A SUSTAINABLE FRAMEWORK MANUFACTURING IN A DIGITAL ERA BASED ON LEAN SIX SIGMA AND INDUSTRY 4.0

Nicoleta-Mihaela CĂSĂNEANU (DASCĂLU)[1],
Marius PÎSLARU[2]

Rezumat. *Industria 4.0 prin tehnologie sincronizează mașinile inteligente pe tot parcursul procesului de producție, în timp ce Lean Six Sigma (LSS) îmbunătățește eficiența și calitatea producției. Integrarea Lean Six Sigma și Industria 4.0 creează un parteneriat puternic pentru dezvoltarea producției durabile. Sinergia LSS cu Industria 4.0 este crucială pentru organizații prin valorificarea interacțiunii dintre tehnologii avansate si angajați. Instrumentele LSS pot facilita implementarea tehnologiei Industriei 4.0 și producției inovativă durabilă. Conceptul de producție în masă personalizată și produse inovatoare oferă oportunități pentru avansarea tehnicilor LSS, ca angajații capabili să utilizeze potențialul tehnologiei pentru personalizare și dezvoltare de produse. Acest studiu își propune să îmbunătățească înțelegerea legăturii dintre Lean Six Sigma (LSS) și Industria 4.0, prin examinarea literaturii existente și colectarea de date printr-o revizuire tematică. Obiectivul este de a genera noi cadre de lucru durabile și perspective. Scopul este de a propune un cadru de producție durabilă bazat pe factorii*.

Abstract. *Industry 4.0 technology coordinates intelligent equipment throughout the manufacturing process, and Lean Six Sigma (LSS) improves production efficiency and effectiveness. The marriage of Lean Six Sigma and Industry 4.0 makes for a solid partnership that supports sustainable production development. Integrating LSS with Industry 4.0 is critical for organizations to leverage diverse interactions and use advanced technology for employee improvement. LSS tools can facilitate Industry 4.0 technology implementation and sustainable innovation in manufacturing. The concept of customized mass production and innovative products offers opportunities for advancements in LSS techniques, as workers can utilize technology's potential for customization and product development. The aim of this study is to enhance knowledge of the synergistic relationship between Lean Six Sigma (LSS) and Industry 4.0 by reviewing current literature and gathering information through a thematic review. The objective is to generate new frameworks and viewpoints. The goal is to propose a framework for sustainable manufacturing based on the significant key elements that result from the issues raised.*

Keywords: LSS 4.0, resilience, digital, conceptual model, industry

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[1]Ph.D. Student, Faculty of Industrial Design and Business Management, Gheorghe Asachi Technical University of Iasi, Iasi, Romania, (nicoleta-mihaela.dascalu@student.tuiasi.ro).
[2] Professor, Ph.D., Eng., Faculty of Industrial Design and Business Management, Gheorghe Asachi Technical University of Iasi, Iasi, Romania, (email: marius.pislaru@academic.tuiasi.ro).

1. Introduction

Industry 4.0 is an approach that aims to improve output through the adoption of cutting-edge technologies, including the Industrial internet of things (IIoT), robotics, and artificial intelligence (AI). Industry 4.0 illustrates an important development in innovation, incorporating the internet of things (IoT), big data collection, robotics, and intelligent technologies including machine learning and artificial intelligence (AI).Integrated intelligent technology has the potential to eliminate human errors and limits in future processes, but it cannot completely eliminate the necessity for human involvement.Industry 4.0 will definitely play a significant role in the smart factories and industries of tomorrow. Through the full implementation of real-time data and artificial intelligence, the ecosystem enables the acceleration of production and research and development processes for manufacturers. It additionally boosts production capacity, minimizes production costs, improves product quality, and optimizes product yield [1].The approach of digital evolution allows manufacturers to develop smart, interconnected systems that increase operational efficiency, provide real-time data analysis for decision-making, and enable proactive maintenance.Industry 4.0(I4.0) integrates advanced technologies, including cyber-physical systems (CPS), the internet of things (IoT), and the internet of services (IoS),cloud-based solutions, artificial intelligence (AI), and big data analytics into smart manufacturing systems[2].The key drivers in manufacturing include expanded flexibility, mass customization, increased speed, improved quality, and greater efficiency[3].I4.0 technology offers advanced manufacturing solutions, including additive manufacturing, augmented reality, simulation, horizontal and vertical integration, industrial internet, cloud storage, cyber-security, and big data analytics. It provides the ability to adjust, boost efficiency, and improve processes by guiding operators, optimizing operations, and facilitating interactions between technology and workers. Decentralization, learning, and knowledge sharing are essential components of intelligent production. Shared innovation depends on collaboration and the modification of current technology. During periods involving technological change and market change, the ability to adapt manufacturing processes and possess robust design skills is essential for sustaining innovation [4]. Lean Six Sigma is a complementary methodology that combines the most effective principles of Lean and Six Sigma, a pair of highly efficient process improvement methods.It reduces an organization's costs by eliminating "waste" from a process and resolving the issues generated by that process. The manufacturing industry utilizes Lean Six Sigma (LSS), a highly effective and emerging technology, to detect and eliminate waste, enhance performance, efficiency, and customer satisfaction [5]. The data-centric approach of Industry 4.0 utilizes IoT sensors to monitor and regulate waste in real-time, ensuring high-quality standards and efficient use of resources. This strategy also aligns with Lean Six Sigma manufacturing goals, including

processes and compliance with regulatory requirements. The adoption of a model can result in the development of innovative and unique approaches [6]. Research demonstrates that the implementation of LSS and I4.0 has a positive influence on business performance. This includes improvements in operational excellence, productivity, efficiency, knowledge sharing, agility in processes, regulatory compliance, customer satisfaction, cost reduction, and increased profits [7].The development of I4.0 has completely transformed the production process, making approaches such as LSS, which focus on continuous process improvement, of great value.These data-driven approaches, backed by innovative technology, help organizations leverage innovative technologies, particularly data collection and analysis, ensuring successful automation and waste reduction. Applying I4.0 technology in addition to LSS principles leads to an important change in production, which results in higher productivity, flexibility, and quality management.This partnership integrates advanced digital technologies with process optimization approaches, allowing for immediate data-driven decision-making, predictive maintenance, and efficient supply chain management [8].Adopting this integration involves a change in culture, emphasizing continually improving the skills of the workers to establish a competitive advantage in the changing manufacturing industry. The intelligent manufacturing ecosystem, which integrates I4.0 technologies such as automation, artificial intelligence, machine learning, big data analytics, and the internet of things (IoT), optimizes manufacturing processes in real-time. This leads to decreased production costs, improved production capacity, and improved product quality. This technology is appropriate for modern businesses and traditional labor-intensive sectors, highlighting the process of changing and enhancing production activities [9]. Integrating LSS with I4.0 is critical for organizations to leverage diverse interactions and use advanced technology for employee improvement. LSS tools can facilitate I4.0 technology implementation and the sustainable innovation ecosystem. The concept of customized mass production and innovative products offers opportunities for advancements in LSS techniques, as workers can utilize technology's potential for customization and product development [10]. This study aims to improve understanding of the synergy connection between LSS and I4.0 by examining existing literature and collecting data through a thematic review. The objective is to generate new frameworks and perspectives. The objectiv is to propose a framework for a sustainable manufacturing ecosystem based on the critical tools that result from the questions raised.

2. Methodology

The study of both innovative manufacturing concepts, LSS and I4.0, began with the need to digitally change a flexible manufacturing factory. Adopting Industry 4.0 technologies and continuously improving through LSS manufacturing

methods is an issue of strategy for many managers when it comes to modernizing current factories. The study used a systematic approach to create a framework that integrates Lean and I4.0, potentially enhancing the manufacturing and management of state-of-the-art manufacturing plants. We established the following research objectives, using a systematic approach, to identify new opportunities for the development of a model for an innovative strategy for a sustainable manufacturing ecosystem. The present research is focused on reviewing the literature the progress and utilization of LSS tools and I4.0 technology. Its goal is to synthesize the most important papers published in recent years on this topic. After conducting an in-depth review of the literature and industry practices, we identified the objectives and key elements for efficient and effective process excellence in the manufacturing sector. Through an examination of a literature review on current manufacturing processes, we have developed research hypotheses by focusing on current processes in the manufacturing field. We have developed a framework for a sustainable manufacturing ecosystem, applying the goals and key elements of LSS and I4.0 technology.

2.1 Literature review

The purpose of the reviewed literature is to determine the present principles and relationship between the LSS approach and I4.0, with the goal of developing a conceptual integration framework that can be applied to industry. The review will concentrate on the evolution of two manufacturing concepts. Within the present context, it is essential and helpful to do thorough research on this rapidly advancing subject to determine the advantages connected with improvements in system performance. Primarily, this applies to the collaborative development of digitization and connectivity in I4.0, in addition to the implementation of LSS principles, in order to provide effective, sustainable manufacturing in the next few years. In order to improve manufacturing performance, the integration model should incorporate I4.0 objectives and LSS manufacturing approaches. Organizations that use these components seek to modify manufacturing to use new connection and digitalization technologies, and they also modify their existing LSS management methods to create new business models. This necessitates research into how I4.0 affects LSS organizations, with the goal of increasing process efficiency and output optimization.

Even though I4.0 introduces major technological advances, it also applies the LSS methodology to find value additions and cut waste. Adapting the LSS tools and technology to the new industry poses hurdles for businesses looking to boost organizational and operational performance. Issues with robotics, artificial intelligence, machine learning, big data analytics, and the Internet of Things (IoT) are all addressed by LSS manufacturing solutions. I4.0 fulfills client requests by providing personalized, high-quality products that align with the value production

objectives of LSS manufacturing. The review aimed to address the following two questions in particular: The review aimed to critically examine the relationship between I4.0 and LSS principles.

RQ1: How do Industry 4.0 and LLS achieve innovation and sustainable manufacturing? When integrated sensors, machines, and robotics interconnect, the CPS can manage, monitor, and operate the physical framework of an organizationto make this a reality. The connection system's development should combine principles of LSS (Lean Six Sigma) in order to strategically design the CPS (Cyber-Physical System) and generate significant benefits for companies. [11]. The internet of things (IoT) is efficient when applied in combination with poka-yoke and Andon systems, providing "zero defects" in the manufacturing process. RFID tags and sensors permit the collection of real-time data from the manufacturing process to supply the VSM [12]. Radio frequency identification (RFID), cloud technologies, big data analytics (BDA), and augmented reality (AR) highlight the value of just-in-time (JIT). Through the use of these technologies, just-in-time (JIT) can effectively minimize inventory in the manufacturing process by monitoring resources and facilitating precision distribution within the system [13]. Statistical Process Control (SPC) is a Lean Six Sigma (LSS) tool that uses data analysis to identify specific causes and variations while monitoring the process. Real-time data collection will be increasingly accurate with the use of technologies like BD, sensors, and the internet of things [14]. Therefore, if there is a variation, we will immediately correct the error to prevent further errors. Intelligent machines in I4.0 self-configure for flexibility, and Single Minute Exchange of Die (SMED) cuts down on setup time. Enhancing machine learning algorithms with Six Sigma analysis improves equipment availability and quality, as well as production optimization. Intelligent machines in I4.0 self-configure for flexibility, and Single Minute Exchange of Die (SMED) cuts down on setup time. Enhancing machine learning algorithms with Six Sigma analysis improves equipment availability and quality, as well as production optimization [15]. In order to provide products to customers on time, additive manufacturing and 3D printing can better support lean principles such as just-in-time (JIT) and one-piece flow. Smart Jidoka with CPSs improves production flexibility and cost efficiency [16]. It automates real-time data collection, detecting waste in information flows. RFID technology improves shop floor control and performance and has developed real-time VSM based on RFID and wireless monitoring. I4.0 technologies and total predictive maintenance (TPM) are improving machine-worker interaction and self-monitoring. Intelligent predictive maintenance systems with integrated methods for data mining are made possible through CPS's integration of Lean, Six Sigma, and Industry 4.0 technologies [17]. RFID technology supports the supply chain through smart reallocations, wireless tracking, and item identification. These technological

advances optimize resource usage and decrease downtime.RFID-based Kanban integrates Lean, Six Sigma, and I4.0 technologies to automate inventory management, procurement, and reordering while minimizing downtime.Smart technology-based pull production more efficiently integrates scheduling, material replenishment monitoring, and monitoring.Collaborative manufacturing can enhance supplier relationships by using improved communication channels and data synchronization.Implementing CPS (Cyber-Physical Systems) in businesses effectively minimizes issues such as overproduction, waiting times, and defects[18].Additionally, the utilization of augmented and virtual reality technologies enhances traditional assembly and layout design processes. Furthermore, the integration of IoT (Internet of Things) based settings significantly improves production energy management. Big Data Analytics (BDA) and Lean Six Sigma together can reduce complexity in processes and products by providing improved analytical and forecasting capabilities. AI can serve as a diagnostic tool for Industry 4.0, identifying waste trends in big data in addition to optimizing capacity, profitability, and on-time delivery [19].Integrating artificial intelligence (AI) with lean six sigma (LSS) can result in reduced costs, accelerated production cycles, enhanced overall capability, and the elimination of major supply obstacles[20].The technology and design principles of I4.0 have the ability to support sustainability in all aspects of the economy, the environment, and social issues. Digital manufacturing is an important technology for advancing the circular economy. Several technological and communications technologies play an important part in improving the skills and knowledge of the labor force. The integration of technological innovations and principles from I4.0 with a sustainable approach contributes to improved resource efficiency, greater manufacturing flexibility, and decreased consumption of energy. The intelligent data approaches of I4.0 facilitate the production of high-quality products on a large scale while reducing their negative impact on the environment.

Q2: How do Industry 4.0 technologies and Lean Six Sigma support sustainable manufacturing? see Table 1.

Table 1. The positive effects of correlation LSS 4.0 and Industry 4.0

LSS 4.0	*IMPACT*	*POZITIVE EFFECTS*
Optimizing the data collection process	The process involves the real-time gathering of vast amounts of information;	The goal is to identify anomalies and issues, provide advantages such as more accurate and precise data, and speed up problem-solving
Accurate Forecasting	Identify potential defects or process variations before they occur;	Decrease defects and improve process stability

Virtual Control	The Internet of Things (IoT) provides sensors and devices that enable the remote control of assets and processes;	The ability to manage and supervise processes from any location around the world allows for international collaboration and knowledge sharing;
Process Automation	It minimizes the potential for human errors and reduces process variability;	Prioritize the optimization of automated processes and the enhancement of operational effectiveness
Continuous Improvement	The role supports the development of a culture that consistently increases performance by providing right-away feedback on the effectiveness of processes;	Lean Six Sigma is the principle of continuously improving processes

Companies have revolutionized their approach to increase quality and optimize costs by combining I4.0 and LSS. Through the utilization of data, automation, and immediate input, organizations can improve their business processes, reduce errors, and sustain their efficiency in a dynamic industry. Despite several challenges, the opportunity for increased effectiveness and standardization makes this integration an attractive option for organizations engaged in continuous improvement. In the current era of digitalization, embracing Industry 4.0 and LSS is not just an option; it is a necessity. necessity

2.2 Results

Utilizing key elements from the established LSS methodology and Industry 4.0, it is achievable to develop a comprehensive and smart framework for process optimization and improvement, allowing organizations to achieve improved overall performance, effectiveness, and operational efficiency.

The sustainable manufacturing ecosystem combines innovation management with a sustainable collaboration between humans and technology. This framework integrates LSS with I4.0, demonstrating the potential of sustainability in innovation strategy manufacturing, see Figure 1.

The requirement for a change from traditional production methods to sustainable manufacturing practices have been driven by the growing awareness of sustainability. I4.0 tools and approaches are essential for manufacturing sustainability because they provide higher accurate and current information collection and additionally useful data analysis. The most efficient approach to

waste elimination has been found to be using Lean instruments. Sigma six By incorporating Lean and Six Sigma methodologies, we minimize process variation and generate a stable system that is equally flexible. LSS implementation can result in superior quality. The common goals of Lean philosophy, Six Sigma, I4.0, and sustainable manufacturing have driven the investigation into incorporating concepts for continuous improvements throughout production.

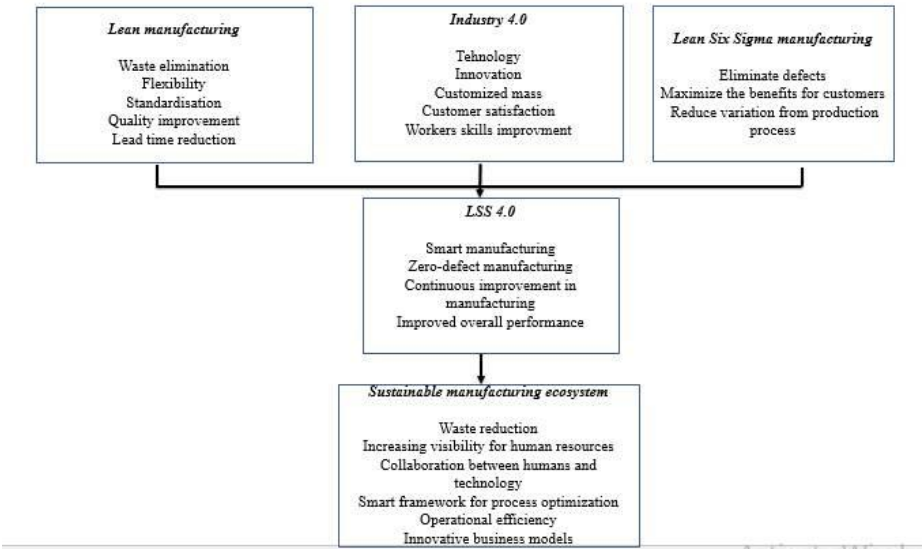

Fig.1. A conceptual framework for a sustainable manufacturing ecosystem

LSS and I4.0 enables businesses to use disruptive technologies like AI, big data, and IoT to innovate business models, such as value streams and customer relationships. It also allows businesses to reinvent their business models, introducing sustainable innovation into their products or processes. This approach promotes sustainable collaboration, green absorptive capacity, talent management, and innovation orientation.

Conclusions

This paper investigates the integration of Industry 4.0, Six Sigma, and Lean in production systems. It focuses the spotlight on how cutting-edge technology can coexist with the sustainability ecosystem and the beneficial features of manufacturing I4.0. Through real-time information exchange and optimized process flow, I4.0's intelligent technologies—such as CPSs, IoT, data science, and AI—make Lean pillars more predictable. The integration of additive manufacturing and 3D printing technology in lean manufacturing facilitates just-in-time (JIT) delivery, while autonomous Kanban systems provide the

identification of stock levels and automatic placing of orders. CPS-based Smart Jidoka enhances production system flexibility, leading to cost reduction and increased reliability. The integration of Industry 4.0 technologies, the internet of things (IoT), artificial intelligence (AI), big data, and machine learning works together with the Lean Six Sigma methodology to improve performance evaluation and processes for making decisions. Organizations can improve product quality and manpower skills through robotics, additive manufacturing, and automated inspection. Integrating these approaches can increase operational efficiency and provide better products and services. To resolve hidden issues and improve sustainable development, LSS practitioners must become prepared to implement cutting-edge technologies like I4.0. While this study demonstrates the benefits of interlinking Lean and Six Sigma with I4.0, more validation is needed through a conceptual model in real-world organizations. LSS, incorporating cutting-edge technology such as cyber-physical systems (CPS), the internet of things (IoT), sensors, big data analytics, artificial intelligence (AI), and machine learning, improves productivity and problem-solving through improving awareness of employee resources. This approach enables data communication, allowing for new insights and reducing waste, while autonomous machines reduce setup and failures. The integration of I4.0 and Lean Six Sigma methods is applied to maximize factory processes within the planned sustainable manufacturing process. Through this integration, supply chain operations become more transparent, and businesses can concentrate on providing high-quality services that satisfy customers. Moreover, workers have the chance to improve the skills and take on increasingly challenging assignments as part of the production proces

Further research is needed to verify the need for human resource adaptation and optimize the interaction between I4.0 and Lean Six Sigma technologies.

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