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Development Trends of Production Systems through the Integration of Lean Management and Industry 4.0

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Abstract: The integration of efficient production and management systems with the new Industry 4.0 concept represents a challenge for any company wishing to adapt its processes in order to increase performance, both at the operational and the organizational levels, through digitization and connectivity. This research proposes an analysis of Lean tools and Industry 4.0 technologies for compatibility in order to provide a framework model for development and integration in industrial applications. Through a systematic review of the literature, this paper contributes to the development of the current vision regarding the implementation and integration of the two "paradigms" of production. An analysis of the current key production strategies was performed through a new conceptual approach from the perspective of correlating the Lean management system, a system that has been stable in recent decades, with the innovative technologies of Industry 4.0. The applicative character of the research consisted of the optimization by simulation of a flexible production system in which the two concepts were integrated. The results showed that the implementation of Lean in the field of flexible manufacturing, correlated with the integration of Industry 4.0 techniques, such as digital twin and simulation, led to improved production processes by fast and flexible reconfiguration, with the two concepts being interdependent.

Keywords: Lean management; Industry 4.0; flexible manufacturing; simulation

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1. Introduction

The changes that have occurred over time in society have left their mark on industrial development. Currently, as a result of the accelerated development of disruptive technologies, over the past few years, industrial companies are seeking solutions to adapt current manufacturing, management, and business systems to the increasing customer demand, aimed at diversified and mass customized products and services [1].

With the development of advanced manufacturing systems, through the implementation of automation, there was the question of finding efficient management methods that could contribute to increased productivity while also increasing quality. Thus, Lean thinking appeared, developed for the first time through the Toyota Production Systems (TPS) concept by Taiichi Ohno (1988) [2]. This substantially changed the ways of creating and managing manufacturing systems and the entire logistics chain within companies. In order to meet the demands for increased manufacturing efficiency and performance, the TPS model underwent continuous transformation and improvement. The purpose of implementing this original manufacturing philosophy, often called "Lean" or "just-in-time" [3], consists of increasing the efficiency of the manufacturing system by eliminating waste, ensuring a continuous manufacturing flow, continuous improvement and increasing quality while shortening the product life cycle required by customers.

At the same time, the TPS system studied, adapted and implemented globally in industry also represented a new work philosophy. Thus, people were given attention and respect with a focus on the complete use of the employees' skills and abilities while also empowering them with responsibilities. Lean manufacturing was defined by Womack in the 1990s as a "set of methods and tools to identify and eliminate inefficiency and waste at company and manufacturing level without the need for additional resources" [4]. With the evolution of technologies, the Lean concept gained new dimensions by moving from the application of hard tools to developing other soft tools called Lean techniques, as highlighted in articles [5,6]. Through the implementation of Lean management, there was a giant leap in increased performance in manufacturing and increased product and service quality by applying specific management tools, complimented by the implementation of new employee training and empowerment methods. All these elements aimed to increase the added value for customers. Nowadays, in a context of extreme uncertainty, Lean thinking can still provide a means to assess progress in manufacturing and in society.

The current industrial tendency is to implement Industry 4.0 (I4.0), considered "the new fundamental paradigm shift in industrial production" [7] that brings profound transformations in companies via intelligent and autonomous manufacturing. The transition to Industry 4.0 involves paradigm shifts, both in technology and in business models and the socioeconomic environment, with digitalization and connectivity being key elements. A first reference paper for the beginning of Industry 4.0 [8] considered that digital transformation could be achieved through the development and implementation of cyber–physical systems (CPS). The research carried out by Rüßmann, M., (2015) on Industry 4.0 had, as a starting point, "the nine pillars of technological advancement: big data and analytics, autonomous robots, simulation, horizontal and vertical system integration, the industrial internet of things, cybersecurity, the cloud, additive manufacturing and augmented reality" [9]. Many companies [10–13] that have taken the first step in implementation consider the development of digitalized industry as opportune, indicating that the future of current manufacturing is developing towards Industry 4.0 and "improves the flexibility, speed, productivity, and quality of the production process" [9]. The authors of Reference [14] consider that "companies that remain out of this revolution could disappear, as they would remain technologically obsolete with respect to their competitors".

The new production strategy for global competition must integrate, as a vital component, flexible manufacturing, being able to respond technically and economically efficiently to variable conditions and rapid and continuous changes in manufacturing, which often cannot be anticipated [15]. Within this framework, the new advanced manufacturing systems will have to constantly adapt their hardware and software components to the industrial and informational environment.

On the one hand, the current manufacturing systems must meet certain manufacturing requirements in the Industry 4.0 environment such as system integration from the perspective of manufacturing leadership; interconnecting material and informational resources; automation and digitalization; flexibility and adaptability to market demands; last but not least, integration of new management concepts. On the other hand, over the past decades, the Lean management system has proven to comprise the most efficient methods and techniques of manufacturing organizations, with wide and successful applicability [16], especially in companies producing goods and services and in the processing and automotive industries. Current studies and research [17–19] assess "synergy", the connection between the two large concepts (i.e., Industry 4.0 and Lean management), and the possibility of correlating the demands imposed on modern manufacturing and integrating new management models. Winkler et al. (2022) [20] holistically approached the development of production organizations from the perspective of integrating organizational management into Industry 4.0, making contributions through the integrated conceptual framework and simulation model, with applicability in increasing the performance of production systems.

The research undertaken by the authors focused on developing the current production systems in Industry 4.0. The research study performed an analysis of Lean tools and Industry 4.0 technologies to identify possibilities for correlating principles into an integration framework model, useful and applicable in streamlining advanced production systems.

The present paper has the following structure: Section 1 (Introduction) provides a description of the context of the occurrence of the two concepts: Lean Management and Industry 4.0. Section 2 includes a summary of some current state-of-the-art best practices for implementing Lean and Industry 4.0 as well as the current view on the possibility of interconnecting them in an industrial environment dominated by digitalization. In Section 3, based on the analysis of the key elements of the two current production strategies, through a conceptual approach a Lean management—Industry 4.0 integration framework is presented, highlighting the favorable effects on production in the industrial environment. Section 4 represents the applicative character of the paper through a case study carrying out the implementation of Lean in the field of flexible manufacturing and improving the process by integrating the techniques of Industry 4.0, digital twin, and simulation. Section 5 is intended to validate the results and discussions. Section 6 presents the conclusions and future research avenues.

2. Materials and Methods

2.1. Methodology

The development of research on the current analysis of the two advanced manufacturing concepts (Lean and Industry 4.0) had its starting point in the need for digital transformation of a flexible manufacturing factory. Adapting existing factories by introducing Industry 4.0 technologies and continuously improving through Lean manufacturing is a challenge for many managers in terms of strategic approach.

With its methodological approach, the paper was directed towards the elaboration of Lean—Industry 4.0 integration models with applicability in the manufacture and management of modern production units. With the purpose of finding new opportunities to elaborate and implement an integration model, the following research goals were formulated via a systemic approach:

- A literature study on the development and implementation of Lean tools and Industry 4.0 technologies and a synthesis of the most relevant papers in recent years. Through a careful analysis of the literature and practices in the field, we identified the goals, key elements of the two practices and the challenges and difficulties companies face when implementing them in the manufacturing industry;
- Development of a synergistic integration model of the two systems, Lean and Industry 4.0, in order to offer an adequate framework for improving production. This can be achieved only through a proper knowledge of the appropriate principles, tools and techniques, of the conditions and methods of implementing and interconnecting common goals;
- Applying and validating the conceptual model on the implementation of Lean management and Industry 4.0 by designing simulation models of case studies on flexible manufacturing;
- Conclusions and future research avenues.

The research study was carried out based on resources, such as books, collections of articles published in specialized impact factor journals and published in international conferences as well as using a state-of-the-art software for production simulation and digitalization. Thus, in a case study, we implemented the Tecnomatix–Plant Simulation 15 [21] and Process Simulation software package (Siemens PLM software, Munich, Germany) used in Industry 4.0 to analyze and assess a system's performance through modeling and simulation, in this case for a flexible manufacturing system. The EdrawMax software (Shenzhen Edraw Software Co., Limited, Shenzhen, China) [22] was used for mapping and analysis of the value stream map to offer Lean solutions for improving the value chain processes and application in Industry 4.0.

2.2. Lean Management Development Framework

In the general sense, the Lean management concept refers to the totality of principles, methods and procedures for the modern organization and management of a company by prioritizing the reduction or elimination of waste in the value chain processes. By identifying the critical points in the system, followed by an analysis of the causes that created them, we can find solutions to improve processes, products or services, which offer added value to customers.

The application of the Lean production concept in different companies and organizations [23,24] "has shown the world the differences between value-creating activities and waste, and has demonstrated how we can incorporate quality in products, from the inside out" [25] in order to develop innovative products and services and to meet customer demands. Since the emergence of Lean philosophy, the authors, Womack et al. (1990) [4] and Jackson and Jones (1996) [26], have developed manuals for the implementation of Lean principles in production, containing the main steps and ways of action, as outlined in Figure 1.

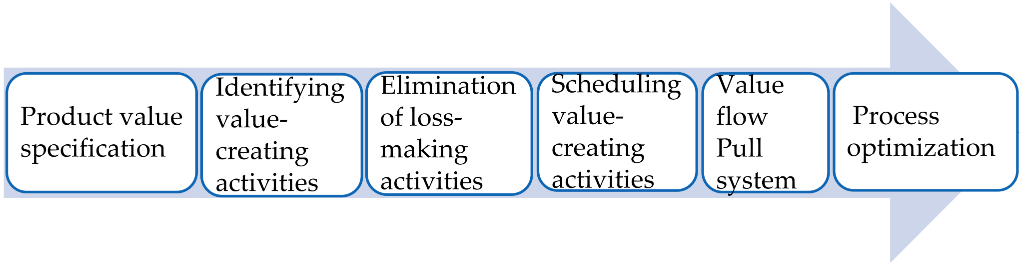

Figure 1. Lean implementation steps.

The organization of Lean production contributes to the acceleration of processes, the reduction of waste and implicitly the increase in the added value to the customer by the delivery of quality products. At the same time, Lean management also brings positive changes to the organizational culture [5] and to the man occupying a central place in any activity he carries out, from the operational level to top-level management. By developing a culture of improvement, employees are called upon to take responsibility but also to equip them with the power to make quick decisions at every level. Using the new knowledge and skills acquired by each individual and working as a team, production performance can be achieved, such as total control of production and stock, increasing effective manufacturing times and decreasing auxiliary times, thus accelerating manufacturing cycles.

The Lean techniques and methods aim to identify and eliminate waste from value chain processes. In manufacturing, the principles of flow-oriented production apply: the "flow" principle, the "takt" principle and the "pull production" principle [27]. The worldwide development and implementation of the Lean methodology was made possible through the creation and development of the Kaizen Institute Ltd., [28] and the Lean Enterprise Institute [29].

By offering the opportunity to implement waste identification and reduction techniques, Lean production brings important benefits to the company, especially at the operational level of production by manufacturing quality products to the customer's taste while increasing customer satisfaction and competitive advantage.

A synthesis of research on Lean management and its applications in the field, since the emergence of its basic concepts as well as the most recent developments in the literature, is presented in Table 1.

It is considered that the Lean production system is a production management model aimed at improving a company's entire field of activity [48]. Aside from the production process, Lean implementation can also improve the supporting activities of production such as logistics management, customer–supplier relationships and human interactions. Additionally, applying Lean techniques can open new horizons for companies to streamline production and increase their competitive advantage. These benefits can be obtained by switching to flexible manufacturing based on total quality, agility and promptness, according to the "just-in-time" principle.

Table 1. Lean management: literature review.

Research Area	Problems Addressed	References
Basic concepts	Toyota Production Systems (TPS) Concept	Taiichi Ohno (1988) [2]; Womack, J.P. et al. (1990) [4];
	The Basics of Lean Thinking The Concept of Lean Manufacturing	Jackson, T. & Jones, K. (1996) [26]; Rother, M. & Shook, J. (2003) [27]; Liker, J.K. & Rother, M. (2011) [29];
	The Kaizen Concept	Massaaki, I. (2013) [28].
Lean techniques and tools	Identifying and Reducing Waste Reducing Costs Continuous Improvement Standardized Work Efficiency Improving System Performance	Kovacs, G. (2020) [24]; Sancha, C. (2020) [30]; Garza-Reyes, J.A. et al. (2018) [31]; Costa, F. et al. (2019) [6];
	Lean Tools: VSM (Value Stream Map) Visual Management 5S Method Cellular Manufacturing	Schoeman, Y. et al. (2021) [23]; Jiménez, M. et al. (2021) [32]; Lagarda-Leyva, E.A. (2021) [33]; Dinis-Carvalho, J. et al. (2019) [34];
	Lean practices: - Lean Startup Methodology, Organizational Culture and Soft Lean Practices - Applications and Models of Lean Practices in Manufacturing, SMEs, Health and Tourism - Lean Practices and Process Innovation	Rise, E. (2013) [33]; Bortolotti, T. et al. (2014) [5]; Mohammad, I. et al. (2019) [35]; Bai, C. et al. (2019) [36]; Akmal, A. et al. (2020) [37]; Foris, D. et al. (2020) [38]; Moldner, A.K. (2020) [39].
Lean management and sustainable development	Lean Integration Models for Sustainable Improvements: - Lean Management and Quality, Environmental and Occupational Health and Safety Management Systems - Lean Management and Supply Chain Management (SCM) - Lean Management and Green Production - Lean Principles and Applications of Environmental Management in Manufacturing - Environmental Sustainability in the Social Dimension	Souza, J. & Alves, J. (2018) [40]; Henao, R. et al. (2019) [41]; Farias, L.M.S. et al. (2019) [42]; Moro, S.R. et al. (2019) [43]; Bhattacharya, A. et al. (2019) [44]; Abualfaraa, W. (2020) [45].
Lean research directions	Current Status and Future Research Directions Bibliometric Analysis of Lean Applications in Production Management	Danese, P. et al. (2018) [16]; Vinodh, S. et al. (2021) [46]; Leong, W.D. et al. (2020) [47].

By analyzing the literature in the field (Table 1), we determined that Lean principles, techniques and methods are the foundation of a company's sustainable development, having a positive influence industrially, socioeconomically and on sustainable environment. The implemented Lean methods aim to use minimum material, machinery and equipment resources as well as minimum financial and human resources.

It can be said that the Lean system, an integrated and coherent system of production management principles and techniques, can be configured following a careful analysis of the manufacturing processes, with the results reflecting a continuous manufacturing flow and a reduction in resource usage. Lean manufacturing has also proven its applicability in the current industrial environment, which is competitive and marked by digitalization and connectivity of all things. In this regard, industrial companies as well as other economic and social organizations are interested to know and implement the Lean methodology for the modern organization of manufacturing in the context of the future transformation of production towards Industry 4.0.

2.3. Industry 4.0 Development Framework

Industry 4.0 aims to develop intelligent manufacturing systems and to implement smart technologies in current manufacturing systems. Cyber–physical systems (CPS), the Internet of Things (IoT), big data analysis, intelligent manufacturing and the new disruptive technologies—robotics, artificial intelligence, virtual reality and simulation techniques—are the main components of Industry 4.0.

Recent specialized studies [49–51] have estimated that switching to Industry 4.0 will lead not only to technology changes but also to changes in business models, followed by social changes. Certain difficulties faced by industrial companies when implementing Industry 4.0 have arisen, even at the operational level of production floors [52] such as human resource training issues for learning new digital skills and competences, human–machine integration, and data security. It is necessary to have the best possible knowledge of industry practices so that the adaptation of current Lean management methods to smart manufacturing can be carried out efficiently. Reference [53] proposed a methodology that outlines general guidelines for the implementation of an Industry 4.0 project, and the steps are shown in Figure 2.

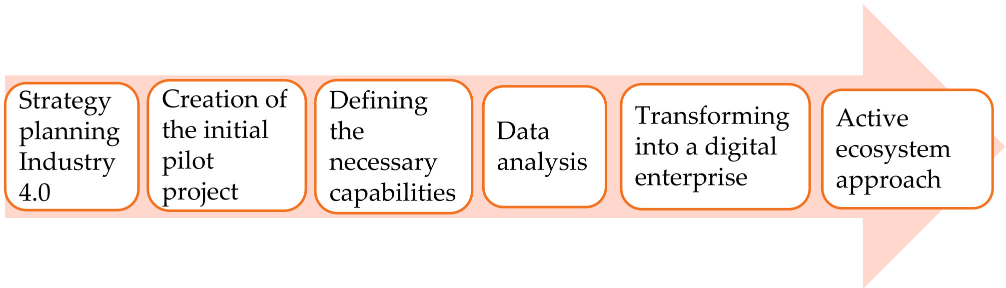

Figure 2. Industry 4.0 implementation steps.

A summary of the current specialized literature and the issues addressed for the development and implementation of Industry 4.0 principles is presented in Table 2.

Table 2. Industry 4.0.: literature review.

Research Area	Problems Addressed	References
Basic concepts	Industry 4.0 Initiative The New Industrial Revolution Industry 4.0 Concept	Ulrich, S. (2013) [54]; Kagermann, (2013) [8]; Bauernhansel, T. (2014) [55]; Burmeister, C. et al. (2016) [56].
Content and structure of Industry 4.0	Industry 4.0 Analysis and Content Industry 4.0 Technologies and Solutions Industry 4.0 Applications and Solutions	Culot, G. et al. (2020) [57]; Thoben, K.D. (2017) [58]; Vrchota, J. et al. (2019) [59]; Gallo, T. et al. (2021) [60]; Dalenogare, L.S. et al. (2018) [61]; Müller, J.M. (2018) [48]; Pereira, A.C. (2017) [62].
Conceptual model of Industry 4.0	Conceptual Development Framework for Industry 4.0 Vertical Integration Implementing Industry 4.0 in SMEs Industry 4.0 Maturity Assessment—A Roadmap for Implementation	Ustundag, A. et al. (2018) [63]; Sony (2018) [64]; Dombrovski (2017) [65]; Gajdzik, B. et al. (2021) [66]; Schumacher, A. (2019) [12]; Amaral, A. (2021) [67]; Santos, R. et al. (2020) [68]; Zoubek, M. et al. (2021) [69].
Industry 4.0 and sustainable development	Industry 4.0 and the Environment Industry 4.0 and Logistics Development and Supply Chain Management	Waibel, M.W. (2017) [70]; Müller, J.M. et al. (2020) [71]; Hahn, G.J. et al. (2020) [72]; Ivanov, D. et al. (2019) [73].
Benefits Industry 4.0 risks and opportunities	Industry 4.0 Creation of Value Impact of Industry 4.0 Implementation Development Trends and Opportunities	Peças, P. et al (2021) [74]; Moeuf, A. et al. (2020) [75]; Kiel, D. et al. (2017) [76]; Mourtzis, D. et al. (2019) [77]; Petrillo, A. et al. (2018) [14]; Veile, J.W. et al. (2020) [10]; Zheng, T. et al. (2020) [11]; Karatas, M. et al. (2022) [78].

By analyzing research in the field, we can highlight the positive effects in the successful implementation of the new concepts, technologies and solutions of Industry 4.0 materialized via industrial activity through an increase in systems performance standards and improvements in technical and economic indicators and working conditions.

2.4. Sinergy between Lean and Industry 4.0

Currently, Lean management and Industry 4.0 can be considered two different production philosophies for industrial companies that are applied in order to streamline manufacturing processes by eliminating waste and digitalizing manufacturing. The concept of Industry 4.0 is relatively recent, having emerged over the last decade in Germany [8] and representing a starting point of the 4th Industrial Revolution; however, Lean management is a method already established in production management over the last decades, and it has been applied and validated mainly in the processing and automotive industries [30,31] but also in other organizational systems such as services [35], SMEs [36], health [37,78], and tourism [38].

In recent research [79–81], through a meticulous review of the literature, a number of questions have been raised regarding the benefits and compatibility of Lean–Industry 4.0. Research hypotheses have been formulated based on existing practices, especially in the manufacturing industry. Studies [49] have been carried out in order to identify common goals and to find solutions to the possibility of integrating the two concepts: Lean and Industry 4.0. Varela et al. (2019) [17] developed a reference model that integrates the three dimensions of production—sustainability, environment and economy—into Industry 4.0. In [82], following the analysis, it concludes that many studies and research confirm the positive effects of integrating the two production strategies, but it is not very clear how they interrelate. However, they also discovered the existence of certain gaps, barriers and difficulties in carrying out suppliers–production–customers processes. Gallo et al. (2021) [60] considered two important Industry 4.0 technologies (IoT and big data) that are integrated into Lean manufacturing and can increase productivity and flexibility. There are also questions and analyses regarding the existence of many synergistic principles, but some contradictions between the two concepts also exist, when applied, for example, in the supply chain [68]. Wagner et al. (2017) introduced the concept of "Cyber Physical Just in Time" [83] by associating Industry 4.0-specific CPS technology with the basic JIT concept of Lean management. Duarte, S. (2019) [84] considers that Industry 4.0 facilitates a Lean and green supply chain with environmentally friendly implications. Research in the field has often provided models that are difficult to adapt to practical applications in a real industrial environment [85]. Given this research gap, this paper aimed to contribute by applying Lean and Industry 4.0 to flexible manufacturing. The difficulty resides in the fact that there is currently no unanimously accepted integration model in industrial organizations. The model developed in Reference [62] proposes the grouping of I4.0 components according to the characteristics of various systems, processes and technologies.

Many researchers and managers ask themselves questions regarding the compatibility between the already applied Lean principles and the "new paradigm", Industry 4.0, and the possibility of correlating the two. Challenges are also noted regarding the ability of Industry 4.0 to implement Lean principles and techniques and, vice versa, the adaptability of these principles to the new paradigm of Industry 4.0 manufacturing [86]. Analyzing and evaluating good manufacturing practices in several manufacturing companies (SMEs) in Germany, Sanders et al. (2017) believe that Industry 4.0 can provide "high end solutions which possess the necessary tools to implement Lean" [86]. However, at the same time, they specify the fact that the majority of research is theory oriented and not applicable, and they recommend the elaboration of a conceptual framework to integrate cybernetic systems with Lean manufacturing.

An interesting point on this subject is discussed in [24], which emphasizes that "Lean production and Industry 4.0 are not mutually exclusive" but, on the contrary, could be integrated, even if there currently is no unanimously accepted idea in this regard. Vinodh, S. et al. (2020) [46] examined the application of the Kaizen principles of continuous improvement and Lean Six Sigma and concluded, by combining the solutions offered by Industry 4.0 with the methods of continuous improvement, that it can bring important benefits and present a conceptual model of integration. According to certain researchers [17,62,85], the Lean system represents a foundation for implementing Industry 4.0. One of the first integration models [64], proposed by Sony (2018), considered that Industry 4.0 technologies, structured along the three directions of "integrated vertical, horizontal and end-to-end engineering integration", could be superimposed upon Lean principles. Vlachos et al.

(2018) [87] proposed "Lean automation" by introducing autonomous AGV and Internet of Things (IoT) I4.0 technologies, while highlighting the managerial and social implications. Investigations into the automation of Lean production by applying I4.0 technologies were initiated by Kolberg et al. (2015). Industry 4.0 and Lean were considered to support and complement each other [88].

A literature review regarding the development of the two manufacturing concepts aimed to analyze the current principles and relationship between Lean management and Industry 4.0 for the purpose of generating a useful conceptual integration framework applicable to industry. In the analyzed context, there is a need and opportunity to develop in-depth research in this cutting-edge, booming field in order to identify the benefits regarding the increase in system performance. Mainly, this concerns the synergistic development of digitalization and connectivity in Industry 4.0 and the Lean principles to ensure efficient, sustainable and waste-free manufacturing in the future.

3. Lean Management and Industry 4.0 Integration: Conceptual Approach

The Lean essence consists of identifying and eliminating activities with no added product value from the manufacturing process to reduce costs and continuously improve processes. Industry 4.0 involves manufacturing digitalization and systems connectivity by implementing new manufacturing technologies and developing intelligent manufacturing systems to make processes more flexible and optimized. In industrial practice, it is noted that both approaches aim to increase productivity by optimizing and streamlining manufacturing processes.

By analyzing the basic principles of the two manufacturing strategies, Lean management and Industry 4.0, we can consider that their general common goal is to create and develop efficient manufacturing and management systems along three economic development directions—economic, sustainable, and social [17]—while simultaneously adopting new business models in the company. The research methodological flow aims to analyze the two "paradigms" of production in order to establish a relational framework with applicability in the industrial environment. Starting from the analysis of the contributions in the field previously presented and noting the research gap, it is necessary to analyze several research questions: Can the two concepts be correlated through common goals? What is the impact of Lean's integration into Industry 4.0? What are the I4.0 technologies that have a favorable impact on Lean production?

The integration model should build on the analysis of principles, components and goals of implementing Lean management and Industry 4.0. To that end, a recent research methodology approach in a specialized study [49] considered that by integrating a few key elements of Lean management and Industry 4.0 (presented in Figure 3), we can attain manufacturing performance. The implementation of adequate solutions in the new industrial environment will take into account the requirements of productivity—adaptability and flexibility of production—on the one hand, and customer demands by offering high-quality, customized, value-added products and services, on the other hand.

To ensure innovative development through Industry 4.0, current companies that had previously implemented the Lean system aim to adapt their production by integrating the new digitalization and connectivity technologies. At the same time, companies want to adapt their current Lean management systems to develop new business models, considering that Lean principles represent a foundation for Industry 4.0. Thus, there emerges the need for studies elaborating a common integration framework while simultaneously analyzing the impact of Industry 4.0 on Lean enterprises in increasing process performance and streamlining production.

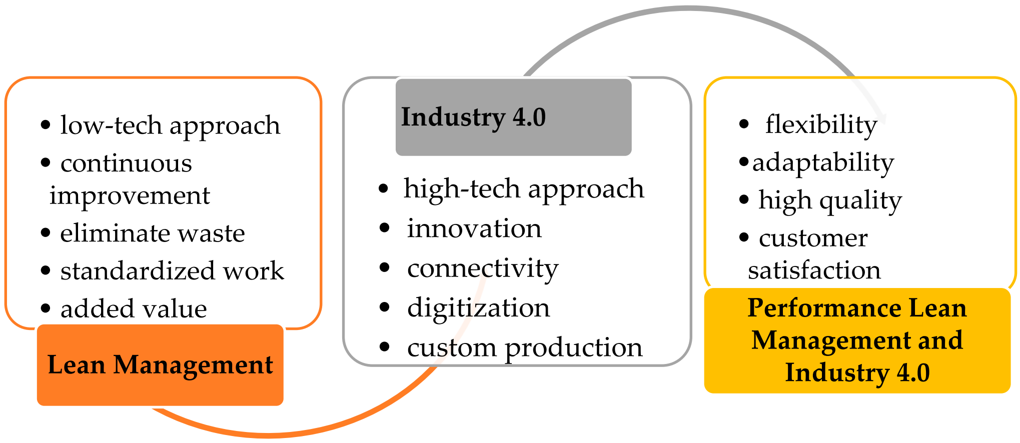

Figure 3. Lean management—Industry 4.0 integration methodological flow.

3.1. Lean Tools and Industry 4.0 Technologies

The Lean management system contains an integrated set of tools and methods frequently used in organizing production, with proven efficiency during the evolution of manufacturing systems, through applications implemented mainly in the industrial environment. Considering the purpose of identifying and eliminating waste and ensuring a continuous production flow, over time, a series of Lean methods have been perfected and verified in production, and the most common are briefly described in Table 3.

Table 3. Basic tools and techniques of Lean management.

Lean Management Tools and Techniques	Description
Value stream map (VSM)	The value stream map (VSM) is a basic tool in Lean manufacturing, useful in identifying waste, critical points in the system (activities that do not bring value) as well as reducing cycle times in manufacturing in order to improve and streamline processes. VSM is presented in the form of a specific diagram in which the information and material flows are drawn as well as data on the need for operators and process times.
Process mapping	Mapping business processes by drawing clear and detailed maps or diagrams that allow organizations to become more efficient through analysis in order to make improvements to the current process.
Visual management	Technique for the rapid visualization of manufacturing processes, flexible production cells through the use of production monitoring panels and stock control and the use of color marking systems.
KAIZEN	A method of continuous improvement that comes from the Japanese language and means changing production processes for the better.
KANBAN	An information-based system that plans and controls the quantity of production, helping to increase production flexibility and reduce stocks, based on the "pull system" principle; it allows the exact definition of stocks in the process and their drastic reduction;
Just-in-time (JIT)	The JIT method expresses manufacturing at the desired time and in the strictly necessary quantity in order to increase production efficiency by minimizing stocks.

Table 3. *Cont.*

Lean Management Tools and Techniques	Description
5S method	Tool used to organize workplaces with five words beginning with the letter S, derived from the Japanese: SEITON–SEIRI–SEISO–SEIKETSU–SHITSUKE. Benefits: eliminates waste, improves production flows, reduces inventory and standardizes processes.
SMED (single-minute exchange of die)	This method means changing the manufacturing benchmark in less than 9 min; it contributes to eliminating waste and reducing costs by reducing downtime and, therefore, quickly reconfiguring manufacturing processes.
Standard work	Standard work is the basis of the concept of continuous improvement. Through a graphical representation of all operating sequences, operational and auxiliary production times and takt time analysis, an overview of systems and production is given.
Poka-yoke	A lean tool designed to prevent and detect errors that may occur in the production flow, through devices of which the use of avoids the unintentional mistakes of operators, signaling the occurrence of errors in the system.
Jidoka	A Lean tool, which by automation allows the automatic shutdown of equipment, machines and processes in the case of the detection of errors and anomalies, and it gives human operators the ability to monitor and safely stop the process immediately as well as prevent defects; the principle of "built-in quality".
TPM (total productive maintenance)	Total productive maintenance concept based on prevention and autonomous and planned maintenance, avoiding unexpected machine and equipment downtime.
TQM (total quality management)	The concept of total quality management contains a set of methods and principles implemented to ensure the qualitative improvement in the products or services offered to customers. All actors in the value chain are involved in quality management, from suppliers–operators in production and managers to customers.

Industry 4.0 is capable of achieving process connectivity and monitoring autonomously, in real time. By using advanced tools and technologies, Industry 4.0 contributes to developing the value-creating chain in advanced manufacturing systems (Table 4).

Table 4. Advanced technologies: Industry 4.0.

Industry 4.0 Technologies	Concepts
Cyber–physical System (CPS)	Intelligent systems designed to achieve the integration of cyber and physical components, with the possibility of real-time monitoring and control through computing and communication networks.
Internet of Things (IoT)	The concept of networking everything in the physical world, objects and devices, through digitization.
Cloud computing (CC)	It contains applications designed to store data, using servers and software networks to provide services over the Internet; in production all the data needed for manufacturing are stored using cloud manufacturing tools.
Big data	A new concept used in intelligent business systems, providing solutions and tools for the analysis and exploitation of large databases using algorithms and software applications.

Table 4. *Cont.*

Industry 4.0 Technologies	Concepts
Artificial intelligence (AI)	Through AI techniques, such as machine learning, algorithms and computer-developed expert systems, human intelligence can be simulated and understood (through intelligent speech recognition programs, facial recognition and natural human languages).
Augmented reality (AR)	State-of-the-art technology that enables real-time visualization of objects in the real environment by superimposing virtual information generated by a computer over the human image in an existing environment.
Virtual reality (VR)	Advanced technology that allows the creation of a cyber environment through simulation so that the user can experience elements of the real world.
Additive manufacturing (AM)	A technology that consists of manufacturing by successive deposition of layers of material, with the whole process being computer controlled including 3D printing and rapid prototyping techniques.
Simulation	A technique by which real physical processes can be modeled on computers using specialized software in order to study their dynamic operation and optimization.
Digital twin	A state-of-the-art technology in smart manufacturing that integrates physical and digital elements. By making a faithful digital copy of a real physical system, simulation can accurately reproduce the behavior of the system to increase performance and process control.

Knowing Industry 4.0 technologies and Lean practices, an analysis can be carried out on the association of the two from the perspective of the benefits and positive effects on the dynamic, ever-changing industrial environment. Industry 4.0 brings substantial changes in manufacturing, through connectivity and digitalization, ensuring flexibility to market changes. Part of Industry 4.0 solutions can be superimposed onto Lean techniques and tools to create a continuous stream by eliminating waste and improving and streamlining manufacturing processes.

3.2. Correlation Model for the Industry 4.0 Solutions with the Lean Practices

Through its intelligent, high-tech solutions and applying the three key elements that create technological value [89] within Industry 4.0 processes—connectivity, intelligence and flexible automation—Industry 4.0 has managed to develop cybernetic manufacturing systems consisting of physical and digital interconnected objects capable of optimizing processes in real time. By applying the new Industry 4.0 technologies to the Lean manufacturing systems guided by the principles of continuous improvement and increase in added value by reducing waste, there are also major transformations of business models that lead to better performance and competitiveness of companies. As a result, a new challenge is the correlation of the two practices applied, often isolated, in the current production and the elaboration of a graphic conceptual model for the integration of the key elements that create added value (Figure 4).

The implementation of Industry 4.0 in production systems can be achieved in three directions of integration [64]: vertical integration, horizontal integration and "end-to-end" engineering integration. Reference [17] states that "the principles of I4.0 are the horizontal and vertical integration of production systems driven by real time data interchange and flexible manufacturing to enable customized production".

According to the model developed in [64], at every stage of Industry 4.0 integration, we can apply the five basic Lean management principles [4]: identifying value in order to eliminate waste in the value chain; drawing the current value steam map (VSM) in order to identify critical points in the system; creating the value stream (future VSM); developing "pull systems" in order to ensure continuous manufacturing stream; continuous process improvement.

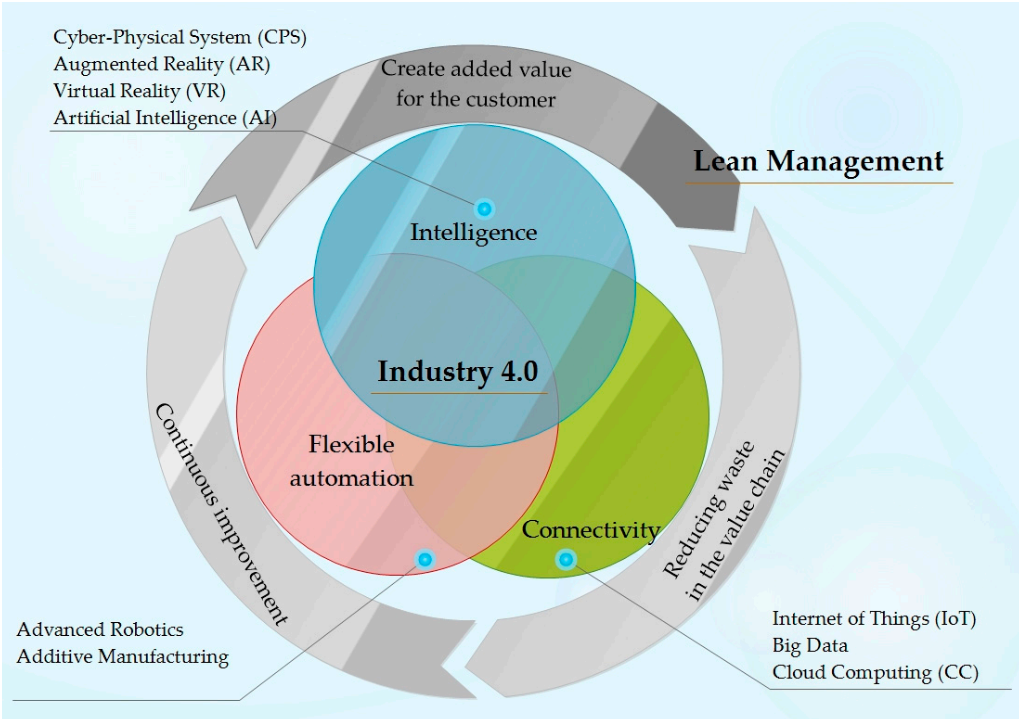

Figure 4. Graphic model of the key elements of value creation in Industry 4.0 and Lean technologies.

Figure 5 displays the developed graphical model of the integration of I4.0 into the application of Lean principles, specifying the main benefits resulting from their correlation.

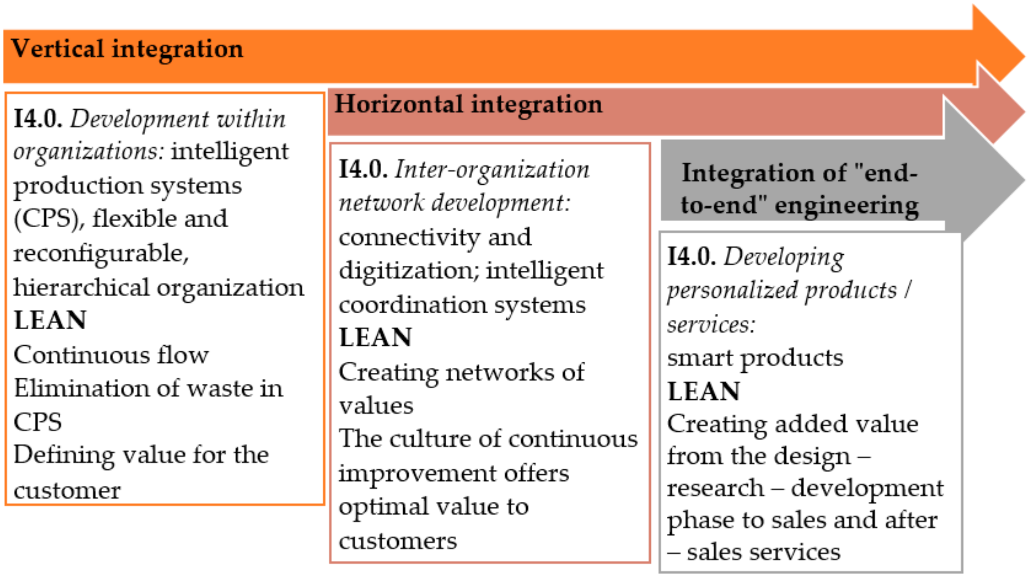

Figure 5. Industry 4.0 integration model and application of Lean principles.

Following the analysis of the principles of Industry 4.0 technologies and Lean tools, a model to identify common goals (Figure 6) was developed to integrate them into a general framework and to analyze the impact on production by correlating the two modern production development tools.

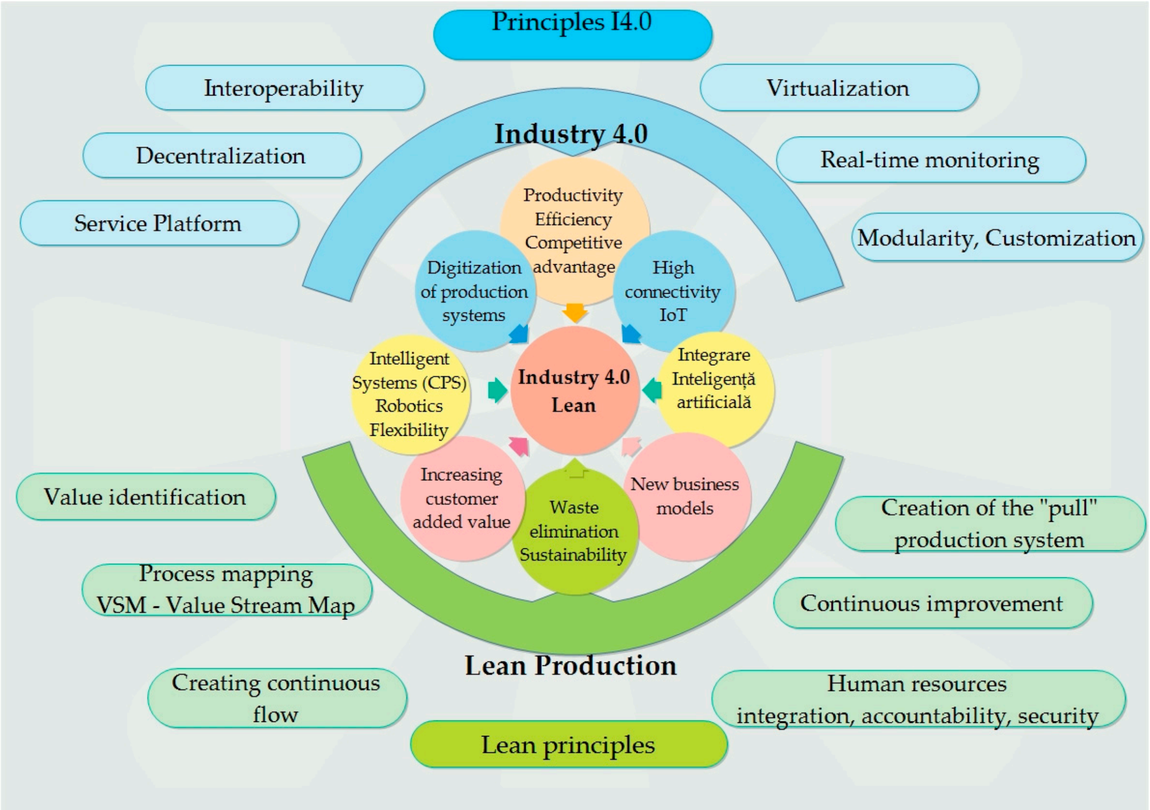

Figure 6. A conceptual model for integrating the principles of Industry 4.0–Lean Production.

It is noted that the principles of Industry 4.0 and Lean manufacturing can be interwoven in order to support company development by generating positive effects on productivity, efficiency and performance. The companies that have implemented Lean management in manufacturing exhibit an openness to switching to Industry 4.0, having already developed a culture of improvement, and they are more receptive to change. They consider that the new Industry 4.0 technologies can contribute to achieving the main Lean goals of reducing and eliminating waste by developing intelligent and value-creating processes, digitalization and connectivity. The approach to the association of Lean practices with the complex technologies of Industry 4.0 requires the development of a framework model that provides an efficient technical–managerial integration and organizational culture.

Conceptual Approach Regarding the Industry 4.0 and Lean Interdependence

Seen from a technical perspective, Industry 4.0 brings major changes in technology, but it does not exclude principles to identify added value and eliminate waste, which are typical of Lean management. Integrating Lean methodology and tools into the new industry represents a challenge for any company wishing to adapt its processes in order to increase performance, both at the operational and the organizational levels, through digitalization and connectivity. Through Lean manufacturing, solutions can be found to certain problems in terms of organizing and managing new high-end technologies implemented through Industry 4.0 such as cyber–physical systems (CPS), the Internet of Things (IoT), robotics, artificial intelligence (AI), additive manufacturing (AM), big data analytics and human–machine interfaces (HMI). Simultaneously, through its solutions and intelligent processes, Industry 4.0 contributes to meeting customer demands by offering customized, quality products (smart products), thus meeting the demands of Lean manufacturing regarding value creation for the end user.

Following the investigation of the key concepts of I4.0 technologies and Lean tools applied in practice, the favorable effects of the combination of the two practices in the

Industry 4.0 industrial environment can be highlighted as increasing the productivity and performance of production systems. Infrastructure Industry 4.0 contributes to the support of Lean systems primarily on the operational levels of the company (i.e., departments, production workshops and manufacturing lines), but it also ensures interconnection at the organizational level and among organizations.

The compatibility and positive impacts of various Industry 4.0 solutions implemented in Lean production are discussed below:

- Cyber–physical system (CPS): An intelligent system implemented in the Industry 4.0 environment that contributes to the improvement in Lean production by identifying, at the operational level, value-creating activities, flow mapping and flexible reconfiguration using digital tools (RDIF technologies, e-Kanban, IoT and cloud technologies). Thus, tools, such as Lean VSM, are adapted as DVSM (digital value stream map) in Industry 4.0. At the organizational level, the integrated delivery activity through CPS brings improvements to the classic JIT system by using IoT in the automatic processing of orders and the reduction in stock along the entire supply–production–customer logistics chain;
- Internet pf Things (IoT): This has positive process improvement effects in association with Lean techniques such as VSM 4.0 mapping by faster identification of waste in the value stream, collection and transmission of information flow on value creation processes and identification and monitoring of variations of functional aspects of the system; continuous flow manufacturing (JIT) improvement, zero defects by integrating Poka-yoke with IoT; interconnectivity of process objects, real-time data transmission and updating by associating IoT solutions with the "pull system" principle (virtual Kanban); streamlining visual monitoring (visual management), real-time decision-making processes and transparency through data and information transmitted quickly online to each employee; facilitating the logistics chain (lean supply chain management) through digitization and interconnectivity solutions and efficient planning of TPM;
- Additive Manufacturing (AM): This facilitates custom batch production of lightweight products but, at the same time, complex configurations that meet the quality characteristics required by customers. 3D printing and rapid prototyping can be combined with the JIT principle by individualizing products according to market requirements and increasing delivery flexibility. This new technology also makes its mark on the industrial maintenance business (TPM) by quickly replacing the various spare parts manufactured by 3D printing and shortening the production cycle. An association with the specific SMED method of Lean manufacturing derives from the elimination of preparation times, tool–device adjustment and the rapid change of parts in manufacturing. Other favorable effects of MA on Lean production include reducing material waste and costs and, thus, increasing sustainability in the industry by replacing expensive materials with others that have more efficient and environmentally friendly features;
- Simulation: In Industry 4.0, this has been developed in three directions: process simulation, product simulation and the new digital twin (DT) concept. Applied together with Lean practices in production, these simulation tools bring additional benefits: continuous flow (JIT), one-piece-flow, organization of pull production (Kanban) and CPS delivery (JIT), reduction of stocks (WIP—work in process) and waste disposal (Kaizen); rapid reconfiguration of the machine (SMED); optimizing the system layout (lean layout) by using VSM in identifying blockages and balancing production lines, by improving lead time, reducing through time and optimizing production capacity; making quality high-performance individualized products (TQM). Through digital twin simulations and virtual representations, processes can be optimized (dynamic VSM 4.0) and decisions can be made quickly and in real time by working in remote multifunctional teams with favorable effects, increasing productivity, reducing costs and accelerating the launch of products to customers.

- Advanced Robotics: By integrating automated intelligent systems for transport, handling and warehousing logistics operations (AIV—automatic intelligent vehicles, AGV—automated guided vehicles), Industry 4.0 contributes significantly to increasing productivity and streamlining processes by facilitating continuous flow (JIT) and increasing operator performance through standardized work (Lean). Implementation in production of high-capacity, interconnected and even integrated work robots with human operators (collaborative robots) through sensors that ensure safety at work can create superior conditions for the application of the principles of Lean production: continuous flow, JIT, lean supply chain, elimination of waste and scrap caused by machine failures (Jidoka) and elimination of human errors (Poka-yoke) through advanced automation.
- Big Data and Analytics: This involves the use of powerful software tools to cover large amounts of data; brings benefits to the continuous improvement of processes (Kaizen) and the elimination of waste through the high capacity of data collection, sharing and use in real time and their automatic analysis; cyber security along with other Industry 4.0 technologies (IoTs, advanced robotics, cloud computing and artificial intelligence). By transmitting useful data in real time in preventive maintenance activity, the principle (TPM) of Lean manufacturing can be supported as well as the improvement in the services of the production lines.
- Artificial Intelligence (AI): Applied in manufacturing, it participates in the efficiency of processes and the elimination of waste, specific objectives of Lean (JIT, Kanban), achieving a high connectivity among data–man–machine. Thus, its self-learning ability creates value by providing human skills and operating facilities to quickly solve production optimization problems through specific applications, machine learning, evolutionary AI algorithms, etc.
- Augmented Reality (AR) and Virtual Reality (VR): cutting-edge technologies implemented in intelligent manufacturing systems (CPS) that, together with simulation, can go hand in hand with Lean manufacturing, supporting JIT waste elimination principles or KAIZEN for continuous improvement and TPM reduction of auxiliary downtime in the process, as well as through effective self-learning and training of employees.
- Human–Machine Interfaces (HMI 4.0): An advanced solution for Industry 4.0, which in the context of Lean production, facilitates the physical and cognitive connection between man–machine–smart devices by increasing the skills and training of operators (Operators 4.0). It is compatible with Lean principles: JIT, standard work, TPM, VSM and 5S.

Table 5 provides a summary of the connection between the main I4.0 technologies and Lean practices as well as the positive effects on production and customers.

Table 5. The correlation between Industry 4.0 technologies and Lean tools.

Technologies Industry 4.0	Methods and Solutions	Lean Tools	Positive Effects of Correlation Industry 4.0—Lean
Cyber–physical system (CPS)	Vertical Integration Smart Manufacturing	VSM, Process Mapping, Visual Management, JIT, e-Kanban	Creating an automated value chain through digital value stream identification tools and virtual process mapping; flexibility; real-time production monitoring; JIT cyber delivery; waste reduction.
	Intelligent machines	Jidoka, Poka-Yoke, Standard Work, TPM, SMED, KANBAN	Increased productivity through automation solutions; creating standardized processes as a basis for identifying and fixing errors; quick configuration and adaptation of machines through self-learning.

Table 5. *Cont.*

Technologies Industry 4.0	Methods and Solutions	Lean Tools	Positive Effects of Correlation Industry 4.0—Lean
Simulation	Process Simulation	Lean layout, One-Piece Flow, JIT, VSM	Transferring elements from the physical world into a virtual real-time simulation model contributes to optimizing the system layout and the digital VSM (DVSM 4.0); continuous flow and waste identification.
	Product Simulation	Customization, Modularity, KAIZEN, KANBAN	Development of smart products, customized by standardizing processes in "pull" systems; continuous improvement.
	Digital Twin	TPM, Multifunctional Team, VSM	Favorable implications for the automatic maintenance of systems by forming a team of people with different skills, responsible for the virtual construction of products and processes.
Advanced robotics	Autonomous Robots	One-Piece-Flow, JIT, Jidoka	Ensuring continuous flow by accelerating the one-piece flow and implicitly optimizing processes; advanced automation solutions and manufacturing efficiency.
	Collaborative Robots	Employees Commitment, Poka-Yoke, 5S Standard work	Changing the ergonomic requirements of work organization; human replacement in difficult work environments and repetitive activities; performing complex tasks with minimal accuracy and error.
	Autonomous AGV	JIT, KANBAN, 5S, SMED, Lean Layout	Supply chain coordination; continuous flow; efficient work organization; site optimization in flexible manufacturing cells.
Internet of Things (IoT)	RFID (Radio-Frequency Identification), Sensor, Horizontal Integration, Cybersecurity	VSM, Visual Management, JIT, Kanban, KPI's, Customer relationship, SMED, Poka-Yoke, Jidoka, TPM, TQM	Value chain interconnectivity; continuous flow; product traceability; continuous improvement; optimization of the supplier–production–customer logistics chain; data collection by sensors; information transparency; cyber-attack protection.
Cloud computing (CC)	MES (Manufacturing Execution Systems) ERP (Entreprises Resource Planning)	JIT	Facilitating big data sharing and analysis through storage platforms and specific cloud software; facilitating complex decision-making processes and developing new business models.
Big data	Descriptive (e-Diagnostic), Predictive, ERP	Statistical Process Control KAIZEN, VSM Employees Commitment TPM	Streamlining the organization's and customers' data management; optimization of intelligent manufacturing processes and real-time decision making; waste reduction; continuous improvement by empowering employees for mobile applications; streamlining maintenance and service.

Table 5. *Cont.*

Technologies Industry 4.0	Methods and Solutions	Lean Tools	Positive Effects of Correlation Industry 4.0—Lean
Artificial intelligence (AI)	Neural Networks Genetic Algorithms Machine Learning	KANBAN, JIT, Heijunka, VSM	Stable production planning and scheduling of pull production; process optimization; reduction of stocks; increase productivity and efficiency; reduction in delivery times.
	Augmented Reality (AR) Virtual Reality (VR) Human–Machine Interfaces (HMI 4.0)	TPM, Jidoka, Employees Commitment JIT, Lean layout, VSM, Kaizen, Haeijunka VSM, 5S, JIT, TPM Standard work, Management Visual, Employees Commitment	Efficient predictive maintenance by programming and automatic calculations of OEE indicators; automated monitoring systems with alert and visual feedback for errors or malfunctions; waste disposal; facilitating employee training. Ergonomically organized human–machine interface; optimizing the process of collecting, transmitting and processing information; facilitating standardized work; creating value by eliminating waste; process transparency
Additive manufacturing (AM)	3D Printing and Rapid Prototype	Customization, Modularity, JIT, SMED, TPM, Poka-Yoke	Customized production, flexible and adaptable to customer requirements; reducing waste by eliminating overproduction and waiting times; quick reconfigurations.

Through its technologies, Industry 4.0 offers practical solutions for adapting, transforming and streamlining current production systems in which Lean tools are also applied. The integration of the two production and management strategies has positive effects, both technical and socioeconomic, leading to performance based on high-quality customized products and services, low costs, flexibility in delivery and adaptability to customer requirements.

4. Industry 4.0 and Lean Approach to Flexible Manufacturing: Case Study

4.1. Lean Manufacturing Production Analysis: Case Study

The analysis of the cursive production is performed in order to identify the basic activities that bring added value to the product, necessary activities. In addition to these activities, there are also support activities that do not add value but are necessary. Another group of activities are those that are not necessary and do not add value to the product, which lead to high waste and should be eliminated as much as possible.

The case study of a small-and-medium-sized enterprise (SME) focused on a "Gemba" analysis by carefully visualizing the actual physical process in order to identify sources of waste and the opportunity to optimize the manufacturing process by properly implementing Industry 4.0 technologies. The analysis was performed on the flexible manufacturing line of parts with cylindrical configuration, the technological flow including supply–transport–transfer–drill–turning–control–rectification–storage operations. For the detailed analysis of the manufacturing process, Lean process mapping tools and VSM value flow mapping tools were used.

The application of the conceptual model for the integration of the Industry 4.0 and Lean principles developed was considered. The need to improve the performance of the manufacturing process arose against the background of a request to increase the availability of the operator in the loading area of semi-finished products and a request of the internal customer represented by the downstream process after the unloading of the finished product. Thus, the Lean process mapping technique allowed the establishment of critical points in the system that led to long waiting times, the interruption of the continuous manufacturing flow and, implicitly, to the accumulation of waste in processes. Difficulties were observed in the manual loading operations of semi-finished products, respectively unloading finished parts that consumed long auxiliary handling times and induced large asynchronisms in the manufacturing process. In order to better capture the activity of the human operator involved in the process operations, as a sequence of actions necessary to achieve an objective, a detailed analysis of the activities was performed, and the times related to each activity were recorded.

Figure 7 shows the sequence with the critical points in the process mapping (Figure 7a) and the proposed solution for improvement (Figure 7b).

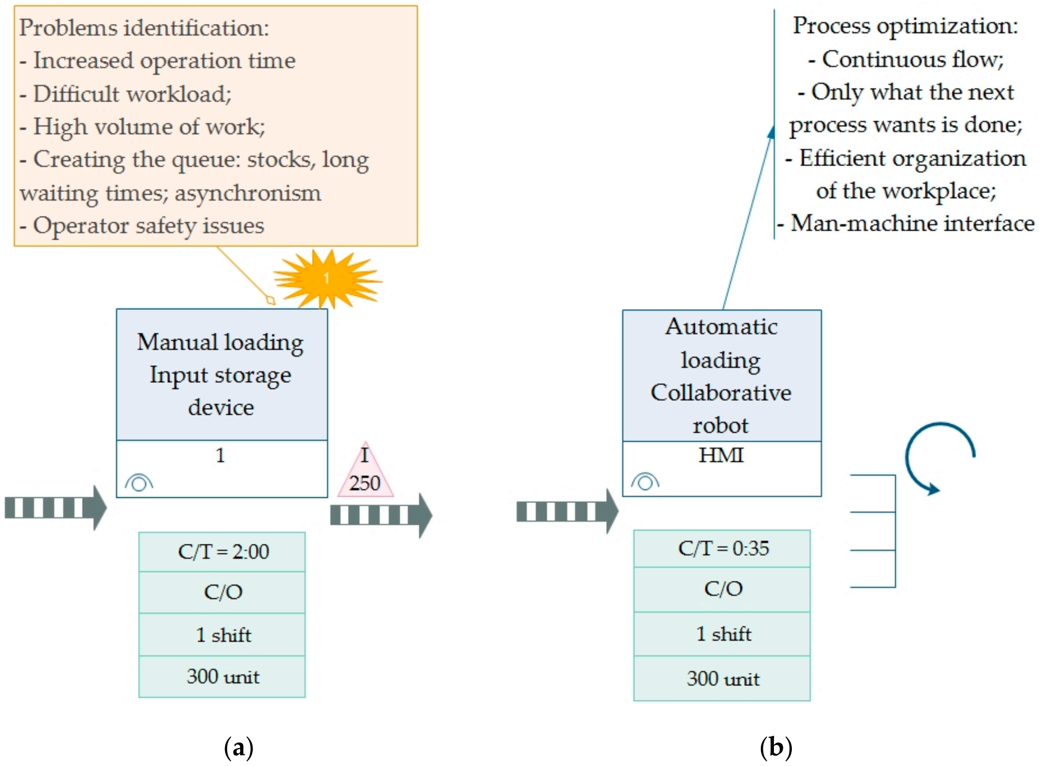

Figure 7. Sequence of the system loading process: (**a**) current Lean status—identification of critical points; (**b**) future status—solution for improvement via Industry 4.0.

Lean process mapping tools and VSM maps were created for detailed analysis of the manufacturing process. This method aimed to streamline process activities and was designed in two stages: (a) the current state identifies the added value transferred to the customer through products and defined the sources of waste; (b) the future state represents the improved situation of the processes and the proposed optimizations.

The proposed improvement solution is an integrated approach to the Lean waste disposal concept by applying Industry 4.0 technologies. Thus, the possibility of implementing two collaborative robots that take over the tasks of human operators for the loading and unloading operations and the realization of a human–machine Interface (HMI) were considered.

4.2. Optimization Solution through Industry 4.0 Technology: Digital Twin

The current trend in the evolution of companies with the implementation of the Industry 4.0 concept is the development of intelligent manufacturing systems, underpinned by computer integrated manufacturing (CIM) driven by flexible manufacturing systems (FMS) [15]. Through the characteristics of flexibility, adaptability, agility and integrated management, manufacturing systems provide conditions for the creation of value streams and the implementation of Lean principles. These are translated into practice by eliminating waste and reducing non-productive time. It is thus envisaged to develop complex structures with increased flexibility, both modular and reconfigurable, in order to increase the production capacity and the degree of utilization of all system components. By integrating elements of artificial intelligence and robotics into their structure, flexible production systems represent a leap towards intelligent manufacturing and a current development trend for companies that are rethinking their processes and want to implement new business models by moving toward Industry 4.0.

4.2.1. The Digital Solution by Implementing Collaborative Robots

The aim of the project was to produce a digital copy of a flexible manufacturing line for cylindrical parts [90] by simulating a real sequential process of feeding–machining–checking–storage.

Process Simulate (Siemens PLM software) has become a standardized tool in the robot simulation industry. Thus, all major robot manufacturers have available cinematic CAD models for their products. Having access to this information makes it very easy to create working scenarios to determine whether the process can be modified, extended or optimized. The image in Figure 8 shows a digital copy made for the studied system in which two collaborative robots were implemented.

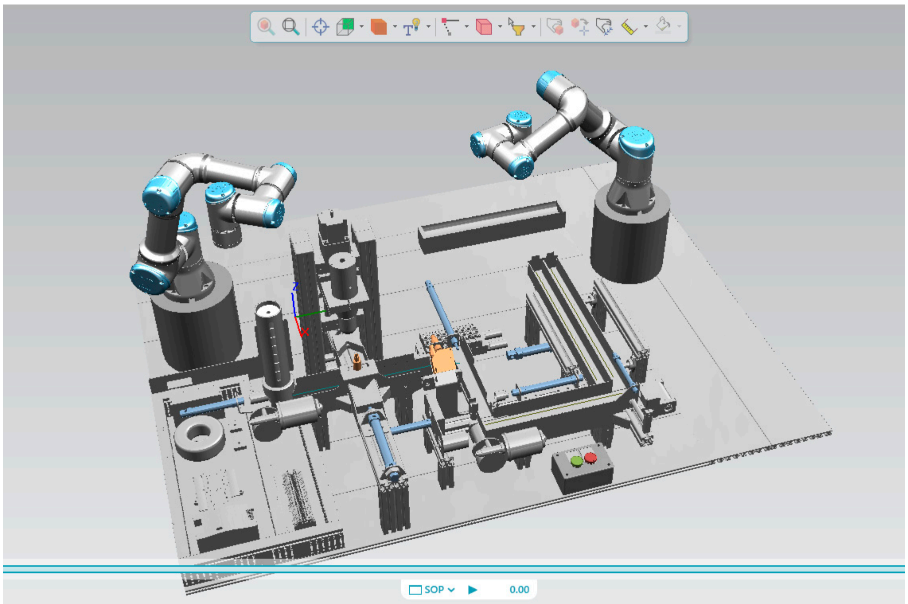

Figure 8. Digital copy of the sequential process of the case study.

Using the introduced equipment, new scenarios for the entry and exit areas of the flexible manufacturing cell were tested. At the same time, it was possible to estimate very well how the project will be affected by extending the process, by observing the interactions between the existing equipment with the newly introduced ones as well as regarding the economic impact.

4.2.2. Human–Machine Interaction (HMI) Analysis: Application

Another very important side of Process Simulate is the studies for operator operations. Thus, realistic representations for human operators can be created to validate their interactions with the equipment (Figure 9).

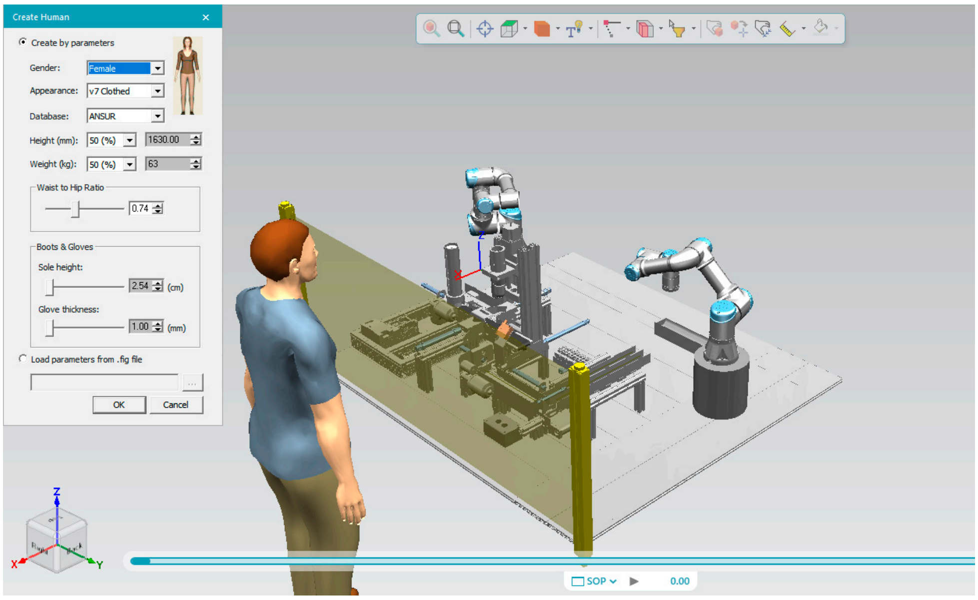

Figure 9. Human operator interaction—HMI. A sequence from the application.

The Human module in Process Simulate was used for the following scenarios:

- Cycle time validation for human operations;
- Testing of safety equipment: light barriers, laser scanners, emergency buttons, etc.;
- Conducting ergonomics studies, accessibility to equipment and tools.

5. Results and Discussions

5.1. Validation of Results through Simulation of Manufacturing in Industry 4.0

The simulation may take place during the design or optimization of a flexible manufacturing system for the determination of static load, in the design phase or for the validation of more elaborate solutions based on "dynamic models". These techniques are used to substantiate decisions on the optimal operation of flexible production systems. The strategic decision to digitize flexible production systems is currently an important area of research, given the complexity of these systems, which aim to increase production capacity in the context of diversifying production, shortening product life cycles and increasing competitiveness. Figure 10 shows a sequence from the simulation application performed in Technomatix—Plant Simulation to analyze and evaluate the performance of the flexible manufacturing system analyzed in the case study.

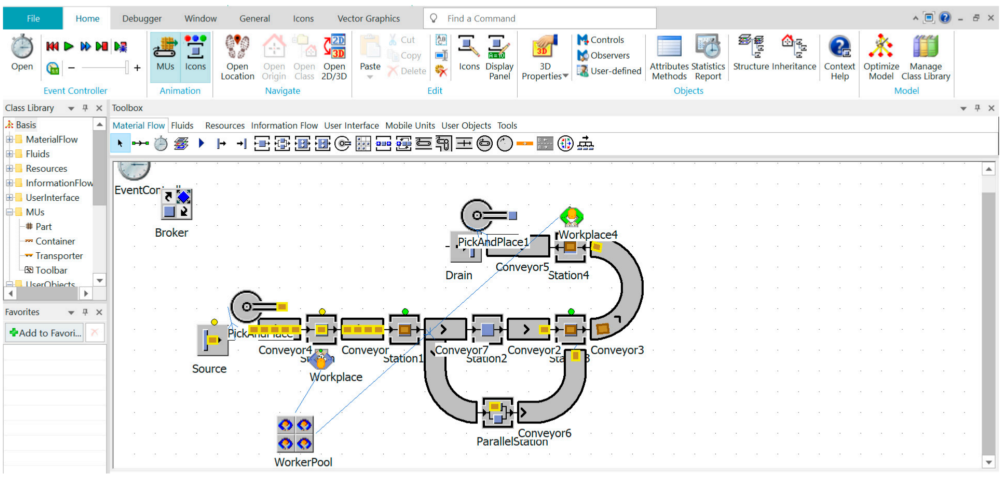

Figure 10. Model sequence simulation of a flexible manufacturing line. Application—2D Model.

Following the simulation analysis, by viewing the statistical data for each workstation, it was observed that one of the workstations in the system was experiencing a bottleneck (Figure 11), with a high bottleneck time (81.53%).

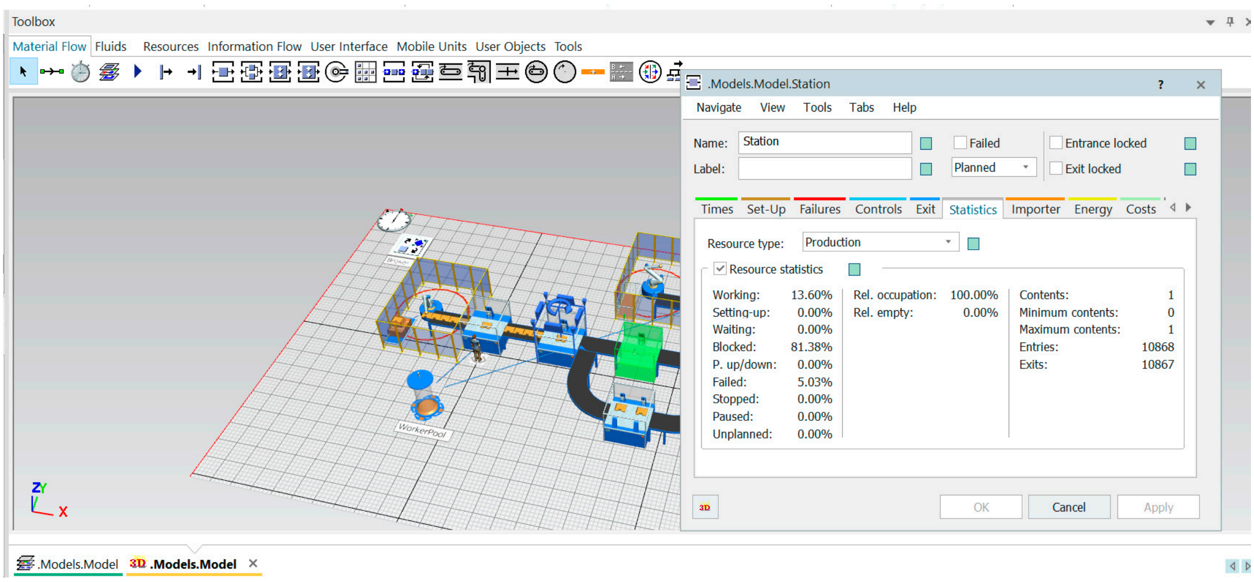

Figure 11. Sequence from the simulation program. Statistical resources—analysis of bottlenecks.

The simulation method was used to set the system performance limits, determine and optimize production times: operating times, weaving times through production, "tight spots" in the system, auxiliary waiting times, blocking times, equipment load, etc.

In the diagram in Figure 11, the operational and auxiliary times per workstation can be evaluated (percentage %). For example, for the workstation "Station": grey—waiting (tw = 0%); green—working (operational time top = 13.68%); yellow—blocked (blocking time tb = 81.83% very high, unmeasurable); red—failed (5.03%) (failed); blue—paused (stopped). In order to eliminate asynchronisms in the system (i.e., deadlocks), measures were taken to optimize operation, for example by arranging a workstation in parallel (Figure 11), increasing effective working times (to 95%) according to statistical resources in Figure 12.

Through Plant Simulation, real-time dynamic simulation of the intended manufacturing process was performed:

- To perform stochastic (partially unpredictable) experiments;
- Modeling and simulation of a manufacturing station/line/system;
- Statistical modelling of flexible manufacturing systems where techno-economic indicators are important, such as production times, machine capacity constraints and auxiliary time constraints (waiting times, blocking times);
- Animation of the movements performed in flexible production systems using simulation software.

Simulation models were developed to allow the user clearer control over the complex flexible manufacturing system at any level without losing any of the aspects being monitored. This modeling strategy supports graphical representations through model visualization.

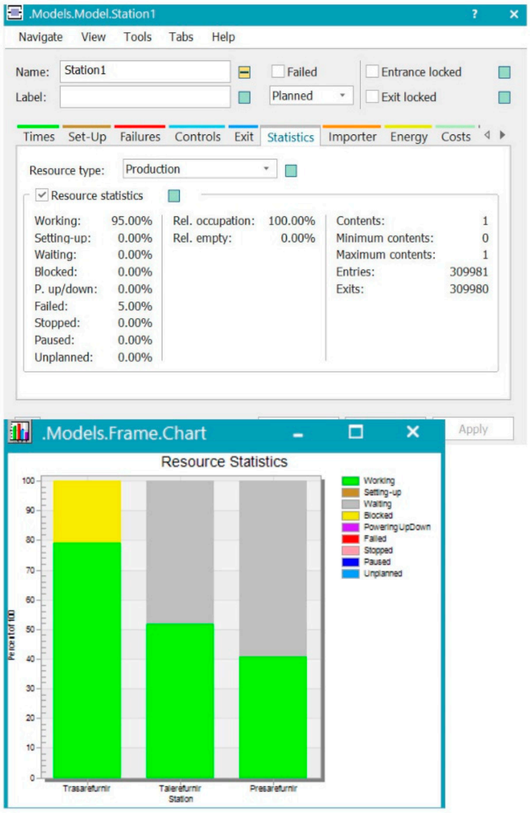

Figure 12. Sequence from the simulation program. Statistical resources—removing bottlenecks.

5.2. Discussions

By applying Lean tools, in association with Industry 4.0 technologies and customizing using a case study in flexible manufacturing, the results were favorable for the company, which will be able to improve its processes and, thus, increase its performance. It was found that the existence of Lean Production is a supporting function for the implementation of Industry 4.0, sometimes being an essential condition for intelligent manufacturing through Industry 4.0.

The analysis performed and the configured graphical models provide a framework for the integration of efficient Lean management and production systems in the Industry 4.0 environment. The system was analyzed from the point of view of Lean management. By mapping the entire production process, the critical points, the sources of waste were identified, in order to ensure the continuous flow of production and streamline production.

The modeling and optimization by simulation with discrete events in real time of the flexible production line allowed to test the behavior of the system, its reconfiguration and the reduction of the asynchronisms appeared. The Industry 4.0 solution, to introduce two collaborative robots on the manufacturing line and then to create the HMI interface, resulted from the design of the Digital Twin of the real system by using specific software. The result of the interaction between the human operator and the collaborative robot had a positive effect of increasing productivity and making production processes more flexible. This research provides an overview of the features of Lean tools and I4.0 technologies and a vision for their integration in order to develop advanced production systems.

6. Conclusions

The adoption of automation solutions for manual activities in Lean manufacturing by applying Industry 4.0 solutions creates the premise of moving to a new stage of transformation of production systems. At the same time, new business models will be developed and Lean management methods for human resource training will be implemented. The current trend of digitizing production at the European level, moving to Industry 4.0, is to configure manufacturing processes and systems as clearly and accurately as possible, with the help of the Internet and software, providing fast and flexible adaptations of production.

In order to respond effectively to new market demands, companies need to rethink their entire production process in this way by implementing smart manufacturing technologies based on the development pillars of Industry 4.0, but also the principles of Lean management.

Future research will focus on the application of the conceptual framework of Lean–Industry 4.0 integration in companies, particularly in SMEs, both in the technical and economic areas by implementing solutions to simulate different production scenarios, and in the management area by facilitating the decision-making process. Future research studies consider the analysis of the managerial and social implications of the digitalization of manufacturing as well as the possible risks for companies and their impact.

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