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Analysis Of The Impact Of Lean Production Methods And Industry 4.0 Technologies On Sustainability And Flexibility

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Abstract

Today's manufacturing companies operate in a turbulent production environment characterized by globalization, mass personalization, and customer-specific product requirements. In this context, Lean Production and Industry 4.0 play an essential role for manufacturing companies. Both paradigms have farreaching production potentials for key performance indicators (KPI), such as time, cost, and quality. In addition to these KPIs, the Production's economic, ecological, and social sustainability and flexibility will also be important in the future. However, the influence of appropriate Lean Production methods and Industry 4.0 technologies on sustainability and flexibility has not yet been sufficiently researched. Therefore, this paper investigates the impact of Lean Production and Industry 4.0 elements on economic, ecological, and social sustainability and flexibility using a comprehensive literature review and an online survey with experts from science and industry. Thus, the results of this contribution support manufacturing companies to achieve their sustainability and flexibility goals with the help of Lean Production and Industry 4.0.

Keywords

Lean Production; Industry 4.0; Sustainability; Flexibility; Survey

1. Introduction

The industrial sector plays a crucial role in Europe. It contributes 75 % of European Union exports and 80 % of all innovations, making it a key driver of economic growth [1]. Nevertheless, with a 20 % share of global CO_2 emissions, the industrial sector is one of the main contributors to the worldwide effects of anthropogenic climate change [2]. Therefore, sustainability receives growing attention in production [3]. In addition, manufacturing companies face many complex influencing factors, such as volatile customer demands or short product life cycles [4,5], which require production flexibility. Since Lean Production and Industry 4.0 represent the two leading production paradigms of manufacturing companies [6], the question arises if Lean Production methods and Industry 4.0 technologies can meet the increasing demands for productions' flexibility and sustainability.

Lean Production is an established production philosophy that aims to reduce complexity in the value chain by eliminating all types of waste [7]. The characteristics of the concept are not limited to the reduction of waste and include the optimization of numerous production processes by implementing Lean Production methods [3]. Due to the advanced digitalization, further development of the production processes is required [8]. Regarding a fourth industrial revolution, Industry 4.0 brings significant changes to the economy, society, and environment. The goal is to enhance productivity by connecting all value chain participants to create a cyber-physical system using innovative technologies, such as predictive maintenance or artificial

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intelligence [9]. Both paradigms have far-reaching production potentials for key performance indicators (KPI), such as time, cost, and quality [10,11]. However, the impact of Lean Production methods and Industry 4.0 technologies on production's sustainability or flexibility needs to be further researched to support manufacturing companies in achieving their flexibility and sustainability goals by selecting and implementing the appropriate Lean Production methods and Industry 4.0 technologies. Therefore, this paper investigates the impact of Lean production methods and Industry 4.0 technologies on economic, ecological, social sustainability, and flexibility.

The following chapter sets the reference frame of the scientific fields and presents an introduction to Lean Production (2.1) and Industry 4.0 (2.1). Also, section 2.2 describes the relevant target dimensions of sustainability and flexibility. Chapter 3 analyzes the state of research (3.1) and identifies the research gap. To close this gap, a methodological approach is derived (3.2). This methodological approach forms the guideline for investigating the impact of Lean Production methods and Industry 4.0 technologies on sustainability and flexibility (chapter 4), which results will be discussed in chapter 5. The last chapter shows the limitations of the results and provides an outlook.

2. Fundamentals

2.1 Lean Production and Industry 4.0

After World War II, the Toyota Motor Corporation had to cope with low sales potentials on the Japanese automobile market. The lack of cost degression meant that mass production, according to Fordism, was not possible for Toyota [8]. Based on this initial situation, Taiichi Ohno designed the Toyota Production System (TPS), first described by Womak et al. [10] and is worldwide known as Lean Production. Lean Production aims to increase the production's economic efficiency by consistently and thoroughly eliminating all types of waste [6]. Moreover, the Lean Production methods aim to optimize production flow, realize a continuous value stream, and increase quality [12]. The two main principles of Lean Production are eliminating waste and continuous improvement, whereby employees should always be involved in the improvement process [13]. According to Dennis [14], Lean Production is based on four essential steps: The harmonization of the 4 M's (man, method, machine, and material), the optimization of the material flow, the introduction of the pull principle as well as the system improvement. To successfully implement the Lean Production approach with methods such as Kanban, value stream mapping, and Poka Yoke, the impacts on relevant target dimensions need to be known [15].

In addition to the Lean Production approach, Industry 4.0 was introduced in 2011 at the Hannover Messe in Germany [16]. Industry 4.0 is a technology-driven vision that aims to design smart factories and connect the physical and the cyber world with innovative technologies [17]. The so-called fourth industrial revolution is transforming the next generation of production systems by becoming intelligent, self-organized, decentralized, and flexible [18]. The digitization and networking of existing products, processes, and machines thus form the core of Industry 4.0 [19]. The goal is to organize the entire value chain, improve the efficiency of the production processes, and produce high-quality products and services. Further advantages are highly flexible mass production, reduction of complexity costs or coordination, and optimization of value chains in real-time [20]. Industry 4.0, therefore, seeks to realize the future factory by connecting employees and all physical resources of a production system, such as products, machines, transportation systems, and other objects, to achieve automated information exchange [9,21].

2.2 Target Dimensions: Sustainability and Flexibility

This study focuses on the impact of Lean Production methods and Industry 4.0 technologies on economic, ecological, and social sustainability and production's flexibility, which have become increasingly relevant in the industrial context. Target dimensions are needed to focus on long-term, strategic company goals rather than short-term improvements [23]. The term sustainability is used in various meanings [24]. The Brundtland Report presents the guiding principle of sustainable development [25]: "Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own. (…) " [26]. The term can be specified by deriving three basic components of sustainability: An economical, ecological, and social dimension. These three dimensions form the triple bottom line and describe sustainable development as the simultaneous and equal implementation of economic, ecological, and social goals [27]. The dimensions can be characterized as follows [28]:

- Economic sustainability: Economic sustainability is the basis for the following dimensions and estimates the possibilities of a company to convert value creation potentials into competitive advantages and achieve long-term company continuity.
- Ecological sustainability: The ecological dimension includes the entrepreneurial influence on protecting and preserving the environment, and this requires a systematic reduction of ecological burdens and risks by companies.
- Social sustainability: The social dimension quantifies the social compatibility of entrepreneurial action and records the relationship construct with all stakeholders, such as employees and suppliers.

Nowadays, companies are confronted with volatile markets and globalization [9]. Therefore, a company's flexibility is increasingly becoming a strategic competitive advantage [29]. Flexibility is the ability of organizations to adapt to changing circumstances. The decisive factors are the timeframe and the extent to which companies react to changing situations, such as customer demands. The increasing complexity of the business environment is reflected in individualized demand and increased global competition. [29] Therefore, the adaptation of the production system is also necessary due to the modification of internal specifications and changes in external requirements [30].

3. State of the Art and Methodical Approach

3.1 State of the Art

A core principle of Lean Production is the elimination of waste, which also impacts sustainability by, for example, reducing costs, energy, and emissions [31]. Carvalho et al. [32] point out that not all waste elimination improves sustainability. The controversy is evident by investigating principles like Just in Time because operational costs are reduced through the effective use of warehouse space. At the same time, more frequent material handling leads to higher packaging material consumption and transportation emissions [32]. In contrast, little attention is paid to the relationship between Lean Production and social sustainability [31], although Lean Production methods, like Kaizen, impact employees' roles, require specific competencies [33], and increase the participation of its employees in decision-making [34]. A comprehensive study at the conceptual level was conducted by Varela et al. [35], who noted that the Lean Production approach is positively linked with sustainability and that, despite some barriers, synergies can be expected.

Also, according to the literature, Industry 4.0 makes it faster and easier to carry out economic decisions [36]. Digitalization influences ecological sustainability through the more efficient use of rare materials. Together with simplified disassembly, the waste of resources is counteracted and thus forms a basis for the circular economy [37]. However, social sustainability is affected in a conflicting way. Even though workers are acting in a safer environment, there is a risk that only highly skilled workers can handle and understand the new technologies, so that low-skilled workers may lose their jobs. [3]. Overall, Industry 4.0 benefits the economic [38–40] and ecological sustainability dimensions [39,41], but the impact on the social dimension remains questionable. The literature affirms that on a paradigm-level Lean Production and Industry 4.0 positively affect the flexibility in production, both individually and in combined applications [42,43]. This influence still needs to be explored on a detailed method and technology level.

According to the current state of the art, there is a positive correlation between Lean Production [35] respectively, Industry 4.0 [39], and the target dimensions of sustainability and flexibility [3]. The findings primarily relate to the overarching connections of the paradigms. However, individual methods and technologies are only presented as examples to visualize the results. Thus, there is a lack of in-depth research showing how individual methods and technologies influence the target dimensions. Also, according to Kabzhassarova et al. [3], there is a lack of empirical investigation of the literature-based findings. Therefore, it is essential to investigate the impacts of Lean Production and Industry 4.0 on sustainability and flexibility on the method and technology level.

3.2 Methodical Approach

In the following section, a systematic approach will be presented to examine the effects of Lean Production methods and Industry 4.0 technologies on economic, ecological, and social sustainability and flexibility in production. In the first phase, the Lean Production methods and Industry 4.0 technologies are collected and classified, resulting in an overview of the appropriate Lean Production methods and Industry 4.0 technologies. Afterward, an expert survey follows to derive the impact of both paradigms' elements on sustainability and flexibility (Figure 1).

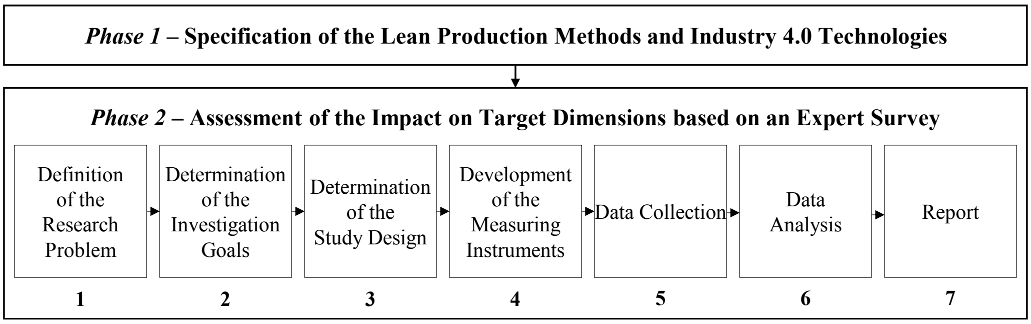

Figure 1: Methodical approach to attain the desired research aim (based on Kuß et al. [44])

The process for designing the research survey, as presented in Figure 1, can be divided into seven steps and is based on the work of Kuß et al. [44]. In the definition phase, the research problem is initially described as precisely as possible to specify the actual problem. Next, the study goals, which concretize and set the research task, are defined, and the study design is determined. The goals influence the study type, which must be considered to choose suitable methods and strategies. Once the structure is determined, measurement instruments must be developed to identify the characteristic attributes of the study subjects in the context. The data collection phase requires the most resources (time, human, financial). Here, possible errors, e.g., human weaknesses or technical problems, should be considered and the work status critically reflected. In the sixth step, statistical methods are used to analyze the collected data. Furthermore, the methods are essential for deriving conclusions that can be extrapolated from the results of a sample to the conditions in the corresponding population. The study's results are presented in the context of report writing or presentation of results, and the research questions should be answered.

4. Impact of Lean Production Methods and Industry 4.0 Technologies on Sustainability and Flexibility

4.1 Phase 1: Specification of the Lean Production Methods and Industry 4.0 Technologies

The selection of the Lean Production methods is based on Aull [45] and the VDI-2870 [47]. After the methods have been preselected by literature, an additional survey with participants from industry and science has been conducted to identify the relevant Lean Production methods [48]. Figure 2 provides an overview of twenty selected methods. In addition, the methods were classified according to Aull [45] into the categories logistics-oriented, employee-oriented, and quality-oriented [45].

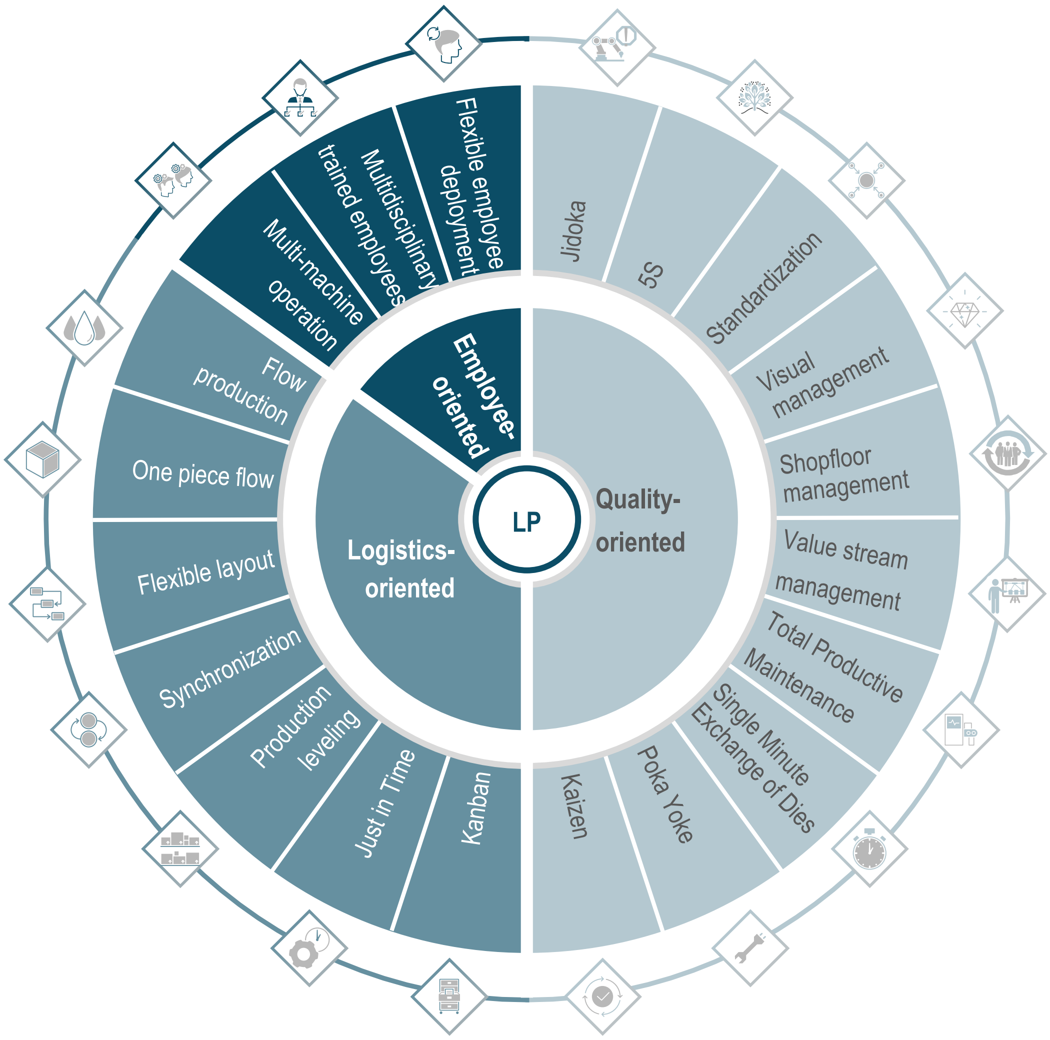

Figure 2: Collection of the Lean Production (LP) methods underlying this study [45]

According to Dillinger et al. [49], the Industry 4.0 technologies selection results from a comprehensive literature review, a use case analysis based on the Industry 4.0 platform of the Federal Ministry for Economics in Germany [50], and an expert survey. Based on the nine key technology of Rüßmann et al. [51], twenty-six Industry 4.0 technologies could be identified by Dillinger et al. [49]. The technologies were also separated into three main technology clusters, resulting from a mapping and clustering analysis using the software vosViewer [51]. The main clusters are smart data, smart operation, and smart interaction [53,52]. Figure 3 provides an overview of the twenty-six Industry 4.0 technologies considered in this study, visualizing the three clusters in the inner circle and the key technology fields in the middle circle. Finally, in this phase, the goals and descriptions for all the selected methods and technologies were formulated and summarized in a glossary given to the participants to ensure uniform understanding.

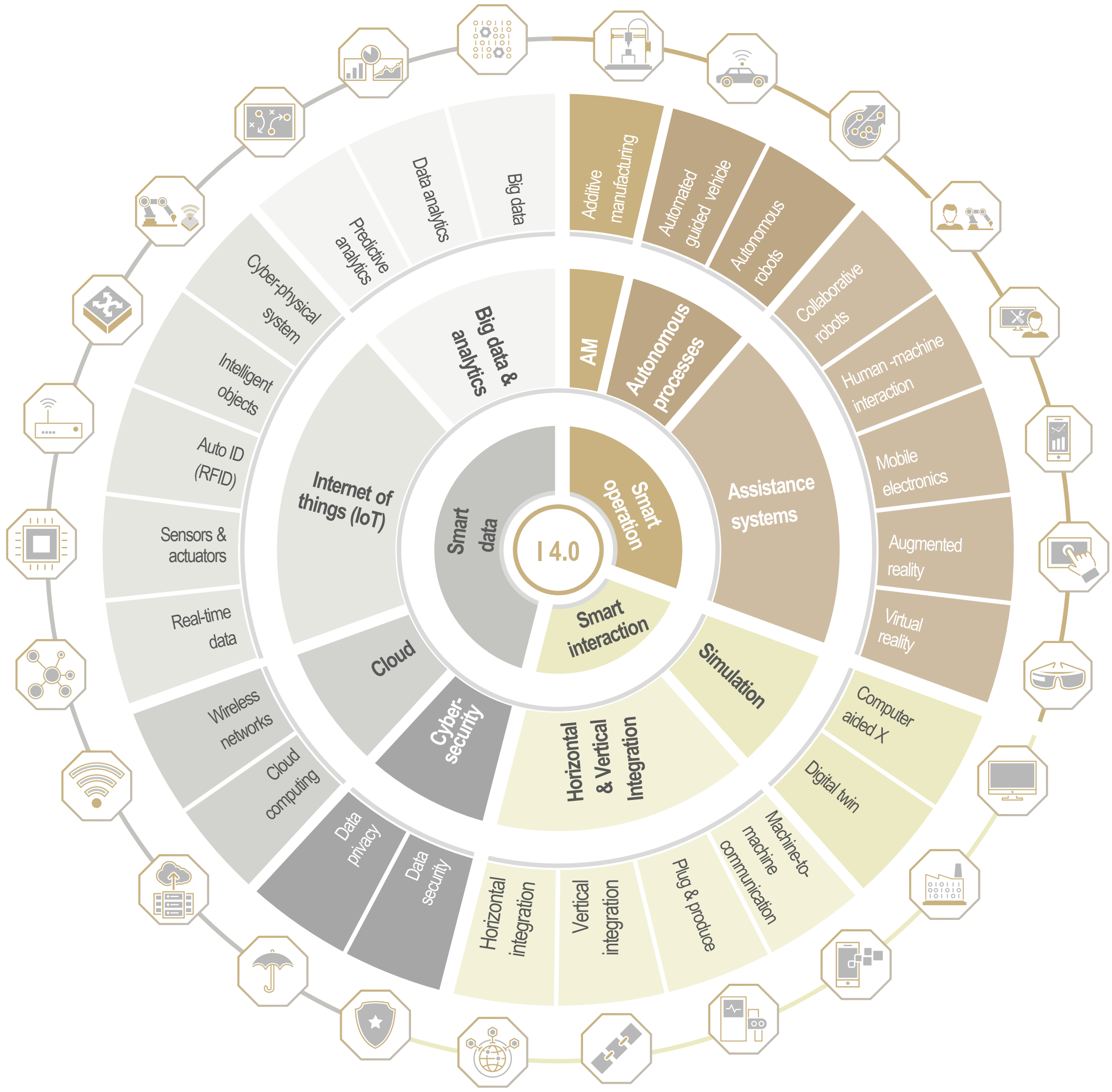

Figure 3: Categorization of the Industry 4.0 (I 4.0) technologies (according to Dillinger et al. [49])

4.2 Phase 2: Assessment of the Impact of Lean Production Methods and Industry 4.0 Technologies on Target Dimensions

In the second phase, an online survey with experts from science and industry was conducted to analyze the impact of Lean Production methods and Industry 4.0 technologies on economic, ecological, and social sustainability and flexibility in production.

The online study was designed according to established guidelines of empirical social research [55,54] and the systematic approach presented in Figure 1. It was conducted over three months and started in July 2021 with participating experts from production or production-related areas. In particular, people with knowledge of Lean Production and Industry 4.0 were required, such as production managers, production planners, or digital managers. In addition, management consultants and scientists were asked to strengthen the heterogeneity of the target group. With 32 experts, a representative cross-section of the German industrial landscape was reached. The study questions were answered using a seven-point Likert scale to determine the influence of Lean Production methods and Industry 4.0 technologies on sustainability and flexibility. The scale is sectioned from a very negative (-3) to a very positive impact (+3). In addition, participants had the option of choosing no effect (0) or could skip the question (k.A.), which ensures that the experts only assess the impact of methods and technologies that correspond to their expertise. The data analysis and the preparation of the report are summarized in Table 1.

Table 1: Assessment of the Impact of Lean Production methods and Industry 4.0 technologies

		Economic sustainability			Ecological sustainability			Social sustainability			Flexibility		
		Ø	±	Impact (-3 Negative impact, 0 No impact, 3 Positive impact)	Ø	±	Impact (-3 Negative impact, 0 No impact, 3 Positive impact)	Ø	±	Impact (-3 Negative impact, 0 No impact, 3 Positive impact)	Ø	±	Impact (-3 Negative impact, 0 No impact, 3 Positive impact)
Lean Production Methods	Jidoka	**1.79**	0.98	2	**1.07**	0.93	1	**1.00**	0.95	1	**1.38**	1.03	1
	5S	**1.27**	0.89	1	**1.30**	0.90	1	**1.61**	0.87	2	**1.06**	0.88	1
	Standardization	**2.03**	0.80	2	**1.47**	0.85	1	**1.29**	0.96	1	**1.32**	1.42	1
	Visual management	**1.33**	0.91	1	**1.00**	0.93	1	**1.50**	0.89	2	**1.81**	0.82	2
	Shopfloor management	**1.57**	0.62	2	**0.97**	0.87	1	**1.58**	0.75	2	**1.45**	1.07	1
	Value stream management	**1.87**	0.81	2	**1.43**	0.88	1	**1.13**	0.83	1	**1.27**	1.03	1
	Total Productive Maintenance (TPM)	**1.93**	0.89	2	**1.50**	0.85	2	**1.16**	1.02	1	**1.35**	0.93	1
	Single Minute Exchange of Die (SMED)	**1.93**	0.87	2	**1.03**	1.10	1	**0.53**	0.76	1	**1.83**	1.21	2
	Poka Yoke	**1.73**	0.89	2	**1.17**	0.97	1	**1.23**	1.07	1	**0.94**	0.88	1
	Kaizen	**2.03**	0.75	2	**1.33**	1.11	1	**1.55**	0.87	2	**1.35**	0.97	1
	Kanban	**1.60**	0.92	2	**1.17**	0.91	1	**0.58**	0.75	1	**1.61**	0.83	2
	Just in Time (JiT)	**1.87**	0.92	2	**0.80**	1.28	1	**0.23**	0.97	0	**1.23**	1.52	1
	Production leveling	**1.56**	0.92	2	**1.10**	1.11	1	**0.93**	0.94	1	**1.18**	1.10	1
	Synchronization	**1.67**	0.86	2	**1.10**	0.87	1	**0.82**	1.00	1	**1.54**	1.02	2
	Flexible layout	**1.57**	0.76	2	**0.90**	0.88	1	**1.00**	1.05	1	**2.13**	0.98	2
	One-piece flow	**1.47**	1.12	1	**1.07**	1.12	1	**0.48**	0.88	0	**1.63**	1.33	2
	Flow production	**1.97**	1.02	2	**1.10**	0.94	1	**0.16**	1.11	0	**0.26**	1.41	0
	Multi-machine operation	**1.80**	0.75	2	**0.53**	0.96	1	**0.26**	1.48	0	**1.31**	1.26	1
	Multi-disciplinary trained employees	**1.50**	1.12	2	**0.97**	1.05	1	**1.87**	0.98	2	**2.45**	0.84	2
	Flexible employee deployment	**1.73**	1.03	2	**0.79**	1.03	1	**1.48**	1.27	1	**2.53**	0.62	3
Industry 4.0 Technologies	Additive manufacturing	**1.45**	1.22	1	**1.28**	1.39	1	**0.27**	1.06	0	**2.20**	0.75	2
	Automated guided vehicles	**1.73**	0.93	2	**1.00**	0.79	1	**0.42**	1.48	0	**1.65**	1.12	2
	Autonomous robots	**1.70**	1.04	2	**0.85**	1.01	1	**0.42**	1.45	0	**1.63**	1.08	2
	Collaborative robots	**1.70**	0.90	2	**0.59**	0.77	1	**0.90**	1.47	1	**1.73**	0.73	2
	Human-machine interaction	**1.41**	0.95	1	**0.59**	0.67	1	**1.00**	1.48	1	**1.79**	0.76	2
	Mobile electronics	**1.25**	0.74	1	**0.62**	0.72	1	**0.90**	1.35	1	**1.57**	0.90	2
	Augmented reality	**1.07**	0.96	1	**0.86**	0.97	1	**1.23**	1.41	1	**1.48**	1.13	1
	Virtual reality	**1.04**	0.98	1	**0.82**	0.97	1	**1.13**	1.41	1	**1.26**	1.19	1
	Computer aided X (CAX)	**1.24**	0.97	1	**0.66**	0.92	1	**0.26**	1.05	0	**1.43**	1.02	1
	Digital twin	**1.61**	1.08	2	**1.19**	0.94	1	**0.39**	1.07	0	**1.80**	1.01	2
	Machine-to-machine communication	**1.32**	0.85	1	**0.93**	0.78	1	**0.42**	1.10	0	**1.73**	0.81	2
	Plug & produce	**1.36**	0.85	1	**0.89**	0.82	1	**0.23**	1.09	0	**2.17**	0.83	2
	Vertical integration	**0.88**	1.14	1	**0.70**	1.01	1	**0.31**	1.12	0	**1.36**	0.89	1
	Horizontal integration	**1.28**	0.92	1	**0.79**	0.82	1	**0.27**	1.16	0	**1.40**	0.94	1
	Data security	**0.48**	1.00	0	**0.07**	0.70	0	**0.97**	1.33	1	**0.03**	0.84	0
	Data privacy	**0.41**	0.99	0	**0.04**	0.57	0	**1.20**	1.38	1	**-0.17**	0.73	0
	Cloud computing	**1.29**	0.99	1	**0.34**	1.29	0	**0.28**	1.11	0	**1.43**	1.02	1
	Wireless networks	**1.50**	0.98	2	**0.62**	0.93	1	**0.66**	1.06	1	**1.61**	0.90	2
	Real-time data	**1.71**	0.84	2	**1.33**	1.11	1	**0.70**	1.16	1	**2.16**	0.72	2
	Sensors & actuators	**1.26**	0.80	1	**0.67**	0.90	1	**0.33**	1.04	0	**1.36**	1.13	1
	Auto ID (RFID)	**1.29**	0.80	1	**0.69**	0.79	1	**0.26**	1.01	0	**1.60**	0.99	2
	Intelligent objects	**1.62**	0.79	2	**1.34**	0.84	1	**0.72**	1.28	1	**1.93**	1.01	2
	Cyber-physical systems	**1.72**	0.87	2	**1.08**	1.03	1	**0.61**	1.26	1	**2.04**	0.82	2
	Predictive analytics	**1.93**	0.84	2	**1.45**	0.85	1	**0.84**	1.17	1	**1.40**	1.05	1
	Data analytics	**1.79**	1.09	2	**1.21**	1.11	1	**0.55**	1.04	1	**1.80**	0.95	2
	Big data	**1.21**	1.19	1	**0.52**	1.23	1	**0.39**	0.94	0	**1.43**	1.26	1

5. Results and Discussion

The survey results from Table 1 will be interpreted in this section, starting with Lean Production methods followed by the Industry 4.0 technologies. The participants attribute the highest positive impact on economic sustainability to the Lean Production methods. In this context, standardization (2.03) and Kaizen (2.03) show the highest positive scores. Concerning ecological sustainability, the impact of the Lean Production methods was weaker, and 95 % of the methods were rated with a low positive effect. The highest average was given to Total Productive Maintenance (TPM) (1.50), which indicates a positive impact followed by standardization (1.47). A reason why TPM has the highest positive impact on ecological targets is that it increases the overall equipment efficiency, which means that machine downtime can be avoided. When considering the impact on social sustainability, the ratings diverge between the methods. The methods 5S (1,61), visual management (1.50), shopfloor management (1,58), Kaizen (1.55), and multi-disciplinary trained employees (1.87) have a medium, positive impact. In contrast, the methods Just in Time (0.23), one-piece flow (0.48), flow production (0.16), and multi-machine operation (0.26) were rated as having no impact. With the latter four methods, the standard deviation must be considered. The standard deviation is higher compared to other methods. It describes a divergence because although the mean value suggests a neutral evaluation, both positive and negative effects were attested depending on the participants. In terms of flexibility, most methods received a low (55 %) to medium (35 %) positive rating. According to the participants, two outliers can be detected with flow production (0.26), which does not affect flexibility, and flexible employee deployment (2.53), which has a high, positive effect on flexibility in production.

The participants rate the importance of Industry 4.0 for economic sustainability by applying the technologies as predominantly low (54 %) to medium (38 %) positive. The highest rating is given to predictive analytics (1.93). Only the implementation of data security (0.48) and data privacy (0.41) is not considered to have any effect. Concerning the impact on ecological sustainability, the picture is uniform. Except for data security (0.07), data privacy (0.04), and cloud computing (0.34), which are not considered to have a significant impact, most of the technologies (88 %) are rated as having a low positive impact on ecological sustainability. When considering social sustainability, the participants rate the impact of Industry 4.0 technologies in part as having a low positive impact (54 %) and in part as having no impact (46 %). The first group primarily includes technologies that directly support employees, such as collaborative robots or human-machine interaction, whereas the second group includes digital twin or Auto ID. In terms of flexibility, most technologies have a medium positive impact (58 %). In particular, additive manufacturing (2.20), plug & produce (2.17), and real-time data (2.16) have the highest positive ratings. In contrast, the participants consider that the technologies data security (0.03) and data privacy (-0.17) have no or even a low negative impact on the flexibility in production.

When comparing the results of the twenty Lean Production methods and twenty-six Industry 4.0 technologies, it is noticeable that the participants assess the impact of Lean Production methods on sustainability more positively than the impact of the Industry 4.0 technologies. There is also a tendency toward a gradation from economic to ecological to social sustainability. According to the survey, Industry 4.0 technologies, in particular, positively influence production's flexibility. The literature review conducted by Kabzhassarova et al. [3] comes to a similar conclusion that Lean Production, in general, has the highest positive impact on economic sustainability and that the influences on the ecological and social dimensions cannot be determined. For Industry 4.0, they attest positive correlations for economic and ecological sustainability but cannot derive the effects on social sustainability. The expert survey shows that both approaches positively affect sustainability and flexibility by implementing their elements.

6. Conclusion and Outlook

This research paper provides a presentation of the impacts of Lean Production methods and Industry 4.0 technologies on economic, ecological, and social sustainability and flexibility in production. For this purpose, twenty relevant Lean Production methods and twenty-six Industry 4.0 technologies were identified, and an expert survey was conducted. The survey results show that the Lean Production methods and Industry 4.0 technologies have the highest positive impact on economic sustainability, followed by ecological and social sustainability. In the cross-paradigm comparison, it becomes clear that Lean Production methods' influence on sustainability is more positive than Industry 4.0 and its technologies. In particular, Industry 4.0 technologies positively impact the flexibility in production. Thus, the results of this contribution should be a first step to support manufacturing companies to achieve their sustainability and flexibility goals with the targeted selection of appropriate Lean Production methods and Industry 4.0 technologies. Future studies should deepen this research, and further experts should be consulted and use cases analyzed. Additionally, the impact of Lean Production methods and Industry 4.0 technologies on specific sustainability KPIs, e.g., CO_2 emissions or effects on employment contracts, should be investigated in detail.

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