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A novel tool-input-process-output (TIPO) framework for upgrading to lean 4.0

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Abstract:

For more than four decades, Lean Manufacturing (LM) has delivered in terms of waste reduction, productivity and sustainability for the benefit of manufacturers, customers and society at large. In the present era of Industry 4.0 (I4.0), the integration of physical and digital systems is providing huge scope for enhancing the performances of conventional lean tools and practices. Although recent literature has emphasized the integration of lean and Industry 4.0 as Lean 4.0, the mode of integration and basis for selecting technologies need to be explored more. The present paper aims to address this gap and presents a novel Tool-Input-Process-Output (TIPO) approach in which 'Inputs' required for the implementation of conventional lean tools are identified and mapped with core characteristics of I4.0 technologies to develop the 'Process' for the integration. Exemplified on three prominent lean tools; Just-In-Time (JIT), *Jidoka* and *Heijunka* to illustrate the proposed framework.

Key words:

Lean Manufacturing, Industry 4.0, Lean 4.0, TIPO, JIT, *Jidoka, Heijunka*.

1. Introduction

As technology continues to advance, the manufacturing industry must adapt and evolve to meet the changing demands of consumers. Staying ahead of the competition in the fast-paced world of modern manufacturing is crucial for success (Tampubolon & Purba, 2021). This has led to a multitude of shifts and advancements in the field of manufacturing, with notable concepts such as Lean and Industry 4.0. Recently, literature has begun to combine these approaches and refer to them as 'Lean Industry 4.0' or 'Lean 4.0' (Gil-Vilda et al., 2021; Najwa et al., 2021; Valamede & Akkari, 2020).

Lean Manufacturing (LM) is a well-established approach in manufacturing which has been used for decades with the goal of minimizing waste and increasing productivity while meeting customer needs (Womack & Jones, 1997). To enhance operational efficiency and gain a competitive edge, many manufacturing companies have implemented lean Manufacturing initiatives with the aim of cultivating a culture of ongoing improvement (Jastia & Kodali, 2015). The principles of LM involve understanding what the customer values, waste reduction, creating products based on customer demand and promoting a steady and efficient process (Marodin et al., 2022). The practices of LM involve low-tech, simple and effective methods that are aligned with the company's vision (Hopp & Spearman, 2021). LM also emphasizes the importance of empowering and involving employees in the change process, regardless of their position or function (Buer et al., 2021; Ciano et al., 2021).

Previous industrial revolutions have greatly advanced society and brought about significant benefits that are still being felt today (Nai Yeen Gavin Lai et al., 2019). Industry 4.0, the fourth stage of the industrial revolution, has the potential

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to revolutionize the manufacturing sector. I4.0, first introduced at 'Hannover Fair' in Germany in 2011, refers to the integration of interconnected machines, smart systems and interconnected solutions to create intelligent production units using digital and computerized components that monitor and control physical systems (Calış Duman & Akdemir, 2021). The rise of Industry 4.0 has transformed the way organizations think about manufacturing and the techniques used to optimize production (Hofmann & Rüsch, 2017). In the current era of I4.0, manufacturers are encouraged to investigate the use of advanced technologies, automation and digitalization as a means of further optimizing the lean enterprise and achieving operational excellence (Sartal et al., 2022). These digital advancements offer the potential for significant gains in productivity and efficiency. By embracing Industry 4.0, manufacturers can stay at the forefront of the industry and maintain their competitive advantage. The principles of lean manufacturing, such as minimizing waste and maximizing value for customers, align well with the goals of I4.0 (Bittencourt et al., 2021; Pereira et al., 2019). According to (El Faydy et al., 2023), the effectiveness of the Lean-Product life cycle framework in the context of Industry 4.0 depends on several factors, including the endorsement and dedication of senior leadership, the utilization of big data, effective change management strategies and the provision of adequate professional training and development opportunities. By leveraging the power of big data analytics and cyber-physical systems, manufacturers can more effectively identify and eliminate waste in their operations (Powell et al., 2018). For example, data from machine sensors can be used to identify bottlenecks in production lines, allowing manufacturers to address these issues and improve flow. Additionally, the automation of certain processes through the use of cyber-physical systems can help manufacturers reduce errors and improve efficiency, leading to leaner operations (Romero et al., 2018).

Moreover, integration of I4.0 technologies with principles and tools of LM can help manufacturers achieve even greater levels of operational efficiency and competitiveness. Numerous studies have explored the potential impact of I4.0 on LM practices and the benefits of LM organizations that implemented I4.0 technologies (Agostinho & Baldo, 2020; Ciano et al., 2021; Schumacher et al., 2020). However, there is a need for an operational framework that guides potential directions for this integration. To address this gap, a novel framework named TIPO (Tool-Input-Process- Output) is proposed and applied in this research paper to illustrate some important lean tools.

In this paper, Section 2 provides an overview of the research background on LM, I4.0 and the correlation between them. In Section 3, the proposed TIPO approach and its application to a LM system are presented. Specific application of TIPO to three lean tools (JIT, *Jidoka* and *Heijunka*) is illustrated in Section 4. Conclusion and future directions for research are given in Section 5 of the paper.

2. Research Background

This section presents the current state-of-art on LM, I4.0 and their interaction through a judicious selection of literature and review. It identifies the research gaps and thus serves as a motivation for the framework proposed in the present study.

2.1. Lean Manufacturing

In response to challenges for industry survival, Taiichi Ohno came up with a system aimed at reducing costs by eliminating waste and treating workers with respect at Toyota Production System (TPS) (Ohno, 1988). This philosophy proved to be successful as Toyota's profits exceeded those of other firms in Japan, Europe, and the United States (Krafcik, 1988). This led to increased curiosity among managers and market experts about Toyota's unique approach. The book 'The Machine That Changed the World' popularized TPS and introduced the world to 'Lean Manufacturing' (Womack et al., 2007). The core principles of lean manufacturing focus on maximizing value and eliminating waste by identifying and meeting customer needs, improving flow, efficiency and continuously pursuing for perfection.

To effectively eliminate waste and improve efficiency, manufacturers must first identify the specific types of waste that may be present in the operations. These wastes include overproduction, waiting, defects, over-processing, excess inventory, unnecessary motion and unused talent. Some of the prominent LM tools are *Jidoka, Heijunka,* Just-In-Time (JIT), Single-Minute Exchange of Die (SMED), Value Stream Mapping (VSM) and Total Productive Maintenance (TPM). Implementing JIT inventory management can help to reduce excess inventory and improve flow, while TPM can improve equipment reliability and reduce maintenance costs (Gunasekaran & Lyu, 1997). Many firms have found that implementing lean practices can lead to significant increases in efficiency and quality with reduction in costs and waste (Karim & Arif-Uz-Zaman, 2013, Carvalho et al., 2019). In addition, the focus on continuous improvement and employee involvement has also been found to lead to a more engaged and motivated workforce. However, it should be noted that implementation of lean manufacturing is not a one-time process but rather a journey that requires commitment and dedication from the entire organization (Drew et al., 2004). Additionally, LM principles can be adapted and customized to fit the specific needs and constraints of an individual organization (Jina et al., 1997).

2.2. Industry 4.0

Ever since its inception, the notion of Industry 4.0 has gained significant traction in both the corporate and educational spheres, serving as a means to describe the impact of the assimilation of emerging technologies within the manufacturing and supply chain domains. In 2011, the German country introduced Industry 4.0 as a component of its advanced technology strategic program (Kagermann, 2013). I4.0 has six key design principles which are the core foundation for all the changes (Table 1). The implementation of I4.0 comprising of diverse technologies like Artificial Intelligence (AI), Internet of Things (IoT), additive manufacturing, cyber physical systems, cloud computing, Virtual/Augmented reality (VR/AR), big data analytics, autonomous robotics, simulation and digital twin (Mittal et al., 2018).

The potential for improvement in operational efficiency of firms through the adoption of empowering technologies and principles of I4.0 is substantial, as it emphasizes enhancing processes, products and business models (Tortorella & Fettermann, 2018). A substantial research reports suggest that these technologies can address the challenges faced by traditional manufacturing such as poor efficiency, managing complex supply chains, offering high levels of customization and meeting the demands of adaptable and service-based markets (Chiarini et al., 2020). The integration of technologies such as digital automation and remote monitoring can have a significant impact on manufacturing processes (Kolberg et al., 2017) and other I4.0 technologies like cloud services, big data, and rapid prototyping can enable companies to achieve substantial advancements in product development and innovation in service delivery (Wan et al., 2015; Zuehlke, 2010). Although there are varying perspectives among researchers on the components of Industry 4.0 and their interconnections can be found, Figure 1 presents

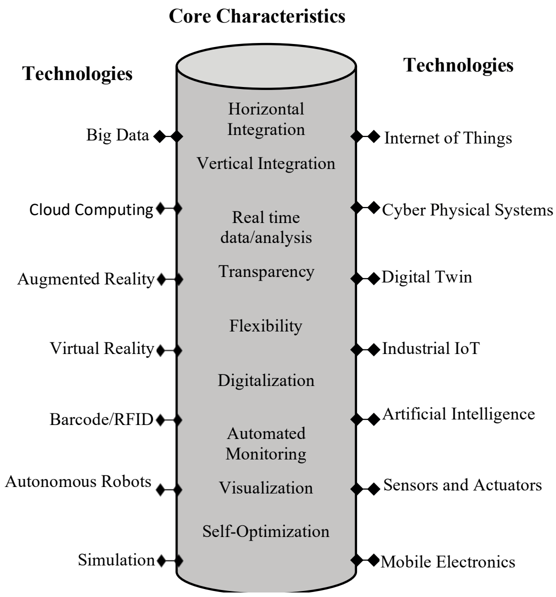

Figure 1. Core characteristics and technologies under I4.0.

Table 1. Key design principles under Industry 4.0.

Principles	Description
Interoperability	The ability of machinery, devices, people in the organization to interact through IoT (Internet of Things) and IoS (Internet of services).
Virtualization	Potential to make virtual replica of the real-world using Sensors, Simulation models, and Plant Framework.
Decentralization	The potential of cyber-physical systems (CPS) to make independent decisions.
Real-Time capability	The ability to collect, analyze and provide critical insights instantly.
Service Orientation	The employees can remotely access the organization through IoS. This can be offered both inside and across organizational borders.
Modularity	The ability to quickly change or replace the modules according to requirements.

an acceptable depiction of the core characteristics and their enabling technologies. A formal definition is presented as “Industry 4.0 is a paradigm shift in the manufacturing industry, characterized by the integration of advanced technologies throughout the supply chain, which leads to an increase in automation, self-regulation, and decentralization of decision-making, ultimately resulting in a more efficient and adaptable production process”.

Given the rapid pace of technological advancements within the realm of I4.0, it is important to acknowledge that categorizations within this field are subject to change. As new technologies emerge and existing ones mature, it is imperative to continuously update and expand upon current categorizations.

2.3. Lean 4.0

The effectiveness and compatibility of combining LM and I4.0 in manufacturing have been a point of discourse in many recent literature (Bittencourt et al., 2019; Kipper et al., 2020; Pagliosa et al., 2021). Some researchers have even suggested that the lean system serves as a basis for executing I4.0 (Mayr et al., 2018; Pereira & Romero, 2017; Varela et al., 2019). A study (Tortorella et al., 2021) proposed that integrating LM procedures with I4.0 could lead to ‘Lean Automation’, which could enhance flexibility and streamline information flow thus enabling businesses to meet the evolving demands of the market. They also noted that the existence of I4.0 technologies alongside lean manufacturing practices will not hinder each other, but instead, it offers a possibility for a collaborative and synergistic effect. In their research, (Kolberg et al., 2017) examined 41 different methods with the goal of creating an interface for the digitalization of LM practices using cyber physical systems. Similarly, (Buer et al., 2018) conducted a study that focused on the relationship between I4.0 and LM. They identified four primary areas of research which include the ways in which I4.0 can support and enhance existing LM methods, how LM can facilitate the adoption of I4.0, the effect of integrating LM and I4.0 on various aspects of production performance and the environmental factors that may influence the integration of these two practices. (Spenhoff et al., 2022) proposed an effective approach to manage production by integrating LM and I4.0. Their scheduling framework prioritizes flexibility, minimizes disruptions and optimizes production scheduling. (Cifone et al., 2021) categorized eight mechanisms that reduce waste and assist with process improvement through digital technologies aiding firms in selecting effective tools. According to (Dahmani et al., 2021), integrating lean and eco design with I4.0 technologies can improve circular business models and sustainable product strategies can be implemented.

Rosin et al. (2020) emphasized I4.0’s impact on LM and its potential to enhance lean practices, specifically JIT and Jidoka, indicating strong support for I4.0 technologies. While (Tortorella & Fettermann, 2018) were able to demonstrate a connection between LM implementation and I4.0 for enhancing operational performance through an empirical study conducted in Brazil. (Buer et al., 2018) examined the relationship between I4.0 and LM, highlighting crucial areas for investigation such as the improvement of LM practices, the support of LM in implementing I4.0 and the impact of integrating LM and I4.0 on various production performances. Studies have also explored the correlation between I4.0 and sustainable performance, with LM serving as a potential mediating variable to examine both direct and indirect impacts on performance (Kamble et al., 2020). Rossini et al. (2019) studied the relationship among I4.0 technology adoption, LM practices and operational performance for European manufacturers. (Ciano et al., 2021) also examined the direct connections between LM and I4.0 through multiple case studies. Yadav et al. (2020) opined that integrating I4.0 technologies can improve organizational performance indicators like productivity, quality performance and sales turnover under different combinations of lean six sigma and quality management systems as implemented in Indian firms.

Saraswat et al. (2021) emphasized the role of technologies such as IoT and data analytics in improving decision support systems and enhancing productivity when integrated with LM. They also identified twelve critical success factors that enable the integration of I4.0 tools and LM in small and medium scale companies. Despite numerous studies demonstrating the positive effects of integration, the individual interaction between tools and technologies remains unclear (Taghavi & Beauregard, 2020). From the literature survey, it is apparent that researchers are increasingly interested in investigating the compatibility and effectiveness of integrating I4.0 technologies and LM practices. However, the existing research has also highlighted the need for further exploration of the ways in which these two can be optimally integrated to achieve maximum positive effect for manufacturing organizations. To contribute towards this research gap, the present study is motivated to propose a novel methodology that seeks to explore the optimal integration of I4.0 technologies and LM practices in a systematic and comprehensive mode.

This methodology can provide practical insights and recommendations for manufacturing practitioners looking to integrate Industry 4.0 technologies and lean manufacturing tools.

3. Proposed TIPO Approach

This research work is presenting a novel methodology Tool-Input-Process-Output or TIPO to draw a broad framework for integrating suitable I4.0 technologies with lean tools and practices. As depicted in Figure 2, the 'Tool' indicates the specific lean tool under consideration. The 'Input' section should identify the inputs required for implementing the tool. Here, some expertise of lean practitioners is required to properly understand the operation of conventional lean tools and their inputs. For example, in the JIT inventory system, data on demands, inventory levels, replenishment records of suppliers, etc. are typical inputs. The 'Process' section will examine the mode of integration based on the inputs and compatibility with I4.0 technologies.

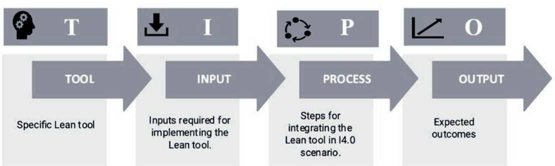

Figure 2. Sections of a TIPO Approach.

The core characteristics and enabling technologies of I4.0 as described in §2.2 are mapped to identified inputs to develop the process. Finally, in the 'Output' section, the expected results and potential improvements in the system will be outlined. The integration of lean tools and practices with Industry 4.0 technologies can be comprehensively understood using the TIPO methodology. It simplifies the mode of integration and serves as a foundation for further improvements in future. Eventually, the TIPO methodology can benefit manufacturers, practitioners and researchers by offering a structured approach to implement this integration. A model lean 4.0 framework followed by three specific lean tools based on TIPO are presented in the subsequent sections of the paper.

3.1. Lean 4.0 Framework

Lean 4.0 framework, an innovative model that integrates the principles and tools of lean manufacturing with advanced Industry 4.0 technologies. This framework has been developed based on an extensive review of the literature with the primary objective of enhancing efficiency, reducing downtime and increasing productivity by leveraging technologies such as big data, artificial intelligence, automation and real-time data analysis. Figure 3 depicts the framework, highlighting its various components and their interrelationships. In a lean 4.0 shop floor environment, machines are connected by IoT and act as CPS, enabling seamless communication among machines and the plant interface system (Rossi et al., 2022). Lean 4.0 requires real-time data collection and analysis, enabling predictive maintenance and efficient production planning (Peter et al., 2022).

Communication between man and machine is possible through smartwatches, Cobots and inventory levels can be identified using RFID cards (Kolberg, 2015). To further improve efficiency and reduce waste in a lean environment, additive manufacturing technology has been widely adopted. In fact, studies have shown that the implementation of additive manufacturing technology has significantly reduced inventory levels and improved overall operational efficiency (Rosin et al., 2020). Further, in this proposed Lean 4.0 framework, the Plant Interface System (PIS) serves as a central hub for information transfer among managers, suppliers and the shop floor. The PIS comprises two key modules: the Advance Maintenance Prediction (AMP) module and the Adaptive Production Planning (APP) module. The AMP module utilizes big data and AI to predict potential failures or bottlenecks in the production process based on the data related to stock level, production process, and machines.

The APP module generates an optimum production sequence based on customer order data and real-time information from the AMP, allowing for dynamic and efficient production flow. Flow of information from the APP module to the AMP module enables real-time updates to the production schedule based on predicted maintenance needs, ensuring optimal production flow and minimal downtime. If equipment is likely to fail, AMP alerts managers and APP adjusts the production schedule. If maintenance is needed sooner than predicted, APP modifies the schedule to keep the production optimized.

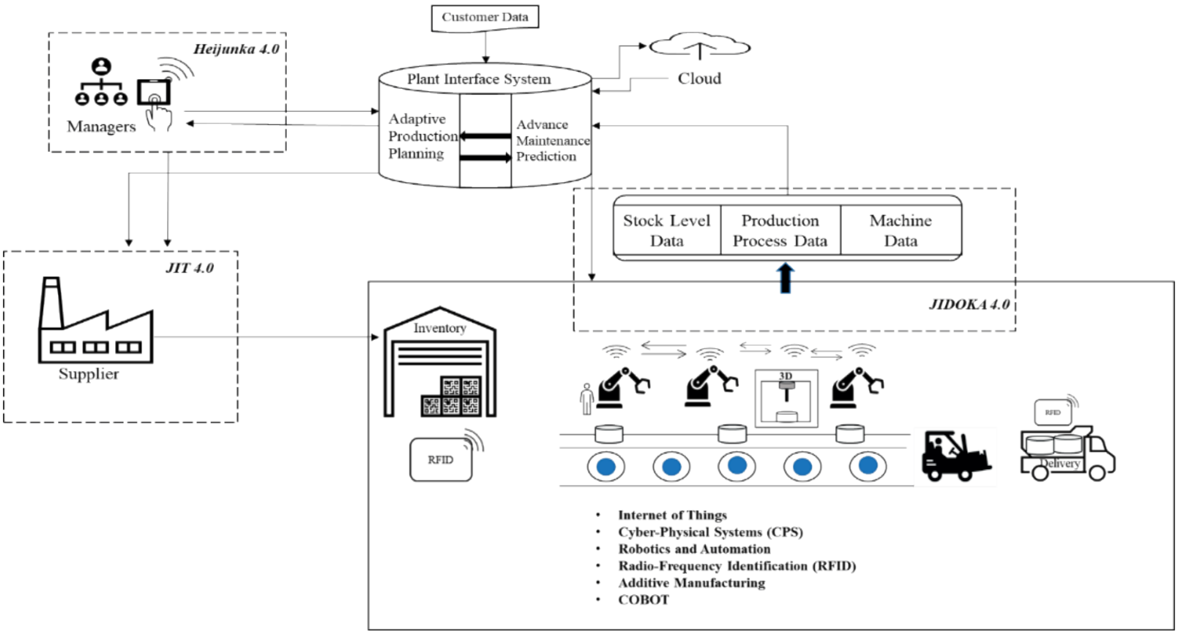

Figure 3. Proposed Lean 4.0 Framework.

This ensures that customer demand is met in a timely and efficient manner. An important aspect of Lean 4.0 is that it empowers managers to be the final decision makers, rather than leaving it all to machines and technology. This approach ensures that the implementation of I4.0 and LM tools aligns with the objectives and goals of the organization, ensuring sustainability and productivity.

The framework can also be customized to meet any specific requirements of the firm. Application of TIPO approach to three prominent lean tools JIT, *Jidoka* and *Heijunka* within Lean 4.0 framework are presented here.

4. TIPO Approach for Lean 4.0 Tools

4.1. JIT 4.0

JIT is a crucial entity of the Toyota Production System and lean manufacturing approach. Its primary goal is to produce in exact quantity, time, location, quality and costs without the need for an inventory backlog (Valamede & Akkari, 2020). In order to achieve this, inventory from suppliers is procured only when required, eliminating unnecessary inventory carrying and movement in the manufacturing plant. JIT significantly minimizes waste and maximizes efficiency by implementing rigorous inventory control systems and closely monitoring production schedules. The achievement of JIT's goals may face obstacles arising from logistical system issues like incomplete product information, discrepancies between the requested and delivered goods and unexpected transportation delays (Sanders et al. 2016; Mayr et al., 2018). Integrating cloud technology with IoT enables wireless tracking of products will improve on-time delivery and logistics operations (Sanders et al. 2016).

To realize the full potential of JIT, it is essential to address these challenges from logistics system and ensure that the right products are transported at the right time and location to meet production requirements. The core characteristics of I4.0, such as real-time data analysis, horizontal and vertical integration, transparency, flexibility, digitalization, and automated monitoring, can significantly improve the JIT (Ciano et al., 2021, Wagner et al., 2017). The utilization of I4.0 tools such as big data, AI, automation, and real-time data analysis (Satoglu et al., 2018; Xu & Chen, 2017) facilitates both the collection of these inputs and the application of their core characteristics, while still adhering to traditional JIT principles. Figure 4 highlights that Industry 4.0 technologies can contribute to achieving JIT goals more efficiently. For this TIPO approach, inputs are identified as customer data, supplier data, and inventory data based on research works of Wagner et al. (2017), Sihle and Sambil (2018), Xu and Chen (2017). The interaction between lean practices and

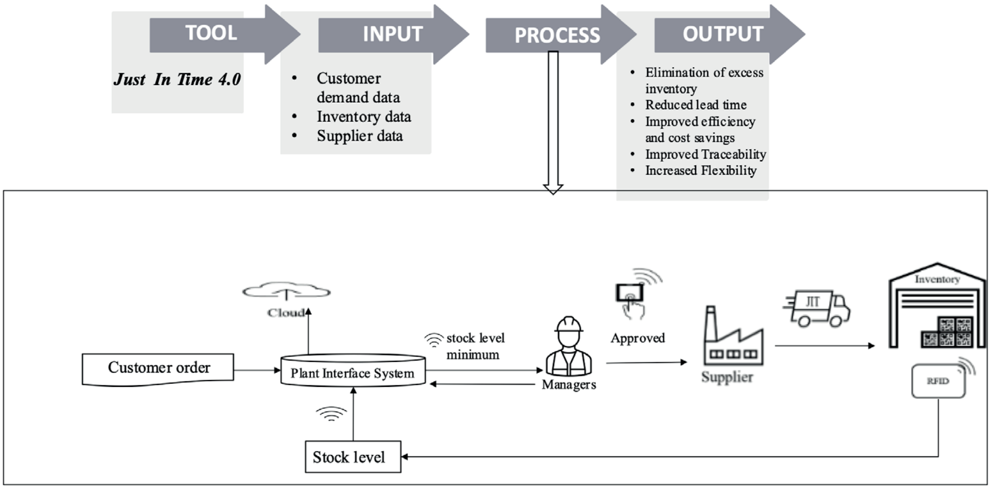

Figure 4. TIPO for JIT 4.0.

I4.0 can improve the flexibility and connectivity of the supply chain throughout different processes, devices, and stakeholder (Santos et al., 2021). The implementation of technologies such as the cloud, big data analytics and additive manufacturing can offer several advantages to JIT. In the process step of the TIPO, the conventional Kanban cards are replaced by real time machine to machine communications using cyber physical systems and IoT.

Real-time data analysis and advanced analytics enable a dynamic and efficient production flow by utilizing customer order data and real-time information from the Advanced Maintenance Prediction (AMP) module. This ensures that the right materials and resources are available at the right time, reducing inventory and waste. Additionally, the flow of information between the Adaptive Production Planning module and the AMP module allows for real-time updates to the production schedule based on predicted maintenance needs, further reducing waste and inventory.

The process step of TIPO for JIT is explained here. Upon receiving a customer order, the plant interface system promptly verifies the inventory level and creates an automatic purchase order for manager approval. Once the manager approves the order, the plant interface systems, sends a copy of it to store in the cloud for record keeping. Additionally, plant interface systems then immediately send an order to the supplier to ensure timely delivery of the necessary materials for production. An optical RFID system will automatically post the delivered materials and factor them into the calculation of future material requirements. Real-time supply chain data obtained through technologies like RFID and GPS are processed and shared via the cloud for advanced analytics and machine learning. In certain circumstances, it may also be possible for the supplier to directly deliver to the machine, eliminating inventory completely, this ultimately improves efficiency, minimizes downtime, and increases productivity. Additive manufacturing technologies facilitate the production of customized orders with high efficiency and precision, while minimizing process time and raw material wastage. By implementing the Just-In-Time 4.0 framework, it is possible to attain various desirable outcomes, such as minimizing excess inventory, shortening lead time, enhancing operational efficiency, realizing cost savings, ensuring traceability, and boosting adaptability.

4.2. *Jidoka* 4.0

Jidoka, a Japanese term for 'autonomation' is a system that monitors the manufacturing process in order to detect defects at their source and prevent the spread of defective products. Further, the *Jidoka* system detects abnormalities and provides feedback through 'Andon' alarms (Rossi et al., 2022). It can detect, diagnose, and prevent problems before they occur (Buer et al., 2018; Mayr et al., 2018).

The evolution of Jidoka systems has progressed from mechanical devices known as 'Poka-Yokes' that simply detect and stop an undesired state in the manufacturing process to more advanced systems with visual and audio alerts (Romero et al., 2019).

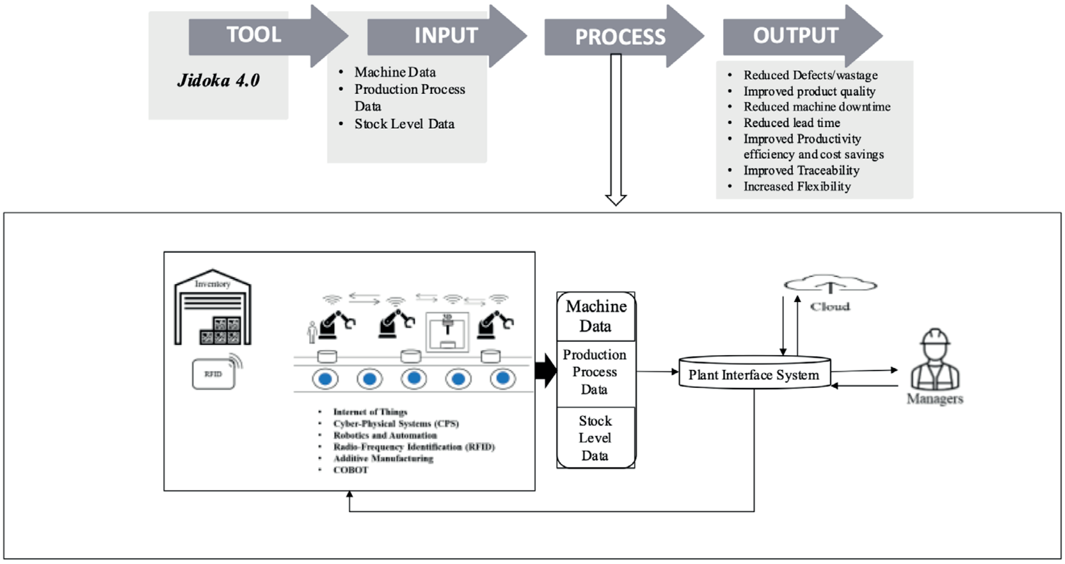

Figure 5. TIPO for Jidoka 4.0.

The present TIPO framework (Figure 5) proposes the use of I4.0 technologies such as IoT, CPS, big data analytics and cloud computing for upgradation to Jidoka 4.0. Based on previous works of (Romero et al., 2019, Rossi et al., 2022 and Deuse et al., 2020), implementing Jidoka in a manufacturing process requires the input data from the machine, production process and stock level. Moreover, the core characteristics of I4.0, such as vertical integration, real-time data/analysis, transparency, flexibility, digitalization, automated monitoring, and visualization can significantly aid in collecting these inputs more quickly and in real-time. In the process step of the TIPO framework for Jidoka 4.0 an advanced maintenance prediction module for the PIS is included. PIS utilizes both supervised and unsupervised learning methods to identify patterns in production process and machine data. By using the advanced maintenance prediction module, the PIS can detect any abnormal production process patterns that may lead to deviations in product quality and anticipate potential failures, allowing for proactive maintenance and minimizing downtime. The Jidoka 4.0 can incorporate human-computer integration devices such as tablets, head-mounted displays, and wrist-worn smart devices. Its main objective is to promptly alert operators/managers of any potential machine malfunctions, replacing the traditional Andon beacons. With the use of such devices, communication between man and machine is streamlined, enhancing productivity, and reducing downtime. The alerts include specific information on machines, estimated failure times, and necessary changes in real-time. When a machine failure is detected, the advanced production planning module of the PIS gets activated. This module generates a new production sequence and adjusts the production process to minimize the impact of the failure. For example, it might reroute materials or adjust machine settings to address the malfunction and ensure continued productivity. By providing managers with real-time data and analysis. The Jidoka 4.0 framework allows them to quickly respond to issues and keep production running smoothly. The output from this TIPO models can be listed as reduction in defects/wastage, product quality improvement, decrease in machine downtime, shorter lead time, increased productivity, efficiency, cost savings, traceability and flexibility in the system.

4.3. *Heijunka* 4.0

Heijunka is a principle in lean manufacturing that aims to level production and balance demand with production capacity (Monden, 1983; Womack & Jones, 1997). This is achieved by breaking down the production schedule into smaller chunks and balancing the workload (Boutbagha & Laila, 2022). Heijunka eliminates uneven customer demand and stabilizes production, using tools such as Kanban cards and workload balancing techniques. The goal is to reduce overburden and idle time for workers and equipment. The traditional approach to Heijunka involves manual calculations for optimal outputs. By leveraging the core attributes of I4.0, such as

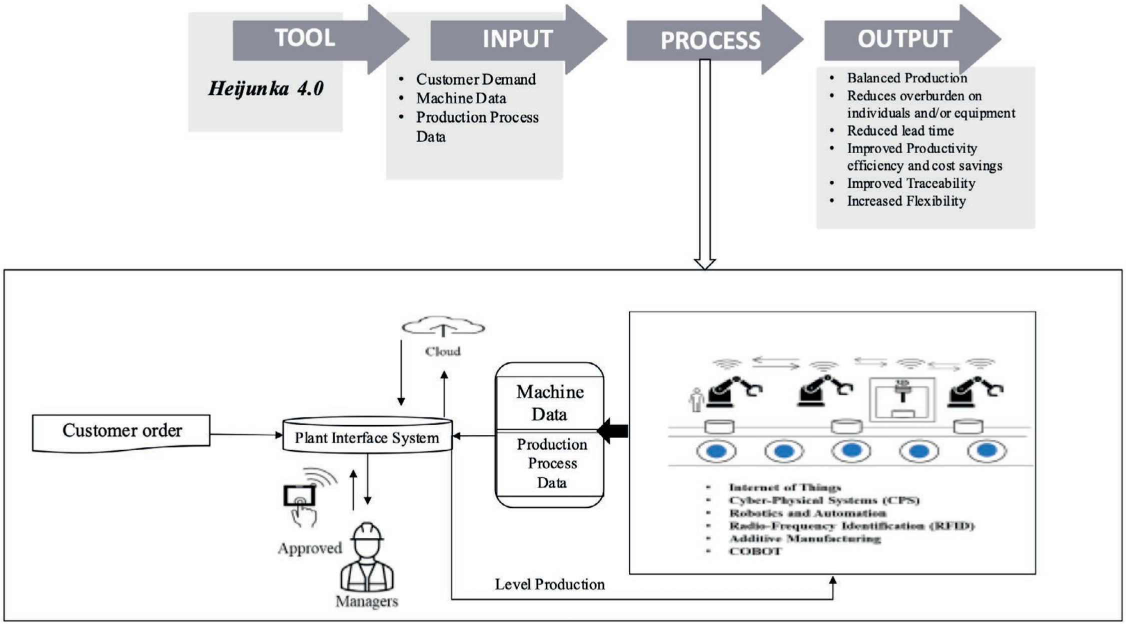

Figure 6. TIPO for *Heijunka* 4.0.

real-time data collection and analysis, automated monitoring, and horizontal and vertical integration, the Heijunka system can be advanced to a new level. This upgraded version of Heijunka 4.0 can take full advantage of I4.0 tools to accomplish all its essential characteristics and enhance its overall performance to a significant extent. According to (Kolberg et al., 2017, Mayr et al., 2018, Pereira et al., 2019 and Spenhoff et al., 2022) Heijunka is well-suited to be used alongside I4.0 technologies, including AI, IoT, CPS, big data, and cloud. The present TIPO framework also emphasizes the use of these Industry 4.0 tools in the process (Figure 6). Inputs for the implementation of Heijunka 4.0 include customer order data (Prinz et al., 2018, Satoglu et al., 2018) and real-time information from the Predictive Maintenance Framework module, such as machine data and production process data.

When customer orders are received, the PIS is notified and generates the best sequence for production. It also checks the cloud for any similar order patterns and updates the sequence accordingly. If the manager approves, the information will be passed on to the Plant Interface System's Adaptive Production Planning module, then it calculates the Takt time needed to meet customer demand and schedules production accordingly. The resulting production sequence and schedule is then sent to the shop floor, automated material handling devices and machines to level out production. The outputs from the TIPO approach are identified as balanced production, reduction in the overburden on operators and equipment, shorter lead time, productivity enhancement, cost savings, improved traceability, and flexibility.

5. Conclusion

Lean 4.0 combines the principles and tools of lean manufacturing and the technologies of Industry 4.0 to create a powerful and efficient system for modern manufacturing to stay ahead of the competition by maximizing customer value.

In this paper, a Lean 4.0 framework is proposed along with the novel TIPO methodology which provides a clear and comprehensive step to integrate the conventional lean tools, such as Just-in-Time, *Jidoka* and *Heijunka* with I4.0 technologies. Based on previous research works and successful implementation of Lean 4.0 case studies, the various I4.0 technologies such as IoT, CPS, cloud computing, data analytics, additive manufacturing, robotics, *etc.* are mapped with the type of inputs required for the conventional lean tools. The potential outputs after integrating these technologies are also identified for each of the three lean tools considered.

More research should focus on the generalization of the integration on the basis of inherent needs of the conventional lean tools and core characteristics of I4.0 technologies. Development of innovative tools and processes that can be used to effectively implement Lean 4.0 in different contexts. By leveraging the power of Lean 4.0, manufacturers can stay ahead of the competition and achieve greater levels of productivity and profitability.

References

Agostinho, V., & Baldo, C.R. (2020). Assessment of the impact of Industry 4.0 on the skills of Lean professionals. *Procedia CIRP*, *96*, 225–229. https://doi.org/10.1016/j.procir.2021.01.079

Bittencourt, V.L., Alves, A.C., & Leão, C.P. (2019). Lean Thinking contributions for Industry 4.0: A systematic literature review. *IFAC-PapersOnLine*, *52*(13), 904–909. https://doi.org/10.1016/j.ifacol.2019.11.310

Bittencourt, V.L., Alves, A.C., & Leão, C.P. (2021). Industry 4.0 triggered by Lean Thinking: insights from a systematic literature review. *International Journal of Production Research*, *59*(5), 1496–1510. https://doi.org/10.1080/00207543.2020.1832274

Boutbagha, M., Laila, A. (2022). Production Leveling or Heijunka: A Bibliometric Study. *Proceedings of 2022 IEEE 3rd International Conference on Electronics, Control, Optimization and Computer Science* (ICECOCS). Morocco. https://doi.org/10.1109/ICECOCS55148.2022.9982975

Buer, S.V., Semini, M., Strandhagen, J.O., & Sgarbossa, F. (2021). The complementary effect of lean manufacturing and digitalisation on operational performance. *International Journal of Production Research*, *59*(7), 1976–1992. https://doi.org/10.1080/00207543.2020.1790684

Buer, S.V., Strandhagen, J.O., & Chan, F.T.S. (2018). The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda. *International Journal of Production Research*, *56*(8), 2924–2940. https://doi.org/10.1080/00207543.2018.1442945

Calış Duman, M., & Akdemir, B. (2021). A study to determine the effects of industry 4.0 technology components on organizational performance. *Technological Forecasting and Social Change*, *167*. https://doi.org/10.1016/j.techfore.2021.120615

Carvalho, C.P., Gonçalves, L.W.N., & Silva, M.B. (2019). Value stream mapping as a lean manufacturing tool: A new account approach for cost saving in a textile company. *International Journal of Production Management and Engineering*, *6*(2), 1–12. https://doi.org/10.4995/ijpme.2019.8607

Chiarini, A., Belvedere, V., & Grando, A. (2020). Industry 4.0 strategies and technological developments. An exploratory research from Italian manufacturing companies. *Production Planning and Control*, *31*(16), 1385–1398. https://doi.org/10.1080/09537287.2019.1710304

Ciano, M.P., Dallasega, P., Orzes, G., & Rossi, T. (2021). One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study. *International Journal of Production Research*, *59*(5), 1386–1410. https://doi.org/10.1080/00207543.2020.1821119

Cifone, F.D., Hoberg, K., Holweg, M., & Staudacher, A.P. (2021). 'Lean 4.0': How can digital technologies support lean practices?. *International Journal of Production Economics*, *241*. https://doi.org/10.1016/j.ijpe.2021.108258

Dahmani, N., Benhida, K., Belhadi, A., Kamble, S., Elfezazi, S., Jauhar, S.K. (2021). Smart circular product design strategies towards eco-effective production systems: a lean eco-design industry 4.0 framework. *Journal of Cleaner Production*, *320*, 128847. https:// doi.org/10.1016/j.jclepro.2021.128847

Deuse, J., Dombrowski, U., Nöhring, F., Mazarov, J., & Dix, Y. (2020). Systematic Combination of Lean Management with Digitalisation to Improve Production Systems on the Example of Jidoka 4.0. *International Journal of Engineering Business Management, 12*(3),1-9. https://doi.org/10.1177/18479790221147864

Drew, J., McCallum, B., & Roggenhofer, S. (2004). *Journey to Lean: Making Operational Change Stick* (1st ed.). Palgrave Macmillan London.

El Faydy, N., El Abbadi, L. (2023). Interpretive structural modelling of critical success factor for lean product lifecycle management in industry 4.0. *International Journal of Production Management and Engineering*, *11*(1), 65–72. https://doi.org/10.4995/ijpme.2023.18840

Gil-Vilda, F., Yagüe-Fabra, J.A., & Sunyer, A. (2021). From lean production to lean 4.0: A systematic literature review with a historical perspective. *Applied Sciences*, *11*(21). https://doi.org/10.3390/app112110318

Gunasekaran, A., & Lyu, J. (1997). Implementation of just-in-time in a small company: A case study. *Production Planning and Control*, *8*(4), 406–412. https://doi.org/10.1080/095372897235217

Hofmann, E., & Rüsch, M. (2017). Industry 4.0 and the current status as well as future prospects on logistics. *Computers in Industry*,*89*,23–34. https://doi.org/10.1016/j.compind.2017.04.002

Hopp, W.J., & Spearman, M.S. (2021). The lenses of lean: Visioning the science and practice of efficiency. *Journal of Operations Management*, *67*(5), 610–626. https://doi.org/10.1002/joom.1115

Jastia, N.V.K., & Kodali, R. (2015). Lean production: Literature review and trends. *International Journal of Production Research*, *53*(3), 867–885. https://doi.org/10.1080/00207543.2014.937508

Jina, J., Bhattacharya, A.K., & Walton, A.D. (1997). "Applying lean principles for high product variety and low volumes: some issues and propositions. *Logistics Information Management*, *10*(1), 5–13. https://doi.org/10.1108/09576059710159655

Kagermann H. (2013). Recommendations for implementing the strategic initiative INDUSTRIE 4.0. April 2013 Securing the future of German manufacturing industry Final report of the Industrie 4.0 Working Group.

Kamble, S., Gunasekaran, A., & Dhone, N.C. (2020). Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies" *International Journal of Production Research*, *58*(5), 1319–1337. https://doi.org/10.1080/00207543.2019.1630772

Karim, A., & Arif-Uz-Zaman, K. (2013). A methodology for effective implementation of lean strategies and its performance evaluation in manufacturing organizations. *Business Process Management Journal*, *19*(1), 169–196. https://doi.org/10.1108/14637151311294912

Kipper, L.M., Furstenau, L.B., Hoppe, D., Frozza, R., & Iepsen, S. (2020). Scopus scientific mapping production in industry 4.0 (2011–2018): a bibliometric analysis. *International Journal of Production Research*, *58*(6), 1605–1627. https://doi.org/10.1080/00207543.2019.1671625

Kolberg, D., & Zühlke, D. (2015). Lean Automation enabled by Industry 4.0 Technologies. *IFAC-PapersOnLine, 28*(3), 1870–1875. https://doi.org/10.1016/j.ifacol.2015.06.359

Kolberg, D., Knobloch, J., & Zühlke, D. (2017). Towards a lean automation interface for workstations, *International Journal of Production Research*, *55*(10), 2845–2856. https://doi.org/10.1080/00207543.2016.1223384

Krafcik, J.F. (1988). Triumph Of The Lean Production System. *Sloan Management Review*, 30(1), 41–52.

Marodin, G., Chiappetta Jabbour, C.J., Godinho Filho, M., & Tortorella, G.L. (2022). Lean production, information and communication technologies and operational performance. *Total Quality Management and Business Excellence*, *32*(1), 183–200. https://doi.org/10.1080/14783363.2022.2035214

Mayr, A., Weigelt, M., Kühl, A., Grimm, S., Erll, A., Potzel, M., & Franke, J. (2018). Lean 4.0-A conceptual conjunction of lean management and Industry 4.0. *Procedia CIRP*, *72*, 622–628. https://doi.org/10.1016/j.procir.2018.03.292

Mittal, S., Khan, M.A., Romero, D., & Wuest, T. (2018). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). *Journal of Manufacturing Systems, 49*(2), 194–214. https://doi.org/10.1016/j.jmsy.2018.10.005

Monden, Y. (1983). Toyota Production System. *Norcross: Industrial Engineering and Management Press.*

Nai Yeen Gavin Lai, Kok Hoong Wong, Dunant Halim, Jiawa Lu, & Hooi Siang Kang. (2019). Industry 4.0 Enhanced Lean Manufacturing. *Proceedings of 8th International Conference on Industrial Technology and Management: ICITM 2019*, 206–211. https://doi.org/10.1109/ICITM.2019.8710669.

Najwa, E., Bertrand, R., Yassine, M., Fernandes, G., Abdeen, M., & Souad, S. (2021). Lean 4.0 tools and technologies to improve companies' maturity level: The COVID-19 context. *Procedia Computer Science*, *196*, 207–216. https://doi.org/10.1016/j.procs.2021.12.007

Ohno, T. (1988). Toyota production system: beyond large-scale production. *Productivity Press*.

Pagliosa, M., Tortorella, G., & Ferreira, J.C.E. (2021). Industry 4.0 and Lean Manufacturing: A systematic literature review and future research directions. *Journal of Manufacturing Technology Management*, *32*(3), 543–569. https://doi.org/10.1108/JMTM-12-2018-0446

Pereira, A., Carvalho, J.D., Anabela, A. and Pedro A. (2019). How Industry 4.0 Can Enhance Lean Practices. *FME Transactions*, *47*(4), 810–822. https://doi.org/10.5937/fmet1904810P

Pereira, A.C., & Romero, F. (2017). A review of the meanings and the implications of the Industry 4.0 concept. *Procedia Manufacturing, 13*, 1206–1214. https://doi.org/10.1016/j.promfg.2017.09.032

Peter, H., Tortorella, G.L., Antony, J., & Romero, D. (2022). Lean Industry 4.0:Past, present, Future. *Quality Management Journal*. *30* (1), 64-68. https://doi.org/10.1080/10686967.2022.2144786.

Powell, D., Romero, D., Gaiardelli, P., Cimini, C., & Cavalieri, S. (2018). Towards Digital Lean Cyber-Physical Production Systems: Industry 4.0 Technologies as Enablers of Leaner Production. *APMS - Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing*, 353–362. https://doi.org/10.1007/978-3-319-99707-0_44.

Prinz, C., Niklas, K. and Bernd, K. (2018). Lean Meets Industrie 4.0 – a Practical Approachto Interlink the Method World and Cyber-Physical World. *Procedia Manufacturing 23*, 21–26. https://doi.org/10.1016/j.promfg.2018.03.155

Romero, D., Gaiardelli, P., Powell, D., Wuest, T., & Thürer, M. (2018). Digital lean cyber-physical production systems: The emergence of digital lean manufacturing and the significance of digital waste. *IFIP Advances in Information and Communication Technology*, *535*, 11–20. https://doi.org/10.1007/978-3-319-99704-9_2

Romero, David, Gaiardelli, Paolo, Powell, Daryl, Wuest, Thorsten, Thürer, Matthias, (2019). Rethinking jidoka systems under automation & learning perspectives in thedigital lean manufacturing world. *IFAC-PapersOnLine, 52*(13), 899–903. https://doi.org/10.1016/j.ifacol.2019.11.309.

Rosin, F., Forget, P., Lamouri, S., & Pellerin, R. (2020). Impacts of Industry 4.0 technologies on Lean principles. *International Journal of Production Research*, *58*(6), 1644–1661. https://doi.org/10.1080/00207543.2019.1672902

Rossi, A.H.G.; Marcondes, G.B.; Pontes, J.; Leitão, P.; Treinta, F.T.; De Resende, L.M.M.; Mosconi, E.; Yoshino, R.T. (2022). Lean Tools in the Context of Industry 4.0: Literature Review Implementation and Trends. *Sustainability*, *14*, 12295. https://doi.org/10.3390/su141912295

Rossini, M., Costa, F., Tortorella, G.L., & Portioli-Staudacher, A. (2019). The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers. *International Journal of Advanced Manufacturing Technology*, *102*(9–12), 3963–3976. https://doi.org/10.1007/s00170-019-03441-7

Sanders, A., Elangeswaran, C., & Wulfsberg, J. (2016). Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing. *Journal of Industrial Engineering and Management, 9*(3): 811–833. https://doi.org/10.3926/jiem.1940

Santos, B.P.; Enrique, D.V.; Maciel, V.B.P.; Lima, T.M.; Charrua-Santos, F.; Walczak, R. (2021). The synergic relationship between industry 4.0 and lean management: Best practices from the literature. *Management and Production Engineering Review*, *12*, 94–107.

Saraswat, P., Agrawal, R., & Meena, M.L. (2021). An Analysis of Critical Success Factors Using Analytical Hierarchy Process for Implementation of Lean with Industry 4.0 in SMEs.. *In Recent Advances in Smart Manufacturing and Materials. Lecture Notes in Mechanical Engineering. Springer,* Singapore. 255–262. https://doi.org/10.1007/978-981-16-3033-0_24

Sartal, A., Llach, J., & León-Mateos, F. (2022). Do technologies really affect that much? exploring the potential of several industry 4.0 technologies in today's lean manufacturing shop floors. *Operational Research*, *22*(5), 6075–6106. https://doi.org/10.1007/s12351-022-00732-y

Satoglu, S., Ustundag, A., Cevikcan, E., Durmusoglu, M. (2018). Lean transformation integrated with Industry 4.0 implementation methodology. *Industrial Engineering in the Industry 4.0 Era. Springer, Cham, pp. 97–107*.

Schumacher, S., Bildstein, A., & Bauernhansl, T. (2020). The impact of the digital transformation on lean production systems. *Procedia CIRP*, *93*, 783–788. https://doi.org/10.1016/j.procir.2020.03.066

Sihle, M., & Sambil M. (2018). The Impact of Just-in-Time (JIT) in Inventory Management System and the Supplier Overall Performance of South African's Bed Mattress Manufacturing Companies. *International Conference on Industrial Engineering and Operations ManagementAt: Pretoria / Johannesburg, South Africa*.

Spenhoff, P., Johan C., & Wortmann & Marco Semini (2022). EPEC 4.0: an Industry 4.0-supported lean production control concept for the semi-process industry. *Production Planning & Control*, *33*(14), 1337–1354. https://doi.org/10.1080/09537287.2020.1864496

Taghavi, V., & Beauregard, Y. (2020). The Relationship between Lean and Industry 4.0: Literature Review. *5th North American Conference on Industrial Engineering and Operations Management in Detroit, Michigan*, USA during August 10-14, 2020.

Tampubolon, S., & Purba, H.H. (2021). Lean Six Sigma Implementation, A Systematic Literature Review. *International Journal of Production Management and Engineering*, *9*(2), 125-139. https://doi.org/10.4995/ijpme.2021.14561

Tortorella, G.L., & Fettermann, D. (2018). Implementation of industry 4.0 and lean production in brazilian manufacturing companies. *International Journal of Production Research*, *56*(8),2975–2987. https://doi.org/10.1080/00207543.2017.1391420

Tortorella, G., Sawhney, R., Jurburg, D., de Paula, I.C., Tlapa, D., & Thurer, M. (2021). Towards the proposition of a Lean Automation framework: Integrating Industry 4.0 into Lean Production. *Journal of Manufacturing Technology Management*,*32*(3), 593–620. https://doi.org/10.1108/JMTM-01-2019-0032

Valamede, L.S., & Akkari, A.C.S. (2020). Lean 4.0: A new holistic approach for the integration of lean manufacturing tools and digital technologies. *International Journal of Mathematical, Engineering and Management Sciences*, *5*(5), 854–868. https://doi.org/10.33889/IJMEMS.2020.5.5.066

Varela, L., Araújo, A., Ávila, P., Castro, H., & Putnik, G. (2019). Evaluation of the relation between lean manufacturing, industry 4.0, and sustainability. *Sustainability*, *11*(5). https://doi.org/10.3390/su11051439

Wagner, T., Herrmann, C., & Sebastian, T. (2017). Industry 4.0 impacts oon lean production systems. *Procedia CIRP*, *63*, 125–131. https://doi.org/10.1016/j.procir.2017.02.041

Wan, J., Cai, H., & Zhou, K. (2015). Industrie 4.0: Enabling technologies. *Proceedings of 2015 International Conference on Intelligent Computing and Internet of Things*, 135–140. https://doi.org/10.1109/ICAIOT.2015.7111555

Womack, J.P., & Jones, D.T. (1997). Lean Thinking—Banish Waste and Create Wealth in your Corporation. *Journal of the Operational Research Society*, *48*(11), 1148–1148. https://doi.org/10.1038/sj.jors.2600967

Womack, J.P., Jones, D.T., & Roos, D. (2007). The Machine That Changed the World. *Free Press*.

Xu, Y., & Chen, M. (2017). An Internet of Things based framework to enhance Just-In-Time manufacturing. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 232*(13), 2353–2363. https://doi.org/10.1177/0954405417731467

Yadav, N., Shankar, R., & Singh, S.P. (2020). Impact of Industry4.0/ICTs, Lean Six Sigma and quality management systems on organisational performance. *TQM Journal*, *32*(4), 815–835. https://doi.org/10.1108/TQM-10-2019-0251

Zuehlke, D. (2010). SmartFactory-Towards a factory-of-things. *Annual Reviews in Control*, *34*(1), 129–138. https://doi.org/10.1016/j.arcontrol.2010.02.008