sustainability performances of company. Reducing employee turnover leads to increase sustainability performance. Therefore, training is important to achieve sustainability and ensure digital technologies. Managers in company should increase awareness on sustainability and create positive employee attitudes for digital technologies. The personnel whose competence level has increased with trainings will facilitate the adaptation of the company to digital technologies.

In order to achieve sustainability in company, the top management needs to adapt organizational culture this manner. This model can be used by both managers and policy makers to assess the impacts of sustainability. Companies should be aligned their capabilities and decisions needs of considering environmental and society.[74] Digital technologies have significant initial investment to enhance capacity of organization. However, investments have valuable contribution to create more sustainable environment in the different stages of a supply chain. By increasing tracking system of components during product production and use, or end of-life product can be achieved with digital technologies.[75] Thus, managers can decide to invest digital technologies considering with analysis of the positive and negative aspects.

Besides, digitalization tools to enhance company's environmental performance by doing effecting use of resources and effective production planning. By adopting digital technologies companies can provide an opportunity to trace and track their supply chain to manage their sources and to identify leverage point and problematic stage of the process. Therefore, Blockchain and big data technologies is beneficial for creating sustainable food supply chain.[76] Governments should also invest in digital technologies and provide incentives to achieve their sustainable goals. Thus, by increasing their production and innovation capacity, they are able to provide global competition.

6. Conclusions

The main focus is to develop a risk-oriented approach in measuring product sustainability. In order to achieve this, the approaches considering the risks related to three dimensions of sustainability need to be considered as a whole. Therefore, three main dimensions of sustainability are considered and the SD modeling approach is used to design a dynamic measurement structure for product sustainability. A real-life application is presented to prove the applicability of the suggested approach. For this, 31 different risks and indicators, which are identified for the company, are considered in the designed model. A causal loop diagram is created to observe risk interactions. By using the relationships considered in a causal loop diagram, an SD model is developed.

The main results of this study, it was observed that technological investments initially increased in costs due to a significant amount of investment costs, but later it indicates degressive rate. Since technological investments provide enhancing production capacity, increasing flexibility and competitive advantage. In addition, the effects of sustainability and digital technologies on social dimensions have been analyzed in this paper. Adaptation to digital technologies requires both competent personnel and improvement in human resources performance. Employee turnover rates are important in achieving the company's effective sustainability goals. It has been argued that the increase in employee turnover has a negative effect on the loss of competent personnel of the firm and thus to ensure sustainable development.

Besides, two different scenarios are used to observe the impacts of the company's current decisions on sustainability and its three main dimensions. As a conclusion, for Scenario I, increasing the production capacity of the company and maintaining the production by emphasizing innovation led to improvements in both product sustainability and the main dimensions of product sustainability in the 12-month period. For Scenario II, through I4.0 applications, when the variables of flexibility, the capability of human resources personnel, and the investment availability were increased, product sustainability and other risks were positively affected. It was concluded that the realization of I4.0 applications could be an effective strategy for the company to increase product sustainability and consequently to gain competitive advantage.[77]

Limitation of this study is to definition of SD model variables and the definition of variable relations are carried out by considering the unique structure of each firm. Thus, different researchers can present the model with different perspectives for causality relations. As a future study, this study can be improved by enhancing sustainability risk indicators. This study can be further extended other sectors. Relations between these indicators can be improved and different future scenarios can be applied. The implementation can be applied for developed country in order to compare digital technology impacts. Besides, impact of specific I4.0 tools such as Big Data and Blockchains on sustainability can be analyzed.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

case studies, Industry 4.0, product sustainability, risk analysis, system dynamics, triple bottom line

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[1] T. Rebs, M. Brandenburg, S. Seuring, *J. Cleaner Prod.* **2019**, *208*, 1265.
[2] A. Babader, J. Ren, K. O. Jones, J. Wang, *Expert Syst. Appl.* **2016**, *46*, 417.
[3] N. C. Onat, M. Kucukvar, A. Halog, S. Cloutier, *Sustainability* **2017**, *9*, 706.
[4] WCED World Commission on Environment and Development, Report of the World Commission on Environment and Development: Our Common Future https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf (accessed: January 2021).
[5] J. Fiksel, J. McDaniel, D. Spitzleyn, *J. Sustainable Prod. Des.* **1998**, *19*, 60.
[6] P. Sarkar, S. Rachuri, H. W. Suh, K. Lyons, R. D. Sriram in *Proc. Int. Design Engineering Technical Conf. & Computers and Information in Engineering Conf.*, San Diego, California, USA **2009**.
[7] M. Ghobakhloo, *J. Cleaner Prod.* **2020**, *252*, 119869.
[8] R. Brozzi, D. Forti, E. Rauch, D. T. Matt, *Sustainability* **2020**, *12*, 3647.
[9] X. Zhang, T. Lu, M. Shuaib, G. Rotella, A. Huang, S. C. Feng, in *Proc. Leveraging Technology for a Sustainable World Proc. of the 19th CIRP Conf. on Life Cycle Engineering*, Berkeley, USA **2012**.
[10] L. T. T. Dinh, Y. Guo, M. S. Mannan, *Environ. Prog. Sustainable Energy* **2009**, *28*, 38.
[11] M. Bevilacqua, F. E. Ciarapica, G. Giacchetta, *Int. J. Prod. Res.* **2007**, *45*, 4073.
[12] S. A. R. Khan, D. Qianli, *Environ. Sci. Pollut. Res.* **2017**, *24*, 16829.
[13] European Commission (EC), 2017. The New European Consensus on Development: Our World, Our Dignity, Our Future, https://op.europa.eu/en/publication-detail/-/publication/5a95e892-ec76-11e8-b690-01aa75ed71a1 (accessed: February 2021).
[14] T. Stock, M. Obenaus, S. Kunz, H. Kohl, *Process Saf. Environ. Prot.* **2018**, *118*, 254.
[15] D. Kiel, J. M. Müller, C. Arnold, *Digital Disruptive Innovation*, UK **2019**.
[16] E. O. B Nara, M. B. da Costa, I. C. Baierle, J. L. Schaefer, G. B. Benitez, L. M. A. L. do Santos, L. B. Benitez, *Sustainable Prod. Consumption* **2021**, *25*, 102.
[17] M. Piccarozzi, B. Aquilani, C. Gatti, *Sustainability* **2018**, *10*, 3821.
[18] C. G. Machado, M. P. Winroth, E. H. D. Ribeiro da Silva, *Int. J. Prod. Res.* **2020**, *58*, 1462.
[19] S. S. Kamble, A. Gunasekaran, R. Sharma, *Comput. Ind.* **2018**, *101*, 107.
[20] G. Beier, A. Ullrich, S. Niehoff, M. Reißig, M. Habich, *J. Cleaner Prod.* **2020**, *259*, 120856.
[21] A. Shafiq, P. F. Johnson, A. Awaysheh, *Int. J. Prod. Econ.* **2019**, *218*, 148.
[22] M. Shuaib, D. Seevers, X. Zhang, F. Badurdeen, K. E. Rouch, I. S. Jawahir, *J. Ind. Ecol.* **2014**, *18*, 491.
[23] C. Feng, Y. Mai, *Int. J. Adv. Manuf. Technol.* **2015**, *85*, 695.
[24] A. K. Yilmaz, T. Flouris, *Afr. J. Bus. Manage.* **2010**, *4*, 162.
[25] M. Sabaghi, C. Mascle, P. Baptiste, R. Rostamzadeh, *Expert Syst. Appl.* **2016**, *56*, 69.
[26] M. Giannakis, T. Papadopoulos, *Int. J. Prod. Econ.* **2016**, *171*, 455.
[27] A. Göçer, S. E. Fawcett, O. Tuna, *Sustainability* **2018**, *10*, 27.
[28] G. Whiteman, B. Walker, P. Perego, *J. Manage. Stud.* **2012**, *50*, 307.
[29] S. Lee, Y. Geum, H. Lee, Y. Park, *J. Cleaner Prod.* **2012**, *32*, 173.
[30] A. Marvuglia, E. Benetto, B. Murgante, *J. Environ. Account. Manage.* **2015**, *3*, 213.
[31] N. C. Onat, S. Gumus, M. Kucukvar, O. Tatari, *Sustainable Prod. Consumption* **2016**, *6*, 12.
[32] A. Guevara, O. Silva, H. Hasegawa, D. Venanzi, *Braz. Bus. Rev.* **2017**, *14*, 435.
[33] X. Liu, M. Zeng, *Renewable Sustainable Energy Rev.* **2017**, *73*, 782.
[34] S. Elsawah, S. A. Pierce, S. H. Hamilton, H. Van Delden, D. Haase, A. Elmahdi, A. J. Jakeman, *Environ. Modell. Software* **2017**, *93*, 127.
[35] A. Y. Alamerewa, D. Brissaud, presented at *Proc. 25th CIRP Life Cycle Engineering Conf.*, Copenhagen, Denmark, April–May **2018**.
[36] L. Yao, T. Liu, X. Chen, M. Mahdi, J. Ni, *J. Cleaner Prod.* **2017**, *187*, 852.

[37] A. Williams, S. Kennedy, F. Philipp, G. Whiteman, *J. Cleaner Prod.* **2017**, *148*, 866.
[38] J. D. Sterman, *Calif. Manag. Rev.* **2001**, *43*, 8.
[39] J. W. Forrester, *Industrial Dynamics* (1st ed.), MIT Press, Cambridge, UK **1961**.
[40] D. H. Meadows, J. Randers, D. L. Meadows, *The Limits to Growth*, Yale University Press, London **2013**.
[41] J. W. Forrester, *Syst. Dyn. Rev.* **1994**, *10*, 245.
[42] A. Größler, J. Strohhecker, *System Dynamics and Sustainability*, World Scientific Publishing, Singapore **2012**.
[43] A. Ruiz, J. Guevara, *Sustainability* **2020**, *12*, 872.
[44] E. Kartadjumena, W. Rodgers, *Sustainability* **2019**, *11*, 1673.
[45] A. Genovese, A. A. Acquaye, A. Figueroa, S. C. Lenny Koh, *Omega* **2017**, *66*, 344.
[46] A. Sobhani, M. I. M. Wahab, *Comput. Ind. Eng.* **2017**, *113*, 75.
[47] M. Jalalkamali, A. J. Ali, S. S. Hyun, D. Nikbin, *Manage. Decis.* **2016**, *54*, 796.
[48] S. De Winne, E. Marescaux, L. Sels, I. Van Beveren, S. Vanormelingen, *Int. J. Hum. Resour. Manage.* **2019**, *30*, 3049.
[49] S. Evans, D. Vladimirova, M. Holgado, K. Van Fossen, M. Yang, E. A. Silva, C. Y. Barlow, *Bus. Strategy Environ.* **2017**, *26*, 597.
[50] J. Macke, D. Genari, *J. Cleaner Prod.* **2019**, *208*, 806.
[51] J. J. Ryoo, K. S. Lee, J. W. Koo, *Saf. Health Work* **2020**, *11*, 335.
[52] F. Manzoor, L. Wei, T. Bányai, M. Nurunnabi, Q. A. Subhan, *Sustainability* **2019**, *11*, 2263.
[53] B. Ozkeser, *Procedia Comput. Sci.* **2019**, *158*, 802.
[54] P. M. Bögel, *J. Mark. Commun.* **2019**, *25*, 115.
[55] Z. Turskis, N. Goranin, A. Nurusheva, S. Boranbayev, *Sustainability* **2019**, *11*, 424.
[56] A. De Grave, G. T. Pontoh, in *Proc. 3rd Int. Conf. on Accounting, Management and Economics 2018*, Atlantis Press, Dordrecht, The Netherlands **2019**.
[57] H. Min, *Business Horiz.* **2019**, *62*, 35.
[58] H. Alibeiki, S. Li, R. Vaidyanathan, *Int. J. Prod. Econ.* **2020**, *222*, 107505.
[59] Z. Shi, S. Liu, *Eur. J. Oper. Res.* **2020**, *287*, 133.
[60] N. Barwitz, *J. Retail. Consum. Serv.* **2020**, *53*, 101953.
[61] G. Fragapane, D. Ivanov, M. Peron, F. Sgarbossa, J. O. Strandhagen, *Ann. Oper. Res.* **2020**, https://doi.org/10.1007/s10479-020-03526-7.
[62] N. Jabarzare, M. Rasti-Barzoki, *Int. J. Prod. Econ.* **2020**, *221*, 107480.
[63] M. S. S. Danish, T. S. Senjyu, *Green Building Management and Smart Automation*, IGI Global, Hershey, PA, USA **2020**.
[64] F. Wang, K. Chen, *J. Bus. Res.* **2020**, *106*, 60.
[65] K. Naeem, M. C. Li, *Int. Rev. Financ. Anal.* **2019**, *62*, 53.
[66] D. Wang, R. Nie, R. Long, R. Shi, Y. Zhao, *Resour., Conserv. Recycl.* **2018**, *129*, 432.
[67] X. Sun, W. Tang, J. Chen, S. Li, J. Zhang, *Transp. Res. E* **2019**, *128*, 191.
[68] E. Kusrini, E. Sugito, Z. M. Rahman, T. N. Setiawan, R. B. Hasibuan, presented at *IOP Conf. Series: Materials Science and Engineering*, Yogyakarta, Indonesia, October **2019**.
[69] B. Triatmanto, N. Nirwanto, I. Razak, *J. Consum. Res.* **2016**, *30*, 59.
[70] A. Szalavetz, *Technol. Forecast. Soc. Change* **2019**, *145*, 384.
[71] P. Ralston, J. Blackhurst, *Int. J. Prod. Res.* **2020**, *58*, 5006.
[72] V. Sima, I. G. Gheorghe, J. Subić, D. Nancu, *Sustainability* **2020**, *12*, 4035.
[73] United Nations, *The Sustainable Development Goals Report*, https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf (accessed: January 2021).
[74] C. Isensee, F. Teuteberg, K. M. Griese, C. Topi, *J. Cleaner Prod.* **2020**, *275*, 122944.
[75] Y. Liu, Q. Zhu, S. Seuring, *Int. J. Prod. Econ.* **2020**, *229*, 107889.
[76] A. Upadhyay, S. Mukhuty, V. Kumar, Y. Kazancoglu, *J. Cleaner Prod.* **2021**, *293*, 126130.
[77] J. Ordieres-Meré, T. P. Remón, J. Rubio, *Sustainability* **2020**, *12*, 1460.