LEAN 4.0: AN INTEGRATED ANALYSIS OF LEAN MANUFACTURING AND ADVANCED MANUFACTURING

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The increasing competitiveness of the market forces companies to adapt to new production strategies. In this context, Lean Manufacturing is a method that enables waste reduction and has the ability to optimize the entire production process, thereby reducing costs. Another concept is the technologies derived from Industry 4.0, which have been widely applied in various types of production. Seeking integration between the two systems, with the purpose of further elevating productivity levels. The present study aims to present the benefits of integrating Lean Manufacturing with Industry 4.0 technologies. To achieve this, a systematic literature review was conducted using the SSF method. The databases of Scopus, Web of Science, Emerald, Ebesco, Science Direct, and Compendex were consulted for this purpose. The results allowed for the integration of various Lean Manufacturing tools, such as Just in Time, Kanban, Poka-Yoke, Value Stream Mapping, Kaizen, Total Productive Maintenance, SMED, Heijunka, and Visual Management, along with key Industry 4.0 technologies: Additive Manufacturing, Automated Guided Vehicles, Virtual Reality, Auto-ID, Cloud Computing, and Big Data Analytics. The findings indicated that Lean 4.0 provides low-complexity automation solutions that fit within the Lean Manufacturing environment, aiming to achieve greater adaptability and reduced information flows to meet market demands, thereby strengthening the strategic and operational perspectives of manufacturing companies with competitive prospects.

Keywords: Lean Management, Industry 4.0, Lean 4.0.
1. Introduction

Companies around the world face challenges due to economic crises, leading them to search for new business opportunities and strategies to generate profits and gain market share. Additionally, the environment in which organizations operate is highly dynamic, requiring them to constantly adapt to new market practices and needs in order to sustain their processes (CHANG; CHENG, 2019).

In business organizations, operational processes must increasingly focus on quality, productivity, and low costs in an attempt to ensure competitiveness. Alongside this fact, the growing demands of consumers, especially in the digital era, require organizations to provide quick and effective responses to meet their expectations (VLACHOS et al., 2021; BONAMIGO et al., 2023).

In this context, Industry 4.0, also known as the Fourth Industrial Revolution, aims to integrate various new technologies into production, making it autonomous and more efficient. Additionally, the key priorities of process management are to accelerate production, improve quality, and reduce costs. To achieve these goals, 4.0 technologies are emerging as advanced strategies to enhance process efficiency, reduce operational costs, and maintain global quality standards (RAMADAN; SALAH, 2019). However, it is worth noting that Industry 4.0 has often been presented as the solution that, by itself, will ensure the success of the productive sector in the digital era, leaving a gap in the efforts to improve the organizational processes used until then, such as those associated with Lean Manufacturing (LM) (SUNDAR; BALAJI; KUMAR, 2014; WAGNER et al., 2017).

The LM is considered a management philosophy developed in the 1990s and has since been implemented and adapted in different sectors of industries, resulting in increased organizational efficiency (TAYAKSI et al., 2020). Due to fixed manufacturing sequences and slow responsiveness, combined with the increasing pressures of customer expectations regarding product variability, the LM may not meet the new demands imposed by digital technology applied in the industrial field. As a result, their suitability for future value chains may be limited (MAYR et al., 2018). In this perspective, the question arises of whether the principles advocated by the LM can be applied in harmony with advanced manufacturing.

In this context, the LM faces difficulties in creating flexible industrial processes when confronted with product mix, rapid demand variations, or low-volume production. These situations are linked to the personalization of production according to the needs of each consumer, considering one of the points advocated in the industry-customer relationship in the
digital era. The new manufacturing context may require the introduction of new machines and a new balance of production flow, as well as the need for inventory to stabilize an interrupted flow (SUNDAR; BALAJI; KUMAR, 2014).

Since these two approaches are fundamentally different, with Industry 4.0 advancing production through autonomous and flexible systems based on a technology-driven approach, while the LM adheres to traditional process-focused efficiency, this study proposes a holistic integration of LM tools and Industry 4.0 technologies, considering the perspectives of the industrial environment in the digital era.

The design of a holistic integration provides companies with a way to identify the importance and relationships between LM and Industry 4.0, highlighting the convergences and organizational benefits of the interaction between the Just in Time (JIT), Kanban, Poka-Yoke, Value Stream Mapping (VSM), Kaizen e Total Productive Maintenance (TPM), Single Minute Exchange of Die (SMED), Heijunka and Visual Management with digital technologies.

This proposed integration entails aligning a lean production system with the technological trends arising from Industry 4.0, demonstrating that organizational goals can be achieved jointly through these two approaches.

2. Theoretical framework
2.1. Lean Manufacturing

The concept of Lean Manufacturing originated at Toyota Motor Corporation, a Japanese automotive manufacturer. To ensure the company's development and survival, Taiichi Ohno, the chief engineer at Toyota, introduced the Toyota Production System (TPS) in 1988, a business strategy focused on working with the limited resources available in Japan. Unlike the American manufacturing model, which operates with many different machines and has a large amount of work-in-progress inventory, LM is focused on eliminating any type of waste, aiming to provide the exact number of products required by customers, on time, and with high quality (TAYAKSI et al., 2020).

For the implementation of LM in the organizational context, the use of LM tools, as well as the collective action and motivation of all employees of the company, are necessary. In this study, the LM tools, JIT, Kanban, Poka-Yoke, VSM, Kaizen, and TPM, will be detailed as described in accordance with Table 1.
### Table 1: Lean Manufacturing tools

<table>
<thead>
<tr>
<th>LEAN TOOL</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>Just in Time</td>
<td>Being one of the pillars of the TPS, JIT aims to produce only what is essential, just in time, on the required date and in the necessary quantity, processing materials only if the next operation demands it (MAYR et al., 2018; SANDERS et al., 2016).</td>
</tr>
<tr>
<td>Kanban</td>
<td>This tool ensures that processes and materials flow through cards that represent a sequence of orders and resources on the shop floor while recording key information of the efficient production flow (KOLBERG; ZÜHLKE, 2015).</td>
</tr>
<tr>
<td>Poka-Yoke</td>
<td>Devices that prevent and detect losses of any origin, being able to automatically stop the production line when necessary (SOCCONINI, 2019).</td>
</tr>
<tr>
<td>VSM</td>
<td>Value stream consists of a visual representation of all the actions currently required in the production line, encompassing both value-added and non-value-added activities. (WAGNER et al., 2017).</td>
</tr>
<tr>
<td>Kaizen</td>
<td>The Kaizen philosophy promotes improvements as a result of continuous effort, and Kaizen events are often associated with techniques for waste reduction, lead time reduction, and workstation balancing. (KNECHTGES; DECKER, 2014).</td>
</tr>
<tr>
<td>TPM</td>
<td>This concept aims to improve productivity and quality, as well as motivate employees and contribute to job satisfaction. It has an innovative maintenance approach that optimizes equipment effectiveness, eliminates failures, and promotes operator autonomous maintenance through daily activities involving the workforce. (MAYR et al., 2018).</td>
</tr>
</tbody>
</table>

Source: Knechtges and Decker, (2014); Kolberg; Zühlke (2015); Sanders et Al., (2016); Wagner et al., (2017); Mayr et al., (2018); Socconini (2019)

### 2.2. Industry 4.0

#### 2.2.1 The origin of Industry 4.0

The technologies of Industry 4.0 support the idea of developing smart factories, which have already begun to emerge, adopting a completely new approach to production and manufacturing processes. Naturally, products also tend to become smart to meet functional and usage requirements (OZTEMEML; GURSEV, 2020).

In this research, the most mentioned 4.0 technologies in the literature were studied, including Big Data Analytics, Automated Guided Vehicles (AGVs), Virtual Simulation (VS), Cybersecurity, Cloud Computing, Additive Manufacturing (AM), and Augmented Reality (AR) (KOLBERG; ZÜHLKE, 2015; MAYR et al., 2018; SANDERS et al., 2016).
Big Data Analytics refers to a large amount of diverse data that is processed into actionable insights with high capture speed and increased visibility, improving the efficiency and effectiveness of organizations in decision-making processes (VAIDYA et al., 2018).

In the context of Industry 4.0, Automated Guided Vehicles (AGVs) are defined as autonomous, flexible, cooperative robots with multiple capabilities. They are capable of operating in the real world without any external control for extended periods of time (MAYR et al., 2018).

VS is a computer-based modeling approach that provides real-time data to mirror the physical world in a virtual model that includes machines, products, and humans. (BAHRIN et al., 2016). Cybersecurity technology aims to protect programs, computers, networks, and data, ensuring the security and reliability of communications and the management of resources and information (TISSIR; FEZAZI; CHERRAFI, 2020).

The Cloud provides unified communication between the technology level (smart products and cyber-physical systems) and the higher-level hierarchy of an organization (VAIDYA et al., 2018). AM refers to a set of computer-automated processes that build products layer by layer, based on three-dimensional models designed in Computer-Aided Design (CAD) software (BAHRIN et al., 2016).

Finally, AR technology works with virtual objects overlaid onto the existing environment. In AR displays, virtual and real-time information, previously captured with a camera, is digitally merged and displayed on a screen, creating an interface between employees and digital products or equipment (MAYR et al., 2018).

2.3. Lean 4.0

Mrugalska and Wyrwicka (2018) support the claim that Industry 4.0 and LM can coexist and support each other. Furthermore, committing to Industry 4.0 can help overcome existing barriers to the implementation of LM (SANDERS; ELANGESWARAN; WULFSBERG, 2016; BONAMIGO et al., 2023).

To combine LM and Industry 4.0, existing literature has coined terms such as Lean 4.0, Lean Automation, Smart Lean Manufacturing, and Lean Industry 4.0. As elaborated, most authors have approved the overall compatibility of LM and Industry 4.0. This perspective can be attributed to similarities in goals such as reducing complexity, core pillars, and LM principles (Figure 1).

Thus, both paradigms are managed in a decentralized manner. Kanban in LM, as well as self-organizing systems in Industry 4.0, distribute responsibility to subsystems (HUBER, 2016;
KASPAR; SCHNEIDER, 2015). Additionally, LM and Industry 4.0 focus on a fundamental role of employees (HUBER, 2016).

**Figure 1: Goals of Lean Manufacturing**

![Diagram of Goals of Lean Manufacturing](image)

**Source:** Adapted from Huber (2016)

### 2.3.1 Lean Management as an enabler for Industry 4.0

Several authors name Lean Management as a prerequisite for the successful introduction of Industry 4.0 solutions (HUBER, 2016; KÜNZEL, 2016; KETTELER; KÖNIG, 2017). This is supported by Bill Gates' hypothesis that automating inefficient processes will only increase their inefficiency. In this context, the insights can be summarized as follows:

- Standardized, transparent, and reproducible processes are of fundamental importance for the introduction of Industry 4.0 (HUBER, 2016; STAUFEN, 2016; KOETHER; MEIER, 2017).
- Decision-makers require competence in Lean Manufacturing to consider customer value and avoid waste (KÜNZEL, 2016).
- By reducing product and process complexity, Lean Manufacturing enables the efficient and cost-effective use of Industry 4.0 tools (HUBER, 2016; BICK, 2014).

Thus, lean processes are considered the foundation for the efficient and cost-effective implementation of Industry 4.0. However, Nyhuis et al. (2017) points out that the implementation of LM and Industry 4.0 can influence each other iteratively. Therefore, the progression is not necessarily sequential.

Wagner et al. (2017) as well as Pokorni et al. (2017) describe that lean processes can be stabilized and refined by applying Industry 4.0. While Rüttimann and Stöckli (2016) emphasize...
the ability to improve the flexibility of modern lean production systems, Kolberg and Zühlke (2015) state that Industry 4.0 can enhance LM.

3. Methodological procedures

To substantiate this study, a literature review was conducted, which was exploratory, descriptive, and analytical in nature. For the research design, the Systematic Search Flow (SSF) method, developed by Ferenhof and Fernandes (2016, p. 556), was chosen. This method ensures repeatability and helps avoid researcher bias. The flow of this method is presented in Figure 2.

**Figura 2:** Flow of the SSF method

<table>
<thead>
<tr>
<th>PHASE 1: Research protocol</th>
<th>PHASE 2: Analysis</th>
<th>PHASE 3: Synthesis</th>
<th>PHASE 4: Writing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search strategy</td>
<td>Database search</td>
<td>Document management</td>
<td>Composition of the document portfolio</td>
</tr>
<tr>
<td>Database search</td>
<td>Document management</td>
<td>Standardization and selection of documents</td>
<td>Data consolidation</td>
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**Source:** Ferenhof; Fernandes (2016)

The SSF method consists of 4 main phases, namely: Research Protocol; Analysis; Synthesis; Writing, with each phase having a number of activities to be carried out, totaling 8 activities. Thus, the first phase is the research protocol, and regarding this activity, the use of the logical operator "AND" was defined for article retrieval, as well as the use of "quotation marks" to assist in identifying exact terms in the searches.

In the second activity of the first phase, it was determined to search the databases CAPES Journals, Scopus, Web of Science, Emerald, Ebesco, Science Direct, and Compendex. The searched studies include articles published between 2010 and 2022, using the following descriptors and Boolean operators: "Lean Manufacturing" AND "Industry 4.0" and "Technologies 4.0" AND "Lean 4.0". The following inclusion criteria were established: freely available and fully accessible studies; studies related to the theme; studies written in Portuguese,
English, and Spanish; review articles and original articles published in journals and conferences. The following were excluded: dissertations, theses, and studies without access to the PDF. A total of 357 articles were found.

In the third activity, duplicates and articles without full access or unavailable attachments were excluded. Additionally, dissertations and theses were also excluded. The fourth activity involved the selection of the articles retrieved from the search, which was done by applying the inclusion criteria through reading the abstracts of each study.

Finally, the fifth and last activity of the first phase was the final portfolio of articles. Therefore, data analysis was conducted through the complete reading of the 44 articles. From these selected articles, a synthesis of the main data was made through digital reports, from which relevant data for achieving the objective of this study were analyzed and extracted. This analysis was based on three categories: Technology 4.0, Lean Tool, and Integration of Lean and Technology 4.0.

The overall content analysis was conducted based on the three-phase methodology of Bardin (2011). In the first phase, called pre-analysis, a primary reading of the articles was performed, focusing on their abstracts, to establish the initial path of the study. The second phase involved the exploration of the material, including coding, classification, and categorization of the study's information. Finally, in the third phase, the treatment of results, inference and interpretation of the studies were carried out, integrating the study's data with the author's analysis, thus creating the present study.

4. Results and discussion

4.1 Just-in-time 4.0

The 4.0 technologies can contribute to achieving the objectives of this approach more efficiently, including the application of Cloud, Big Data Analytics, AGVs, AM, and AR. The use of these technologies provides four attributes resulting from the relationship between LM and Industry 4.0, mainly the flexibility of the supply chain and integration among processes, devices, and stakeholders. When these tools are put into practice in the production environment, they provide a continuous, transparent, automated, and customer-oriented flow of products and information.

A large amount of data is received in real time from various devices, sensors, computers, and AGVs in the supply chain. The Cloud is capable of sharing this data with Big Data Analytics, which interprets and transforms the data into meaningful information for stakeholders to
enhance management. The Cloud is also connected to all shop floor employees, sending interpreted data and information to their visual field through AR devices, enabling them to quickly solve problems and make better decisions. Furthermore, the precise personal request from the customer can be prepared by AM technologies, using less raw material and process time, as this innovation produces only the necessary quantity with flexibility by adding layers of material (SANDERS et al., 2016).

4.2 Kanban 4.0
In the context of Industry 4.0, new solutions are available to be incorporated into Kanban systems, such as Big Data Analytics, AGVs, and VS. The integration of these technologies into the system enables the integration of processes, devices, and stakeholders, as well as the minimization and/or elimination of waste. By applying these technologies, intermediate material stocks can be reduced to a minimum, as Big Data Analytics contributes to real-time monitoring of the production flow, which enables automated logistics with intelligent inventory control (SANDERS et al., 2016).

4.3 Poka-Yoke 4.0
AGVs, Cloud, Cybersecurity, and AR 4.0 technologies have relationships with this Lean tool. Poka-Yoke 4.0 presents good attributes of the association between LM and Industry 4.0, with four points of contribution, highlighting the benefit of waste minimization and/or elimination. As the logic of Poka-Yoke is to prevent errors in production systems, AGVs are capable of quickly adapting to potential flow failures and informing the Cloud about the problems encountered for further analysis and resolution. RA, in turn, works together with employees, assisting them in their manual tasks to avoid possible mistakes, and presents instructions and virtual elements on their displays that facilitate understanding and execution of activities. (MAYR et al., 2018).

4.4 Value Stream Mapping 4.0
Smart factories will provide a fully integrated manufacturing environment where data can be transmitted in real time. Similar to Poka-Yoke 4.0, the minimization and/or elimination of waste is the benefit with the highest number of advantages. With Big Data Analytics and the Cloud, VSM will continuously receive new data and information from the entire supply chain, simplifying flow management and obstacle identification. This intelligent management process
is also optimized by VS techniques, allowing multiple mapping possibilities to be studied and interpreted by managers before being implemented, which contributes to decision-making. Through sensors, actuators, and human-computer interaction devices located in robots, products, and intelligent machines, performance data of equipment and object location will be collected automatically, allowing for constant updating of the VSM 4.0 (BAUERNHANSL; TEN HOMPEL; VOGEL-HEUSER, 2014).

### 4.5 Kaizen 4.0
To facilitate the performance of Kaizen, Industry 4.0 technologies act to contribute to continuous improvement, such as Big Data and Analytics, Cloud, VS, and AR. Data from production processes and intelligent devices, as well as stakeholders, are collected and shared in a cloud computing environment with speed and variability. These data are then analyzed by Big Data Analytics, contributing to achieving results and solutions that provide continuous flow and, consequently, align with the Kaizen philosophy. The combination of VS with AR strengthens the human-machine relationship by empowering employees with new knowledge about production processes. As a result, employees become more critical and capable of identifying potential problems to be addressed on the production line (AURICH et al., 2009; WAGNER et al., 2017).

### 4.6 Total Productive Maintenance 4.0
Big Data Analytics, AGVs, Cloud, VS, AR, and AM are Industry 4.0 technologies that contribute to the principles of Lean Manufacturing. Working together, these technologies, for instance, help predict failures in new equipment, quickly detect errors, and send instructions to maintenance teams. Since the Cloud shares real-time data about process and device status, machines are frequently monitored. Additionally, the Cloud sends data to Big Data Analytics to analyze and manage the maintenance team’s activities based on current and future needs of the production line. The combination of VR and AR instructs these employees to perform maintenance tasks efficiently and at the right frequency. (MAYR et al., 2018; SANDERS et al., 2016).

### 4.7 SMED 4.0
In addition to AR, AM is expected to have the greatest impact on setup time. Since AM processes are not product-specific, diverse workpieces can be produced with minimal setup time. Time for tool and workpiece selection, retrieval, and adjustment is eliminated. However,
minor adaptations, temperature adjustments, and cleaning operations may still occur. Thus, Feldmann and Gorji (2017) argue that SMED principles can also be applied to AM. However, since setup times are already technologically minimized, the expected impact is likely to be small.

4.8 Heijunka 4.0

Some Industry 4.0 technologies contribute to improving Heijunka. Data analytics, for example, enhances forecast accuracy. Planning is stabilized by utilizing historical data in combination with a better understanding of customer needs through in-depth market analysis (KÜNZEL, 2016; BAUERNHANSL et al., 2014).

In addition, new software tools using advanced analytics can be utilized to support the planning process itself. For instance, the AnaPro software automatically levels the production schedule based on product specification, process technology structure, workplace, and sales (ŻYWICKI; REWERS; BOŻEK, 2017).

Applying the benefits of Heijunka 4.0 with reduced effort to level the production schedule, planning is automated and short-term adjustments can be seamlessly integrated.

4.9 Visual Management 4.0

The objective of Visual Management is to increase transparency. Thus, deviations can be recognized at an early stage to implement countermeasures accordingly. This is achieved by transferring goals, standards, and specifications into a visual representation. The importance of Visual Management is increasing as the amount of available data grows. The methods for implementing Visual Management are 5S, zoning, and andon (GORECKI; PAUTSCH, 2014).

Auto-ID and AR can help facilitate 5S more efficiently. RFID (Radio Frequency Identification) ensures the identification and location of objects, reducing search time (FESCIOGLU-UNVER et al., 2015).

Zone planning allows for the visual marking of destinations, including pathways, manufacturing cells, and departments. The use of colors throughout the company enhances the value of information (GORECKI; PAUTSCH, 2014). Zone planning does have several drawbacks. Firstly, signs and tapes must be physically adjusted. Secondly, this concept is not suitable for flexible navigation. Human-computer interaction (HCI) devices and AR help overcome this lack of flexibility.
Andon boards display actual and target values to reveal deviations (GORECKI; PAUTSCH, 2014). Unlike traditional andon lights, HCI devices such as tablets, smartphones, monitors, and smartwatches allow for targeted notifications to users. Thus, notifications are displayed in real-time regardless of the distance between the operator and the machine. Smartwatches enable the assessment of the need for action with a glance at the operator's wrist (KOLBERG; ZÜHLKE, 2015; MRUGALSKA; WYRWICKA, 2017).

5. Considerações finais
Although LM and Industry 4.0 technologies are two different approaches, the goal of continuously adding value to production systems is equivalent in both, resulting in the concept of Lean 4.0 integration.

With the aim of eliminating waste in production processes, LM streamlines the production flow by facilitating the digitization of manufacturing steps and emphasizing visual and transparent control, which aids in identifying faults. These principles of LM significantly contribute to the development of Industry 4.0, as 4.0 technologies will be supported by LM practices to maximize production performance. Smart factories, in turn, promote the digitization of the value chain and provide real-time data on inventory levels, equipment status, and product location.

Therefore, Industry 4.0 technologies enhance the maturity of LM as accurate, up-to-date, and shared information is crucial for the success of JIT. With a focus on customer-driven production, Kanban devices are empowered by emerging tools that encompass the entire horizontal and vertical supply chain, rather than just internal production and logistics processes. Smart Poka-Yoke devices, on the other hand, work with real-time data from the production flow, being more effective in waste reduction and preventing problems from spreading to the next workstations. The interconnection between machines, processes, and employees provided by Industry 4.0 technologies makes the VSM tool capable of monitoring value streams in real-time for quick resolution of potential waste, including lead time and machine setup costs. The benefits of Industry 4.0 in terms of module integration, data sharing and analysis, human-machine collaboration, and employee training support the Kaizen philosophy of continuous improvement, as well as planning and maintenance activities.

Indeed, the success of introducing Industry 4.0 technologies depends on various factors, including usability, selective information provision, user acceptance, consideration of ethical,
legal, and social impacts, and profitability. Therefore, the use of Industry 4.0 technologies should be carefully considered and evaluated in relation to process improvements.

REFERENCES


KAGERMANN, H. Use as oportunidades da Indústria 4.0. IN BAUERN-HANSL, T., M. TEN HOMPEL E B.


RÜTTIMANN, B. G.; STÖCKLI, M. T. Lean and Industry 4.0—twins, partners, or contenders? A due clarification regarding the supposed clash of two production systems. Journal of Service Science and Management, v. 9, n. 6, p. 485-500, 2016.


