

9th CIRP Global Web Conference – Sustainable, resilient, and agile manufacturing and service operations:
Lessons from COVID-19

Effect of Lean4.0 on Sustainability Performance: A Review

Marzhan Kabzhassarova^a, Anara Kulzhanova^a, Dinara Dikhanbayeva^a, Mert Guney^a, Ali Turkyilmaz^{a,*}

^a*School of Engineering and Digital Sciences, Nazarbayev University, 53 Kabanbay Batyr Ave, Nur-Sultan 010000, Kazakhstan*

* Corresponding author. E-mail address: ali.turkyilmaz@nu.edu.kz

Abstract

The high consumption of natural resources and their scarcity made sustainability a buzzword and one of the main concerns of society. Based on current research, Lean production and Industry 4.0 strategies are promising in this regard. They argue to offer cost and time efficiency, labor productivity increase, and other benefits. In the literature, there are works on separate effects of Lean and Industry 4.0 on Sustainability, as well as high compatibility between Industry 4.0 and Lean, where one strategy comprehends the use of another. Only a few articles consider the integrated effect and mostly lack empirical validation. This paper aims to address this gap by conducting a systematic literature review on both separate and integrated effects of Lean and Industry 4.0 (Lean 4.0) on three pillars of sustainability (economic, environmental, social). Additionally, several sustainability indicators as differentiation factors are formed and presented as a checklist to assess the effect of Lean and Industry 4.0 concepts. The findings reveal that Lean and Industry 4.0 has a somewhat uncertain or twofold correlation with sustainability, where Lean 4.0 has a strong positive correlation. The results of the study can be used by researchers for another large-scale research that empirically validates the developed hypothesis and by managers in the strategy development and decision-making processes.

© 2021 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of the scientific committee of the 9th CIRP Global Web Conference – Sustainable, resilient, and agile manufacturing and service operations : Lessons from COVID-19 (CIRPe 2021)

Keywords: lean production; industry 4.0; lean 4.0; sustainability; systematic literature review.

1. Introduction

Industry 4.0 is the new era of considerable changes for the economy, society, and environment. The first implementation initiatives of Industry 4.0 (henceforth I4.0) were proposed by the German government in 2011 and presented in the “High-Tech Strategy 2020 Action Plan” [1]. It communicates existing needs of society, customization, and integrity; and is often associated with concepts such as smart manufacturing and digital transformation. Varela [2] and Tasdemir [3] define I4.0 as “the combination of emerging technologies and value chain organization concepts”, others more specifically as “an instrument to better predict, control, and plan the product life cycle through the connectivity of technologies using networked sensors and software”.

Lean production is a well-established Japanese production

philosophy aiming to reduce complexities in the value chain by eliminating waste, including downtime, unnecessary processing steps, and redistribution of people and material; in other words, by doing more with less [4]. Its features are not restricted to the elimination of waste but cover the optimization of many manufacturing processes from product development to distribution. Recently, lean production has become a standard in many industries due to numerous benefits such as productivity, communication, and savings [2, 4, 5].

The concept of sustainability became widely used three decades ago after the consequences of human activities to the Earth's ecosystems had been realized. These were recorded from the first industrial revolution inevitably correlating those issues with industrial capitalism [4]. Since then, special attention is drawn to sustainability.

The present study aims to combine and examine the

integrated effect of Lean production and I4.0 concepts (Lean 4.0) as the separate impact of I4.0 and Lean on Sustainability was already investigated actively. The sustainability assessment approach used in this study is the triple-bottom-line (TBL) framework containing three pillars of sustainability (economic, environmental, social). The relationship of Lean and I4.0 with regards to sustainability will be tested based on the review of the extant literature.

2. Method and Materials

The primary approach used in the study is a systematic literature review (SLR), main search engines being Google Scholar, Taylor & Francis, and ScienceDirect. The procedure of literature collection is divided into two steps: 1) the preliminary database collection, 2) filtering. To collect the preliminary database, keywords associated with each of the three main themes (lean, industry 4.0, sustainability) were identified full list in Figure 1). Further, the development of search strings took place (Table 1) based on the combination of keywords from each section. After four developed search strings, a literature search was conducted, and a preliminary database was developed. In the second stage, papers were filtered based on four criteria: written in English; belongs to last five years with some exceptions used for concept definition purposes only; availability restriction to full papers; and an in-depth investigation of the title, abstract, and full paper to filter for relevance. At the end of these procedures, databases corresponding to relationships among three main concepts are developed (see Table 1, Filtered Results column).

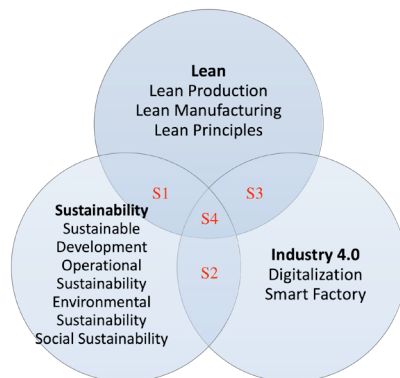


Fig. 1. Selected keywords

3. Results and Discussion

3.1. Lean and Sustainability

Lean manufacturing includes many tools, e.g., Muda, Jidoka, Just-in-Time (JIT), Value Stream Mapping (VSM), Kanban, Poka Yoke, Kaizen, 5S system, Root-cause analysis, Zero defects. To understand how "lean" affects sustainability, each principle and its impact should be considered.

Muda (or wastes) is any activity that consumes resources and time but does not create value. A lean concept, in general, considers seven main losses: overproduction, defects, waiting, over-processing, unnecessary or ineffective inventory, motion

or non-value-generating activities, and transportation [6, 16, 17], where each of these has sustainability impact. Unnecessary transportation, for example, can bring an increase in cost factors, energy use, and emissions [3]. In theory, the likelihood of a philosophy like Lean that stands for the elimination of waste to support sustainability is high. Several works arrive at the same conclusion [2, 3, 8–13]. However, eliminating what Lean perceives as waste does not always necessarily improve sustainability performance [14].

Table 1. Search strings for each block.

#	Block	Search String	Filtered Results
S1	Lean and Sustainability	allintitle: ("lean" OR "lean production" OR "lean manufacturing" OR "lean management" OR "lean principles") AND ("sustainability" OR "sustainable development" OR "operational sustainability" OR "environmental sustainability" OR "social sustainability")	[2], [3], [6-15]
S2	Industry 4.0 and Sustainability	allintitle: ("industry 4.0" OR "digitalization" OR "smart factory") AND ("sustainability" OR "sustainable development" OR "operational sustainability" OR "environmental sustainability" OR "social sustainability")	[5], [16-28]
S3	Lean and Industry 4.0	allintitle: ("lean" OR "lean production" OR "lean manufacturing" OR "lean management" OR "lean principles") AND ("industry 4.0" OR "digitalization" OR "smart factory")	[1], [29-39]
S4	Lean 4.0 and Sustainability	allintitle: ("lean 4.0" OR "lean automation" OR "lean production systems 4.0") AND ("sustainability" OR "sustainable development" OR "operational sustainability" OR "environmental sustainability" OR "social sustainability")	[2], [13], [14-16], [37], [40], [41]

Jidoka works on the basis that if a problem occurs, production should be stopped, mitigating the further production of defective products. At the same time, JIT, theory of «right product, in the right time, and the amount needed" acts as a catalyst in achieving sustainable development goals [14]. The JIT principle, however, also seems to be controversial. JIT leads to buffer minimization and effective use of inventory that decreases the operation cost. The side effect of frequent inventory and material transport, packaging, and handling, however, is an increase in volatile organic compounds and CO2 emissions, categorized as air pollution issues [14, 15, 17].

Value Stream Mapping (VSM), Kanban, Poka Yoke, Kaizen, 5S system, Root-cause analysis, and Zero defects are not an exception and may also have a detrimental impact on sustainability [2, 3, 6-16]. For example, the 5S (sort, set in order, shine, standardize, and sustain) philosophy has been useful in the reduction of non-renewal energy consumption and waste management, demonstrating the potential to improve the workplace environment and safety [10]. VSM helps improve

labor management and is useful in transparent production flow and elimination of economic waste [10]. Additionally, it is suggested to complement [15] VSM with 5S and Kaizen while dealing with air pollution. Many articles disregarded the relationship between Lean and social sustainability due to lack of resources [2, 3, 14] because as Tasdemir [3] argues, the social pillar gained the least attention. Overall, Lean principles and tools are positively associated with general sustainability and their synergies are advised despite some barriers [3, 6].

3.2. Industry 4.0 and Sustainability

I4.0 is a wide concept including the digitalization of most of the processes and stages in production: digital product design, creating a virtual copy of it, automatically ordering necessary components in required quantity, controlling their delivery, monitoring the path of finished products from warehouse in factory to store and end customer, etc. [16–20]. The essential constituent of I4.0 is not the product but data. To read, collect, analyze, process, store and transmit data, appropriate information systems and technologies are needed [16]. The main ones are additive technologies (3D printing), cloud services, visualization, Radio Frequency Identification (RFID), cybersecurity, energy-efficient technologies, robotization, augmented and virtual reality, Big data, and remote maintenance [17, 23]. A combination of these technologies allows creating an enterprise digitized, fully automated, and competitive. On the contrary, from the social sustainability perspective, with the introduction of such technologies, a significant part of the production would occur without human participation [17–22]. Despite promised improvements that these technologies bring, they may also cause unemployment and some may negatively affect human health [16, 17]. These technologies influence all three pillars of sustainability (economic, environmental, and social).

Due to the merger of technologies, digitalization of all economic processes is taking place: The Internet and artificial intelligence penetrate all industries and operations [18]. Now economic activity is being reoriented to large volumes of data in electronic form, which allows making economic decisions faster and easier [16]. Automation of industrial facilities reduces labor costs, making production less expensive while avoiding unnecessary repair and defective products [25]. Thus, there is a positive correlation between I4.0 and economic sustainability.

The integration of I4.0 technologies in industrial manufacturing not only benefits companies from an economic standpoint but can also provide clear advantages in terms of environmental sustainability [23]. Digitization of manufacturing processes allows companies to use raw materials efficiently, as well as to store and manage information about product assembly. Thus, it also simplifies disassembly and reduces the waste of resources [22, 23]. This serves as the basis for the so-called “circular” economy, one of the key achievements from an environmental perspective [23].

While I4.0 brings economic and environmental benefits, this transformation also means possible social threats to workers and the general population if job safety is not ensured. Some experts argue that the digitalization of the industry reduces the number of accidents and ensures the safety of

employees [24–26], which positively affects social sustainability [18]. For example, the adoption of the I4.0 facilitated the separation of all health-threatening steps (e.g., glazing process, which was fully automated) [18]. The workforce can now operate away from dangerous phases in a much safer work environment [17, 18]. What is not mentioned is that only highly skilled workers can work with such technologies [16]. This leads to the fact that low-skilled workers could lose their jobs. Training takes time and effort outside of normal working hours, which not every employer can afford [19]. Even highly skilled workers may face a situation when their education and skills become outdated and not in demand and the need for human labor decreases in production [16]. Despite such facts, experts are also convinced that there will be no job shortages as workers act as the main driver of continuous tuning and improvement of the I4.0 assembly line [17]. Overall, while I4.0 technologies provide benefits for economic and environmental aspects of sustainability, the overall impact on the social aspect is still questionable.

3.3. Sustainability Measures

Although sustainability is the key driver of innovation [4], there are no criteria/KPI or universal models that can characterize and evaluate the degree of sustainability of an organization [2, 4, 5, 16]. Sustainability is therefore measured through indirect quantitative parameters using the TBL approach consisting of economic, environmental, and social pillars. Also, each pillar affects a certain indicator, which was identified through the literature review presented earlier and supported by other authors [4, 5, 16, 17]. To create more classified criteria assessing how concepts such as Lean, I4.0, and their integration affect sustainability, several sustainability indicators were identified as the most important, grouped, and illustrated (Table 2) a checklist.

Table 2. Sustainability indicators for three dimensions.

Economic	Environmental	Social
Profit	Renewal Energy production	Working conditions
Turnover	Product durability	Workplace safety
Market Share Process Performance	Development of new green technologies	Decision-making liability (Autonomy, Worker engagement/Satisfaction)
Operational Costs	Industrial Waste	
Production Cost	Non-renewal energy consumption	

3.4. Lean 4.0: Integration of Lean and Industry 4.0

Based on the reviewed literature on Lean and I4.0 interconnection, the perspectives could be grouped into three categories: Lean as a basis to I4.0, I4.0 enhances Lean and positive correlation between the two [1, 28]. The third perspective stating that Lean principles are changing is added in some works [36, 41]. It argues that the current demand for digitalization needs an extension of the Lean Production System to integrate new technologies on the shop floor [36]. Specific attention is drawn to the first perspective, “Lean as a

basis or prerequisite to Industry 4.0". The main argument is that prior Lean implementation helps to overcome some I4.0 integration-related barriers [31]. As it is stated, I4.0 is a new revolution that involves new technologies and new opportunities. However, opportunities cannot be reached if the technologies are applied without the "guidance". Lean is indeed the guidance for effective management of processes and people. Its implementation can resolve the standardization and transparency issues. Moreover, prior Lean-to I4.0 adoption was argued to yield better results in operational performance [33, 34]. Another perspective, "Industry 4.0 impact on Lean" is often drawing a correlation between specific lean principles and I4.0 technologies. It is linked to the third perspective that suggests that Lean principles are changing due to these technologies, with specific examples are presented below.

JIT is a production management concept aimed at reducing inventory in lean manufacturing systems [8]. One of the collaborative I4.0 technologies is Auto-ID, a set of automatic identification solutions increasing the speed and accuracy of work [40]. Through the coordinated work of these, a feature of real-time monitoring and localization of materials that helps reduce the number of human errors, empty trips and ensure accurate material delivery and a robust logistics network has become available [40]. By contrast, to get automatic transportation of materials, JIT approach should be combined with a Smart Product [41]. Another way to achieve monitoring and localization of materials is to combine JIT with Big Data, which will improve system performance [29]. Using JIT with Additive manufacturing or Simulation will result in more accurate maintenance or better route optimization for vehicles and bottlenecks detection. All these combinations will have a common name as JIT 4.0 integrated system [30] and promise substantial improvements in Quality, Cost, Delivery, and Safety metrics [38].

Jidoka is a principle of Lean manufacturing that optimizes the production lifecycle. It autonomously detects problems (e.g., equipment malfunction) and signals when the need to fix them. In other words, it emphasizes the root cause of an error before it has occurred. In collaboration with Augmented Operator and CPS, they are named Jidoka 4.0, expanding the range of applications including improvement with tracking and timely maintenance provision [1]. Moreover, Jidoka 4.0 provides a "continuous learning" experience for the workforce rather than eliminating them with full automation [39].

Another method of identifying economic losses and implementing improvements in the framework of "lean manufacturing" is VSM. I4.0 upgraded the VSM tool from static to dynamic, where creating a dynamic shop floor picture allows the efficient use of production area and technological equipment [38, 40]. To achieve this, VSM 4.0 is used, which is a combination of the VSM method and Auto ID, Big Data, and Digital Twin technologies. In addition, it is possible to get real-time data collection and waste monitoring [1].

Kanban 4.0 is a combination of Kanban (pull management system of lean used for the production control) with Simulation. It ensures the determination of ideal Kanban parameters such as lot size, stock, or delivery frequency [40]. This system allows to make the project visual, track the readiness of work, and control specialists' workload. Another branch of Kanban 4.0 is the Kanban connection with the Auto-

ID system. It provides continuous monitoring of work, increasing the transparency of material movement and reducing unnecessary stock [16], with special attention needed for security and accessibility issues [37]. Thus, it can be suggested that JIT 4.0, Jidoka 4.0, VSM 4.0, and Kanban 4.0 are the most promising integrated systems so far.

Lastly, there is an agreement on the third perspective. Two philosophies, Lean and I4.0, are complementary [37] and they can influence each other iteratively [28]. Lean 4.0, Lean Automation (LA), Lean Production Systems 4.0 (LPS 4.0) concepts (proposed by Mrugalska [1], Tortorella [35], and Schumacher [36]) are the direct illustration of support given to Lean and I4.0 integrated implementation. In this paper, "Lean 4.0", is used to define the integration.

3.5. Lean 4.0 and Sustainability

The combination of lean and I4.0 (Lean 4.0) is argued to not only bring short-term operational excellence but also to contribute to long-term sustainability. There is some literature quantitatively assessing the relationship between I4.0, Lean, and their impact on sustainability. For example, Varela et al. [2] argued that there is no significant correlation between Lean and Sustainability, but a strong one between I4.0 and Sustainability. Kamble et al. [13] discussed that I4.0 alone has an insignificant and even negative correlation with Sustainability, and only if implemented with Lean manufacturing practices as a mediator, it can reach a positive correlation. More specifically, they argue that the integrated Lean and I4.0 approach strongly correlates with environmental performance, followed by social, and lastly economic. This literature tends to consider the overall I4.0 and lean effect on sustainability and doesn't emphasize the merge of specific technologies and principles.

For the economic dimension, all principles of Lean production contribute to an increase in process performance. For JIT 4.0, for example, an increase in performance was associated with higher transparency, shorter lead times, and improved flexibility [41]. Other impacted parameters are a decrease in operational and production costs [31]. Schumacher [36] argues that JIT combined with Additive Manufacturing in addition to speed, versatility, and adaptability, reduce the material cost, which contributes to production cost, while stating that VSM accompanied with simulation allow staff to investigate multiple options and choose the best, thus, saving money for the operation, production, and time [36].

For the environmental dimension, VSM 4.0 has many offerings directed towards waste reduction enabled thanks to immediate real-time management [25]. Meanwhile, JIT 4.0 is argued to increase the product durability. For the social pillar, JIT 4.0 is associated with worker engagement and VSM simulation with better working conditions due to engaging training opportunities. No information is present on Jidoka 4.0 and its relationship to sustainability.

To portray the relationship between specific merge of Lean and Industry technologies and principles on three pillars of Sustainability, a checklist (Table 3) was developed. It gives a glance at the most effective principles and tools that need to be prioritized if the company preserves sustainability policy or would like to deal with some specific sustainability indicator.

Table 3. Lean 4.0 and Sustainability assessment rubric.

	Lean	Industry 4.0	Lean 4.0
<i>Economic</i> ↑ in Profit ↑ in Turnover ↑ in Market Share ↑ in Process Performance ↓ in Operational Costs ↓ in Production Cost,	JIT production enables buffer minimization and better inventory management, which saves money on operational activities [15]. Process performance improvement is noted for all Lean principles [13]. An increase in Profit, Turnover, and Market share is expected with Lean application although not written explicitly.	Automation of industrial facilities controls repair and logistics work, which makes production less expensive. Since unnecessary work in production, as a replacement for defective products, is less likely, labor costs and costs of enterprises are reduced [23].	Lean 4.0 has a lot to increase the process performance [29]. Specifically, JIT 4.0 increases the speed and accuracy of companies' work [40], reduces human errors and empty trips, ensures accurate material delivery, and creates a robust logistics network [40]. VSM 4.0 spots the economic losses and ensures the improvement provision [36].
<i>Environmental</i> ↑ in Renewal Energy production ↑ in Product durability ↑ in Development of new green technologies ↓ in Industrial Waste ↓ in Non-renewal energy consumption	JIT can be hazardous when frequent transportation of materials/inventory, packaging, and handling is produced, thus, creating high amounts of industrial waste [11,16]. VSM balances industrial waste production and decreases non-renewable energy consumption [16], e.g., via elimination of unnecessary transportation, which reduces emissions.	The digitization of production processes allows companies to work on energy conservation and the development of eco – production [22]. In other words, recycling waste (which also makes production cheaper) and repairing equipment instead of purchasing new equipment reduces waste of resources [23].	Only a positive correlation between Lean 4.0 and environmental sustainability is noted. More precisely, several benefits listed in the literature are the capability of Kanban to reduce unnecessary stocks [40], and the capability of VSM to decrease industrial waste.
<i>Social</i> ↑ in Working conditions ↑ in Workplace safety ↑ in Decision-making liability ↑ in Contract duration ↑ in Employee health ↓ in Work Pressure	5S enables improved workplace safety and conditions through space “cleaning” [11].	I4.0 technologies create a safe work environment for workers, where the latter can only control the process. This reduces the number of accidents and ensures the safety of employees [24, 26]. However, only highly qualified workers will be able to work with such technologies [17].	Kanban 4.0 helps control specialists' workload, thus maintaining their work pressure within the allowable limit. In addition to the decrease in work pressure, it also increases employee health and well-being [26, 40].

4. Conclusion

This paper discussed the impact of the relationship between separate and integrated Lean and I4.0 effects on sustainability. Based on the analysis of the literature, it was found that Lean has a positive correlation with economic sustainability, while the correlation with environmental one is generally rejected and it was undefined for social dimension due to scarcity of research. For I4.0, a positive correlation with the economic and environmental pillars was present, while the social aspect was undefined. It is noted that both approaches had a positive correlation with the economic dimension. Lean did not have a strong correlation with the environmental pillar, as I4.0 with social. A positive correlation between Lean 4.0 and sustainability is also noted, with further validation needed.

The literature argues that before the introduction of I4.0, a company should use Lean manufacturing methods so that the production is ready to adapt new technologies and work with them. This paper has shown that the combination of the two systems will result in a stronger technology that will increase the speed and accuracy of companies' work from the perspective of specific Lean principles and I4.0 tools.

Among all, JIT 4.0, Jidoka 4.0, VSM 4.0, and Kanban 4.0 were found to be the most promising integrated systems as a result of the improved working conditions that they provide. For example, the JIT 4.0 system includes the combined

operation of JIT with different systems. One of them is the combination of JIT with Auto-ID, which ensures accurate delivery of materials and a reliable logistics network, whereas, route optimization for vehicles and bottleneck detection is achieved by combining JIT with additive manufacturing. The second system, Jidoka 4.0, is a combination of Jidoka with Augmented Operator and CPS, which improves the work of tracking and timely maintenance [1]. VSM 4.0, a combination of the VSM with Auto-ID and Big Data, offers advantages in real-time data collection and waste monitoring. Finally, Kanban 4.0, the connection of Kanban with the Auto-ID system, provides constant monitoring of work, which increases the transparency of the material transportation and reduces unnecessary stocks. Thus, the combination of I4.0 technologies and Lean manufacturing help bring production to a higher level while promising a positive impact on sustainability as well.

As an outcome of this study, a rubric was developed to assess the efficiency of different Lean and I4.0 combinations on Sustainability. Some preliminary assessment was made in favor of Lean 4.0, but it is advised to conduct an empirical study to obtain quantitative results. This work is important as the knowledge could influence the decisions of companies in the production systems and bring insights into the correlation between industrial practices and their long-term consequences.

Acknowledgments

This research was funded by Nazarbayev University Faculty Development Competitive Research Grants Program (FDCRGP, Grant No.: 240919FD3919).

References

- [1] B. Mrugalska and M. K. Wyrwicka, "Towards Lean Production in Industry 4.0," *Procedia Eng.*, vol. 182, pp. 466–473, 2017.
- [2] L. Varela, A. Araújo, P. Ávila, H. Castro, and G. Putnik, "Evaluation of the relation between lean manufacturing, industry 4.0, and sustainability," *Sustain.*, vol. 11, no. 5, pp. 1–19, 2019.
- [3] C. Tasdemir and R. Gazo, "A systematic literature review for better understanding of lean driven sustainability," *Sustain.*, vol. 10, no. 7, 2018.
- [4] L. Monostori and J. Váncza, "Towards living manufacturing systems," *Procedia CIRP*, vol. 93, no. 2019, pp. 323–328, 2020.
- [5] S. S. Kamble, A. Gunasekaran, and S. A. Gawankar, "Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives," *Process Saf. Environ. Prot.*, vol. 117, pp. 408–425, 2018.
- [6] A. de Carvalho, A. Granja, & V. da Silva, "A Systematic Literature Review on Integrative Lean and Sustainability Synergies over a Building's Lifecycle," *Sustainability*, vol. 9, no. 7, pp. 1156, 2017.
- [7] C. Tasdemir and R. Gazo, "A Systematic Literature Review for Better Understanding of Lean Driven Sustainability", *Sustainability*, vol. 10, no. 7, p. 2544, 2018.
- [8] V. Taghavi and Y. Beauregard, "The Relationship between Lean and Industry 4.0: Literature Review", *IEOM Society International*, 2020.
- [9] C. Prinz, N. Kreggenfeld and B. Kuhlenkötter, "Lean meets Industrie 4.0 – a practical approach to interlink the method world and cyber-physical world", *Procedia Manufacturing*, vol. 23, pp. 21–26, 2018.
- [10] H. C. Martínez León and J. Calvo-Amodio, "Towards lean for sustainability: Understanding the interrelationships between lean and sustainability from a system thinking perspective," *J. Clean. Prod.*, vol. 142, pp. 4384–4402, 2017.
- [11] N. Carvalho, O. Chaim, E. Cazarini, and M. Gerolamo, "Manufacturing in the fourth industrial revolution: A positive prospect in Sustainable Manufacturing," *Procedia Manuf.*, vol. 21, pp. 671–678, 2018.
- [12] D. De, S. Chowdhury, P. K. Dey, and S. K. Ghosh, "Impact of Lean and Sustainability Oriented Innovation on Sustainability Performance of Small and Medium-Sized Enterprises: A Data Envelopment Analysis-based framework," *Int. J. Prod. Econ.*, vol. 219, no. July 2018, pp. 416–430, 2020.
- [13] S. Kamble, A. Gunasekaran, and N. C. Dhone, "Industry 4.0 and lean manufacturing practices for sustainable organizational performance in Indian manufacturing companies," *Int. J. Prod. Res.*, vol. 58, no. 5, pp. 1319–1337, 2020.
- [14] A. C. V. de Carvalho, A. D. Granja, and V. G. da Silva, "A systematic literature review on integrative lean and sustainability synergies over a building's lifecycle," *Sustain.*, vol. 9, no. 7, 2017.
- [15] M. Dieste, R. Panizzolo, J. A. Garza-Reyes, and A. Anosike, "The relationship between lean and environmental performance: Practices and measures," *J. Clean. Prod.*, vol. 224, pp. 120–131, 2019.
- [16] M. Fathi, A. Nourmohammadi, M. Ghobakhloo, and M. Yousefi, "Production sustainability via supermarket location optimization in assembly lines," *Sustain.*, vol. 12, no. 11, 2020.
- [17] T. Bányai, P. Tamás, B. Illés, Ž. Stankevičiūtė and Á. Bányai, "Optimization of Municipal Waste Collection Routing: Impact of Industry 4.0 Technologies on Environmental Awareness and Sustainability", *International Journal of Environmental Research and Public Health*, vol. 16, no. 4, p. 634, 2019.
- [18] Y. Meng, Y. Yang, H. Chung, P. Lee, and C. Shao, "Enhancing Sustainability and Energy Efficiency in Smart Factories: A Review", *Sustainability*, vol. 10, no. 12, p. 4779, 2018.
- [19] L. S. Dalenogare, G. B. Benitez, N. F. Ayala & A. G. Frank, "The expected contribution of Industry 4.0 technologies for industrial performance," *International Journal of Production Economics*, vol. 204, pp. 383–394, 2018.
- [20] L. Varela, A. Araújo, P. Ávila, H. Castro, & G. Putnik, "Evaluation of the Relation between Lean Manufacturing, Industry 4.0, and Sustainability," *Sustainability*, vol. 11(5), 2019.
- [21] G. Magdalena & E. Pessl, "Industry 4.0 and sustainability impacts: critical discussion of sustainability aspects with a special focus on future of work and ecological consequences," *International Journal of Engineering*, vol. 14, pp. 131–136, 2016.
- [22] D. Dikhanbayeva, S. Shaikholla, Z. Suleiman and A. Turkyilmaz, "Assessment of Industry 4.0 Maturity Models by Design Principles", *Sustainability*, vol. 12, no. 23, p. 9927, 2020.
- [23] P. Ghadimi, C. Wang, M. K. Lim & C. Heavey. "Intelligent sustainable supplier selection using multi-agent technology: theory and application for Industry 4.0 supply chains," *Computers & Industrial Engineering*, vol. 127, pp. 588–600, 2019.
- [24] J. Oláh, N. Aburumman, J. Popp, M. Asif Khan, H. Haddad & N. Kitukuth, "Impact of Industry 4.0 on Environmental Sustainability," *Sustainability*, vol. 12, pp. 1–21, 2020.
- [25] C. Bai, P. Dallasega, G. Orzes, and J. Sarkis, "Industry 4.0 technologies assessment: a sustainability perspective," *International Journal of Production Economics*, vol. 229, pp. 1–15, 2020.
- [26] A. Sanders, C. Elangeswaran, and J. Wulfsberg, "Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing," *J. Ind. Eng. Manag.*, vol. 9, no. 3, pp. 811–833, 2016.
- [27] S. V. Buer, J. O. Strandhagen, and F. T. S. Chan, "The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2924–2940, 2018.
- [28] K. Ejsmont, B. Gladysz, D. Corti, F. Castaño, W. M. Mohammed, and J. L. Martinez Lastra, "Towards 'Lean Industry 4.0'—Current trends and future perspectives," *Cogent Bus. Manag.*, vol. 7, no. 1, pp. 0–32, 2020.
- [29] U. Dombrowski, T. Richter, and P. Krenkel, "Interdependencies of Industrie 4.0 & Lean Production Systems: A Use Cases Analysis," *Procedia Manuf.*, vol. 11, no. June, pp. 1061–1068, 2017.
- [30] F. Rosin, P. Forget, S. Lamouri, and R. Pellerin, "Impacts of Industry 4.0 technologies on Lean principles," *Int. J. Prod. Res.*, vol. 58, no. 6, pp. 1644–1661, 2020.
- [31] M. P. Ciano, P. Dallasega, G. Orzes, and T. Rossi, "One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study," *Int. J. Prod. Res.*, vol. 0, no. 0, pp. 1–25, 2020.
- [32] N. Davis, A. Companiwal, B. Muschard, and N. Petrusch, "4th Industrial Revolution Design Through Lean Foundation," *Procedia CIRP*, vol. 91, pp. 306–311, 2020.
- [33] M. Sony, "Industry 4.0 and lean management: a proposed integration model and research propositions," *Prod. Manuf. Res.*, vol. 6, no. 1, pp. 416–432, 2018.
- [34] M. Rossini, F. Costa, A. P. Staudacher, and G. Tortorella, "Industry 4.0 and lean production: An empirical study," *IFAC-PapersOnLine*, vol. 52, no. 13, pp. 42–47, 2019.
- [35] G. L. Tortorella and D. Fettermann, "Implementation of industry 4.0 and lean production in Brazilian manufacturing companies," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2975–2987, 2018.
- [36] S. Schumacher, A. Bildstein, and T. Bauernhansl, "The impact of the digital transformation on lean production systems," in *Procedia CIRP*, Jan. 2020, vol. 93, pp. 783–788.
- [37] V. L. Bittencourt, A. C. Alves, and C. P. Leão, "Lean Thinking contributions for Industry 4.0: A systematic literature review," *IFAC-PapersOnLine*, vol. 52, no. 13, pp. 904–909, Sep. 2019.
- [38] Powell, D. Romero, D., Gaiardelli, P., Cimini, C. and Cavalieri, S. 2018. Towards Digital Lean Cyber-Physical Production Systems: Industry 4.0 Technologies as Enablers of Leaner Production. IFIP AICT Series, Part II. pp. 353–359.
- [39] Romero, D., Gaiardelli, P., Powell, D.J., Wuest, T and Thürer, M. 2019. Rethinking Jidoka Systems under Automation & Learning Perspectives in an Emerging Digital Lean Manufacturing World. IFAC PapersOnLine, 52, 13, pp. 889–903.
- [40] A. Mayr et al., "Lean 4.0-A conceptual conjunction of lean management and Industry 4.0," *Procedia CIRP*, vol. 72, pp. 622–628, 2018.
- [41] T. Wagner, C. Herrmann, and S. Thiede, "Industry 4.0 Impacts on Lean Production Systems", *Procedia CIRP*, vol. 63, pp. 125–131, 2017.