Journal of Transportation and Logistics
JTL 2024
DOI: 10.26650/JTL.2024.1329972

RESEARCH ARTICLE

Road-mapping for smart and lean tools with a sustainability perspective: A new model proposal

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ABSTRACT

This paper introduces a pioneering model designed to evaluate the readiness and maturity of smart-lean manufacturing by seamlessly integrating sustainability principles. In the dynamic landscape of Industry 4.0, where digitalization and connectivity redefine manufacturing paradigms, the convergence of smart and lean principles emerges as a powerful strategy. However, existing frameworks often lack a comprehensive approach that incorporates sustainability. Our model addresses this gap, systematically assessing organizations' smart-lean manufacturing capabilities and their alignment with sustainability goals.

The proposed model employs a novel algorithm to assess the relationship between the maturity of smart and lean tools and their economic, social, and environmental contributions. Through a carefully designed process, decision-makers determine correlation ratings, evaluate tool maturity, and calculate contribution gaps, providing a roadmap for prioritized implementation. To illustrate the model's applicability, an anonymous case study is presented, showcasing the step-by-step application of the algorithm.

This contribution is significant for enterprises seeking operational excellence and competitive advantage in the Industry 4.0 era. By incorporating sustainable lean principles into the smart-lean framework, our model guides organizations in enhancing their capacity development and making informed investment decisions. This paper not only advances academic discourse but also offers a practical tool for industry practitioners navigating the complexities of smart-lean manufacturing, ensuring a sustainable and environmentally responsible approach in the pursuit of long-term performance improvements.

Keywords: Smart manufacturing, lean manufacturing, smart-lean capabilities, smart-lean maturity, smart-lean sustainability, readiness and maturity model

1. Introduction

The global manufacturing industry is currently undergoing a profound transformation, driven by technological advancements, evolving customer demands, and an increasing awareness of the imperative for sustainability (Benkhati et al., 2023; Dahmani et al., 2021; Shahin et al., 2020). In the era of Industry 4.0, characterized by digitalization and connectivity that revolutionize product design, production, and delivery processes, the integration of smart manufacturing and lean principles has emerged as a potent strategy for achieving operational excellence and gaining a competitive advantage (Treviño-Elizondo et al., 2023).

The advent of Industry 4.0 signifies a paradigm shift, with smart manufacturing leveraging advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and big data analytics (Shahin et al., 2020). Through these technologies, smart manufacturing facilitates real-time data collection, analysis, and decision-making, resulting in improved productivity, enhanced quality, and increased flexibility and responsiveness across production systems. This holistic approach optimizes the entire manufacturing value chain, encompassing design, production, supply chain management, and customer service (Shahin et al., 2020).

Concurrently, lean manufacturing has long been acknowledged as a highly effective methodology for waste elimination, efficiency improvement, and the delivery of superior-quality products at reduced costs (Shahin et al., 2020). Emphasizing continuous improvement and the elimination of non-value-added activities, lean principles enable organizations to achieve operational

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Submitted: 20.07.2023 • **Revision Requested:** 12.11.2023 • **Last Revision Received:** 22.11.2023 • **Accepted:** 08.12.2023 • **Published Online:** 05.03.2024

excellence. This is realized through a relentless pursuit of perfection, engaging all employees in problem-solving and process improvement initiatives (Shahin et al., 2020).

Despite the individual merits of smart and lean manufacturing, a critical need exists for a comprehensive model that integrates both approaches with a sustainability perspective (Benkhati et al., 2023; Dahmani et al., 2021; Treviño-Elizondo et al., 2023). Such a model would enable enterprises to evaluate their readiness and maturity in adopting a combined smart-lean manufacturing approach. Addressing this gap, this paper proposes a novel model that incorporates sustainable lean principles into the existing smart-lean framework. This model serves as a roadmap for organizations, aiding in the enhancement of their capacity development and informed investment decision-making. The overarching goal is to facilitate enduring performance improvements, successful lean implementations, and the adoption of a sustainable and environmentally responsible approach (Benkhati et al., 2023; Dahmani et al., 2021).

The integration of smart and lean manufacturing presents a compelling proposition for organizations in the Industry 4.0 era, where smart manufacturing provides digital infrastructure and advanced technologies, while lean principles contribute a systematic approach to process improvement and waste elimination (Shahin et al., 2020). Together, these approaches can drive significant productivity, quality, and responsiveness improvements. This integrated strategy positions organizations to adapt swiftly to changing customer demands and dynamic market conditions (Shahin et al., 2020).

The primary objective of this paper is to propose a novel model that integrates smart-lean capabilities with sustainability principles. This model aims to assess an organization's readiness and maturity in adopting smart-lean manufacturing practices. The subsequent sections delve into the background and rationale for integrating smart and lean manufacturing, outlining the benefits and challenges associated with this approach. Additionally, the paper discusses its objectives, which include the development of a readiness and maturity model, the incorporation of sustainable lean principles, and the provision of a roadmap for capacity development. The proposed model's key components, assessment criteria, and integration of smart, lean, and sustainability principles are presented in detail, followed by a discussion of potential implications and benefits. The paper concludes by emphasizing the significance of the proposed model and suggesting avenues for future research.

2. Research Framework

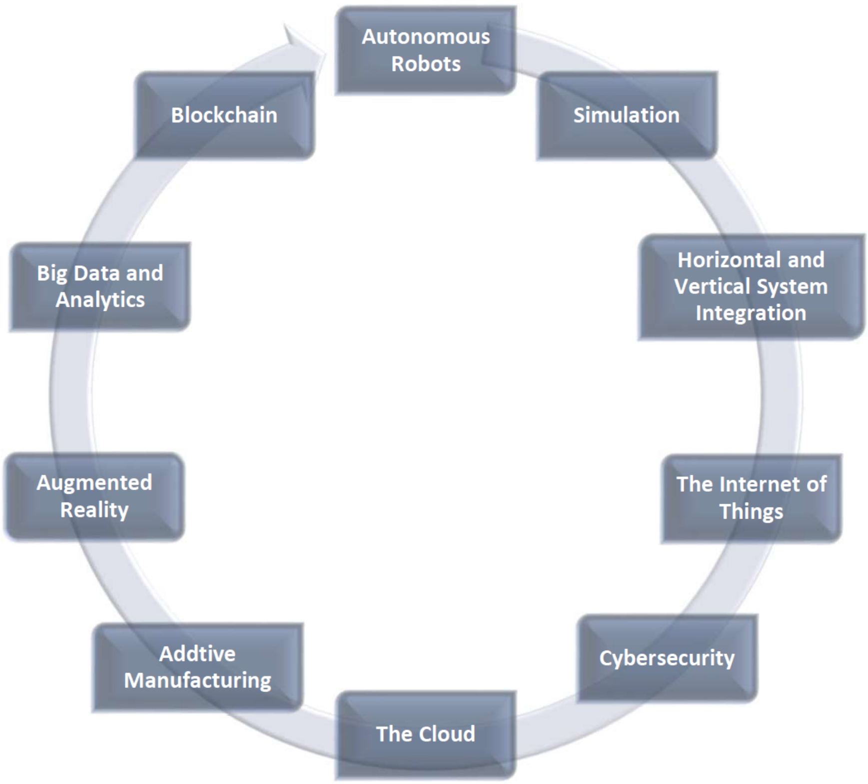
In this section, we present a literature review on smart manufacturing tools, lean manufacturing tools, and smart and lean sustainability, subsequently. Afterward, we highlight the literature gap.

2.1. Smart Manufacturing Tools

The concept of "smart manufacturing" refers to fully integrated, cooperative production systems that rapidly adapt to changing customer demands and conditions in the production systems, the supply chain, and the expectations of customers (NIST, 2018). Smart manufacturing aims to use the proper techniques to increase the production and quality performance of existing manufacturing environments. The ability to produce a variety of products in small batches and increase productivity and yield rate are two examples of enhancements that smart manufacturing provides (Chien et al., 2017). Smart production aims to make production processes more flexible and resource-efficient. Smart products and smart factories are two essential components of smart production (Dhungana et al., 2015). Smart manufacturing is a technology-driven strategy that streamlines every step of production and management, employing the proper embedded technologies for manufacturing processes. It aims to automate operations and use data analytics to optimize system performance and increase effectiveness and efficiency (Ku et al., 2020). Smart manufacturing systems use emerging technologies to reshape and optimize the production process. These smart technologies are shown in Figure 1.

Industry 4.0 combines advanced control systems and internet technology to enable communication among workers, objects, and manufacturing systems. The core idea behind Industry 4.0 is to use the capacity of cyber-physical systems to give intelligence and communication for artificial, technical systems that are called smart systems (Anderl, 2014). Smart production aims to make production processes more adaptable and resource-efficient. Smart production has two essential foundations: smart products and smart factories (Dhungana et al., 2015).

Figure 1. Smart technologies reshaping the production process (Source: Demir et al., 2020)



2.2. Lean Manufacturing Tools

Lean Manufacturing (LM) is a production philosophy that involves minimizing waste and eliminating non-value-added tasks to better use resources, increase productivity, maximize quality, and lower costs (Abobakr et al., 2022). Lean manufacturing comprises extensive techniques that eliminate Ohno's seven wastes (e.g., overproduction, waiting, transportation, over-processing, inventory, movement, and defects) and create leaner, more flexible, and more customer-responsive companies. When a lean manufacturing system is appropriately implemented, less inventory and labor force are used, less space is needed, and less investment is made. Lean manufacturing techniques remove ambiguities and disorders in traditional manufacturing environments and help employees work comfortably, safely, and with greater confidence (Demir and Paksoy, 2023).

The impact of lean principles on sustainability has been extensively studied in the literature. Afum et al. (2021) focus on how lean production, internal green practices, green product innovation, and sustainable performance metrics interact with one another. Ali et al. (2020) investigate the effects of lean, Six Sigma, and environmental sustainability on SMEs' performance. Alves and Alves (2015) introduce a production management model incorporating sustainability and lean manufacturing principles. The cultural transformation in the firm supports the proposed model and uses lean manufacturing tools to reduce waste and increase productivity. Cherrafi et al. (2016) review and deliver an analysis of the existing papers in the literature that focus on incorporating lean manufacturing, Six Sigma, and sustainability. Ben Ruben et al. (2020) examine the relationship between Lean Six Sigma and sustainability measures and their impact on enhancing organizational performance using the structural equation modeling (SEM) technique. Burawat (2019) explores the structural relationship between sustainable and transformational leadership, lean manufacturing techniques, and sustainability performance in the Thai manufacturing sector.

The terms lean and green are frequently used together in literature. Cherrafi et al. (2017) introduce a model that helps companies to successfully implement Green, Lean, and Six Sigma strategies to enhance their sustainability performance. Cherrafi et al. (2019) introduce a Gemba-Kaizen-based framework combining Lean and Green practices. Choudhary et al. (2019) present a novel Green Integrated Value Stream Mapping model that applies lean and green paradigms and assesses a manufacturing system's operational efficiency and carbon footprint. Ciannella and Sansos (2022) examine how employee social sustainability (ESS) dimensions are affected by lean manufacturing techniques. The authors apply an AHP model to prioritize eight lean manufacturing tools and four ESS dimensions. Demir and Paksoy (2023) investigate lean manufacturing tools (see Table 1) and propose a multidimensional lean maturity model.

Table 1. Lean Manufacturing Tools

Lean Management Tool	Description
Value Stream Mapping (VSM)	VSM is a lean tool that aids in understanding the flow of material and information through every step of a manufacturing process. The purpose of VSM is to detect and eliminate waste by implementing a future state value stream that can turn into reality in a short time (Chaple and Narkhede, 2017).
Pareto Chart	Pareto chart is a frequency block diagram displaying the relative frequency of different attributes in descending order (Grosfeld-Nir et al., 2007).
Spaghetti Plot	Spaghetti plot is a method to view the movement of an object, such as a worker or material, in a system with the help of a line (Senderská et al., 2017).
Genchi Genbutsu	Genchi genbutsu is one of the critical elements of the TPS, and it means going and seeing the real facts in the actual workplace for a complete and careful understanding of a situation (Gao and Low, 2014).
Jidoka	The Japanese word Jidoka means intelligent automation" or "autonomous automation." The main objective of Jidoka is to establish small and autonomous control cycles to monitor and detect defective products and prevent them from being disseminated (Deuse et al., 2020).
Just-in-time (JIT)	JIT is an operating concept that aims to eliminate waste and make the process more efficient. It was developed in the 1950s and achieved significant success at Toyota (Canel et al., 2000).
Total Productive Maintenance (TPM)	TPM is a manufacturing approach that aims to maximize the effective use of equipment by means of the participation and motivation of all workers (Cua et al., 2001).
Kanban	The Japanese word Kanban means "card" or "sign", and in lean practices, Kanban refers to control cards used in a pull system. Kanban is a visual control system that aims to eliminate waste such as overproduction, increase flexibility and agility in response to volatile customer demand, and reduce cost by eliminating waste (Arbulu et al., 2003).
Daily Management System (DM)	DM is a continuous process that allows people to visualize whether the work is done in the right way and whether the performance is good enough or not to achieve the expected business performance (Ferro and Gouveia, 2015).
One-Piece-Flow	One-Piece Flow refers to moving one part at a time between sequential operations in a production process. One-Piece Flow production system emphasizes factors such as sequencing, setup time, and make-to-order policy during production scheduling (Sundar et al., 2014).
Cellular Manufacturing	Cellular manufacturing refers to the physical division of a facility's machinery into production cells, each aiming to produce a family of parts (Drolet et al., 1996).
Heijunka	Heijunka is a sequencing discipline that aims to balance the production of different products over a certain period to achieve a constant flow of various parts in a manufacturing system (Furmans, 2005).
Computer Integrated Manufacturing (CIM)	CIM aims to develop superior IT solutions and establish a foundation for the implementation of integrated and computerized systems into manufacturing processes (Delaram and Valilai, 2018).
SMED	In Japan, SMED was developed by Shigeo Shingo in the 1950s in response to increasing flexibility in customer demand and a requirement to produce smaller lot sizes. This method is rapid and efficient for converting a manufacturing process from running the current product to running the next product (Ulutas, 2011).
Poka Yoke	Poka Yoke is a quality management technique that helps prevent human errors in a production line. The Japanese word Poka Yoke means "avoiding inadvertent errors." Shigeo Shingo developed this technique to eliminate defective products (Malega, 2018).
Visual Management (VM)	VM is a lean tool that helps workers track their jobs and assess whether they are being done correctly. Hence a worker can know whether the activity is being carried out safely or might cause an injury. Some VM systems are information boards, space boundaries,

Table 1. Continued

	and andons which are electronic panel systems that notify employees when a problem occurs (Sá et al., 2021).
5S	The 5S method is a lean management tool to create a highly efficient, organized, and ergonomic working environment. 5S is the shortened form of five words that represents the concept: Seiri (selection), Seiton (systematization), Seiso cleaning), Seiketsu (standardization), and Shitsuke (self-discipline) (Falkowski and Kitowski, 2013).
ABC Analysis	ABC analysis is an inventory categorization method that classifies inventory items into three groups: A, B, and C. Category A items are the most valuable and fast-moving items, category B items are of lower value than category A items, and category C items are the least valuable and slow-moving items (Nallusamy, 2016).
Andon	Andon is a visual management device that shows the status of operations in a system and signalizes any abnormality (Kemmer et al., 2006).
Pull System	Pull system is the application of just-in-time system to material management where the amount and time of material flow are determined based on the actual utilization rate of material. Toyota uses Kanban to operate the pull system (Kim, 1985).
Customer Relationship Management (CRM)	CRM is a strategic management technique that merges the potential of IT and relationship marketing strategies to develop strong relationships with key customer segments and build an efficient value chain (Payne, 2012).
Suggestion System	Suggestion system is a management technique that aims to encourage the employees to be active in a process by empowering them to present their ideas and suggestions through surveys, meetings, and suggestion forms (Schröders and Cruz-Machado, 2015).
Takt Time	Takt time is a metric used to synchronize manufacturing and sales velocity. It represents the frequency in which a product needs to be manufactured to meet a customer's demand (Chaple and Narkhede, 2017).
5 Whys Analysis	Five whys analysis is a lean management technique to identify the root cause of a specific problem by asking why the problem happens until finding the root cause (Chen et al., 2010).
Problem-solving Methods	Problem-solving methods are necessary tools for the management and process improvement efforts. The first step of problem-solving is to rapidly identify the root cause of the problem and implement an appropriate solution that guarantees that the problem will not occur in the future (Wojtaszak and Biały, 2015).
Ishikawa Diagram (Fishbone Diagram)	The Ishikawa diagram shows the relationship between an effect or problem and its potential causes. It allows the categorization of the causes and produces good results in a short time since the visual representation is easy to construct. This diagram is also called a fishbone or cause-effect diagram (Iuga and Rosca, 2017).
Scatter Diagram (Scatter Plot)	Scatter plot is a tool that shows how two variables are related to one another. These plots help detect the amount of correlation, or the degree of linear relationship, between two variables (Syduzzaman et al., 2014).
Workflow Diagram	A workflow diagram is a basic visual layout of a business process that shows the movement of material, identifies waste areas, and helps plan future improvements (Wang, 2010).
Histogram	A histogram is a graphical representation of recorded values in a data set based on their frequency of occurrence (Lai and Cheng, 2016).
Quality control charts/ Process Capability Analysis (PCA)	Quality control charts are graphs plotting the changes of a process in chronological order (Abujudeh et al., 2017). PCA is a quality technique used to estimate the proportion of parts that do not meet engineering requirements in a stable production process (Gildeh and Moradi, 2012).
Check Sheet	Check sheet tables are used to record the frequency of defects or problems, and it is a useful method of systematically recording, collecting, and illustrating data patterns from observations (Lai and Cheng, 2016).

Source: Demir and Paksoy (2023)

2.3. Smart and Lean (S-Lean) Sustainability: Literature Gap

Integrating smart technologies, lean principles, and sustainability considerations has gained significant attention in various domains, including urban management, manufacturing, maintenance, and product design. However, there needs to be more literature regarding a comprehensive road map or framework that outlines the strategic integration of these three dimensions.

Smart and lean manufacturing have emerged as key paradigms in contemporary industrial practices, offering innovative approaches to enhance operational efficiency, reduce waste, and improve sustainability. This literature review synthesizes insights from several papers that delve into the integration of smart and lean principles, exploring their impact on various industries and organizational processes. The study by Tsai et al. (2021) focuses on healthcare, introducing the application of Lean and Six Sigma methodologies alongside smart technology to streamline perioperative management. This integration, guided by the DMAIC architecture, successfully reduced waiting times, enhanced process efficiency, and improved patient satisfaction. The findings emphasize the potential of smart and lean integration in healthcare settings to deliver high-quality services while minimizing operational inefficiencies (Tsai et al., 2021). In Mahmood and Montagna's (2013) paper, a system-of-systems (SoS) approach is proposed to make lean practices smarter. The integration of SoS principles aims to optimize manufacturing systems, though the paper lacks detailed insights into practical implementations. However, it opens avenues for future research to explore the real-world application and impact of such an integrated approach in diverse manufacturing settings. Bortolotti et al. (2023) contribute to the literature by investigating the impact of integrating smart manufacturing into lean companies, specifically focusing on shop-floor employees' autonomy and empowerment. The study employs the Job Characteristics Model, revealing that smart manufacturing supports job rotation and enhances decision-making speed without compromising the principles of lean manufacturing. This research provides valuable insights into maintaining "soft" lean practices while adopting smart manufacturing technologies, offering practical implications for organizations aiming to enhance employee experiences (Bortolotti et al., 2023). The bicycle industry in Taiwan serves as a case study in Li's (2019) research, showcasing the practical implementation of "Lean Smart Manufacturing." Using the case of GIANT, the study highlights the potential of balancing differentiation and open innovation through the establishment of a co-creative platform. While still in the development stage, this case study presents a promising application of "Lean Smart Manufacturing" in a competitive industry, demonstrating its potential to strengthen competitiveness through a strategic blend of lean production and smart manufacturing (Li, 2019). Treviño-Elizondo et al. (2023) propose a maturity model for organizations to become smart by integrating Lean and Industry 4.0. This model provides a roadmap for organizations to transition towards smart operations, emphasizing Lean as a key enabler for driving Industry 4.0 adoption. By structuring the types of Lean principles, methods, and tools alongside Industry 4.0 technologies, the model offers a comprehensive guide for organizations seeking to evolve into smart entities (Treviño-Elizondo et al., 2023). The study by Tripathi et al. (2023) explores the integration of lean, green, and smart manufacturing for enhancing sustainability on the shop floor in Industry 4.0. The novel framework presented in this research demonstrates significant improvements in productivity, machinery utilization, and environmental impact. The integration of smart manufacturing features with lean and green practices offers a holistic approach to sustainability in manufacturing operations (Tripathi et al., 2023). The interplay between smart, lean, and resilient manufacturing is investigated by Benkhati et al. (2023), exploring their linkages for sustainable development. The research reveals the moderating effect of smart manufacturing on the relationship between lean manufacturing and resilience. The findings suggest that smart manufacturing enhances the components of a sustainable system, allowing firms to achieve both lean and resilient capabilities for high sustainable performance (Benkhati et al., 2023). Shahin et al. (2020) contribute to the literature by providing a comprehensive review of the links between Lean practices and Industry 4.0 technologies. The study explores existing and potential enhancements of Lean practices enabled by Industry 4.0 technologies such as wireless networks, big data, cloud computing, and virtual reality. The paper emphasizes the integration of a cloud-based Kanban decision support system as a real-world demonstrator, showcasing the practical application of Industry 4.0 technology alongside a major Lean tool (Shahin et al., 2020). The paper by Schmiedbauer et al. (2020) addresses the evolving complexity of asset and maintenance management in the context of Industry 4.0. The Lean Smart Maintenance (LSM) maturity model is extended to incorporate aspects of digitization and digitalization. The study contributes to understanding the influence of cyber-physical systems, data management, and condition monitoring on industrial asset management, highlighting the need to adapt existing models to the changing landscape of Industry 4.0 and data science (Schmiedbauer et al., 2020). The integration of lean design, eco-design, and Industry 4.0 for smart circular product design is explored by Dahmani et al. (2021). The proposed framework emphasizes the importance of decisions made during the product design stage in achieving sustainability throughout the product life cycle. The study provides insights into the synergistic use of lean, eco-design, and Industry 4.0, offering a structured and methodological approach to designing eco-efficient products (Dahmani et al., 2021). The book chapter by Akbal and Doğan (2023) explores lean and smart supply chain management in healthcare. The authors emphasize the significance of supply chain functions in healthcare settings, highlighting the role of smart and lean practices in ensuring a continuous and efficient flow of materials and services. The integration of smart and lean principles in supply chain management is presented as crucial for maintaining operational effectiveness in healthcare organizations (Akbal & Doğan, 2023). Rahardjo et al. (2023) present a novel Smart and Sustainable Manufacturing System (SSMS) that integrates Industry 4.0 technologies and Lean Manufacturing tools. The authors introduce Dynamic Lean 4.0 tools, such as Sustainable Value Stream Mapping, Extended Single Minute Exchange of Die, and Digital Poka-Yoke, as outputs of synergistic relationships that optimize production processes. The case study presented in the paper demonstrates the practical implementation of SSMS, indicating improvements in process capability and various operational metrics (Rahardjo et al., 2023). The review by Touriki et al. (2021) investigates an integrated framework that combines smart, green, resilient, and lean manufacturing for sustainable development. Drawing on a hybrid methodology, the study explores the moderating effect of smart manufacturing on the relationship between lean and resilient manufacturing. The findings suggest that smart manufacturing fosters a synergy that enables firms to be both lean and resilient, contributing to high sustainable performance (Touriki et al., 2021). In summary, the integration of smart and lean manufacturing practices offers a multidimensional approach to enhance efficiency, sustainability, and competitiveness across various industries. While each study contributes unique insights and perspectives, a common thread emerges: the potential synergies between smart and lean principles hold promise for organizations seeking to navigate the complexities of contemporary manufacturing environments.

Several studies emphasize the integration of smart technologies and lean principles to enhance operational performance in various contexts. For instance, Rößler (2017) proposes the Smart Factory Assessment (SFA) methodology, which combines lean and digital manufacturing principles to assess and improve production and logistics systems. Bokhorst et al. (2022) explore the adoption of smart manufacturing technologies in conjunction with lean principles, highlighting the necessity of lean for successful smart implementation. Hosseinizadeh Mazloumi et al. (2023) present a model for designing a synchronizer module in computerized maintenance management system (CMMS) software based on lean, smart maintenance and process mining, emphasizing the importance of internal integration, measurement, and improvement in maintenance processes. These studies demonstrate the potential synergies between smart technologies and lean principles in achieving operational improvements but do not explicitly explore lean smart maintenance's sustainability perspective.

The literature also recognizes the importance of integrating sustainability considerations into smart and lean practices. Dahmani et al. (2021) discuss combining lean design, eco-design, and Industry 4.0 technologies to develop eco-efficient products based on circular economy strategies. Fiorello et al. (2023) propose a smart lean green production paradigm that leverages Industry 4.0 tools to improve operational performance while addressing environmental impacts. These studies highlight the need to align smart and lean practices with sustainability goals, emphasizing the role of green principles and eco-design approaches. Despite the growing interest in smart and lean practices with a sustainability perspective, there needs to be more comprehensive road maps or frameworks that guide organizations in strategically integrating these dimensions. The literature offers valuable insights into specific aspects of this integration, such as the application of lean principles to evaluate the smartness of cities (Herscovici, 2018) or the incorporation of sustainability in the design of smart and lean production systems (Biedermann et al., 2016). However, a comprehensive road map encompassing the scope of smart lean sustainability still needs to be included. Such a road map could outline the stages of adoption, identify critical success factors, and guide the selection and implementation of smart and lean practices to achieve sustainability objectives. Furthermore, the road map should account for contextual factors, such as industry-specific challenges, organizational capabilities, and stakeholder engagement.

3. Methodology

This subsection describes our methodology by providing detailed information on the sampling strategy, respondent qualifications, and data collection methods.

3.1. Sampling Strategy

Our study employed a purposive sampling strategy to ensure that participants had relevant experience and expertise in smart-lean manufacturing practices within the context of sustainability. The participants were selected based on their roles in the case study company, including managers, engineers, and practitioners directly involved in the implementation of smart and lean principles. This approach aimed to gather insights from individuals with a comprehensive understanding of the integration of smart-lean practices and sustainability in manufacturing operations.

3.2. Respondent Qualifications

The qualifications of the respondents played a crucial role in providing valuable and informed perspectives. Participants were required to have a minimum of five years of experience in roles related to manufacturing, with a focus on smart and lean initiatives. The qualifications ensured that respondents possessed in-depth knowledge and practical insights into the challenges and opportunities associated with the integration of smart and lean manufacturing principles from a sustainability standpoint.

3.3. Data Collection

Data collection for this study involved a questionnaire with sample company experts to gather quantitative evaluations and obtain a comprehensive understanding of the research questions. The conduction of the questionnaire aimed to provide a robust dataset for the analysis of the integration of smart and lean manufacturing practices with a sustainability perspective.

4. Proposed Model

This conceptual model evaluates the relationship between the maturity of smart and lean tools and their economic, social, and environmental contributions to sustainability. The decision-maker determines a correlation rating of 1 to 5 between the dimensions of sustainability and smart and lean tools. A smart or lean tool's current maturity level indicates a gap that needs to be filled. To understand the potential impact of bridging this gap on sustainability, we multiply the relational values for each dimension by the gap value and sum them up. The resulting prioritization score indicates a smart or lean tool's significance and guides us to develop a roadmap for its implementation. Next, the steps of computing the smart and lean tools' priority score for road mapping are summarized in the present sub-section:

Step 1. Establishing the smart and lean tools' sustainability contributions: The computations start by determining the relationship between smart and lean tools and their economic, social, and environmental contributions to sustainability. The decision-maker rates these correlations on a scale of 5, where 1 indicates a weak relationship, and 5 indicates a strong relationship. Each dimension is calculated by averaging a set of indicators. The indicators are presented in Table 2.

Table 2. Indicators of sustainability dimensions

Sustainability Dimension	Indicators
Environmental	A1. Waste A2. Pollution A3. Emission A4. Land use A5. Energy use A6. Natural resource use A7. Reuse A8. Recycling
Economic	B1. Cost B2. MLT B3. OEE B4. Inventory turnover B5. Facility space use B6. Damage and loss B7. Stock-exchange value B8. Sales revenue
Social	C1. Social responsibility C2. Perks and bonuses C3. Positive work environment C4. Occupational health and safety C5. Career development C6. Job satisfaction C7. Job security C8. Flexible work schedule

Step 2. Evaluating the smart and lean tools' maturity: The smart and lean tools' maturity level is assessed by taking the geometric mean of its dimension scores (asset/tool status, application status, and adoption status). The maturity score indicates the degree of tools and how they are appraised regarding smartness and lean maturity.

Step 3. Calculating the contribution gap: The contribution gap is determined by subtracting the current maturity level from the ideal level which equals 5 on a scale of 1 to 5. The methodological framework highlights the importance of bridging the gap between the current tool maturity and the desired level. A higher gap score means higher priority since a higher score indicates that a more significant gap exists between the desired and target levels.

Step 4. Analyzing the impact on sustainability: To understand the potential impact of closing the contribution gap on sustainability, the relational values (correlation ratings) for each dimension (economic, social, and environmental) are multiplied by the contribution gap. For each dimension of sustainability, we took the weight equal and then multiplied by the gap. However, if the decision maker wishes, he or she can weigh the three dimensions separately such that the sum becomes 1 and then multiply the relation values by weights and the gap as: (individual weight of subdimension of sustainability) * (relation values) * (gap).

Step 5. Deriving the priority score: The prioritization score is obtained by summing up the products of the relational values and the contribution gap for each sustainability dimension. This score indicates a smart or lean tool's significance and potential contribution to sustainability.

Step 6. Developing a roadmap: With a prioritization score, the smart and lean tools are given priority in the roadmap for implementation. This roadmap will guide firms on incorporating smart and lean tools with the potential to positively impact sustainability, offering both a measurement and a path to future development.

In the application of the proposed model, data was collected from a leading automobile spare parts manufacturing company, referred to as "Auto Parts Innovate" for confidentiality. Due to the sensitive nature of the industry and company policies, specific details regarding the location, size, and exact processes of AutoParts Innovate have been intentionally distorted to ensure the privacy and security of the organization. AutoParts Innovate, founded in 2005 and headquartered in Turkey, is a prominent player in the automobile spare parts manufacturing industry. Specializing in the production of high-quality components, the company offers a diverse range of products, including engine components like pistons and camshafts, chassis parts such as suspension systems and brake components, electrical components like alternators and starters, body and interior parts including bumpers and mirrors, and transmission parts like clutches and gearboxes. Renowned for its commitment to innovation, Auto Parts Innovate integrates cutting-edge technology into its manufacturing processes and invests significantly in research and development to maintain a competitive edge. The company places a strong emphasis on quality assurance, subjecting all products to rigorous testing to ensure durability and compliance with safety standards. With a global presence and distribution networks reaching key markets worldwide, Auto Parts Innovate serves the needs of various automobile manufacturers and repair facilities. Additionally, the company prioritizes environmental responsibility through eco-friendly practices, and it actively engages in corporate social responsibility initiatives, contributing to local communities and supporting causes related to education, healthcare, and environmental conservation.

Furthermore, it is important to note that the data presented in Table 3 has been intentionally distorted and altered to comply with the company's policies and protect sensitive information. Table 3 provides a case study example to illustrate the application of the proposed model. For the sake of simplicity and adherence to the company's policies, we have obscured specific details and distorted data. This anonymized example serves to demonstrate the practical application of the model within an industrial setting while respecting the privacy and confidentiality of the involved company. The results indicate that simulation ranks as the top priority for road mapping with a prioritization score of 35.578. Following closely, Heijunka secures the second-highest prioritization score of 30.000, and additive manufacturing takes the third position with a prioritization score of 27.502. Figure 2 illustrates the methodological steps for the proposed model.

Figure 2. The methodological steps for the proposed method

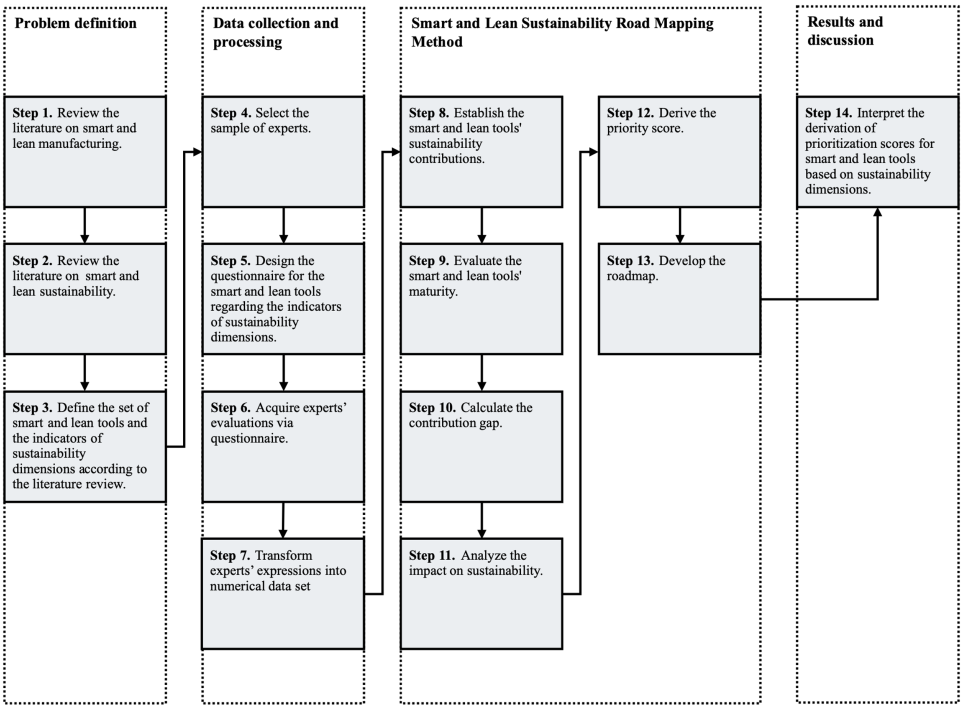


Table 3. Anonymous example

	Environmental Sustainability Contribution Score	Economic Sustainability Contribution Score	Social Sustainability Contribution Score	Component Maturity	Gap	Action Prominence for Environmental Dimension	Action Prominence for Economic Dimension	Action Prominence for Social Dimension	Tool Action Prominence Score for Road Map	Road Map Priority Rank
Artificial Intelligence	3.000	3.000	4.000	2.621	2.379	7.138	7.138	9.517	23.793	5
Augmented Reality	3.000	3.000	3.000	4.000	1.000	3.000	3.000	3.000	9.000	20
Cloud Computing	4.000	4.000	2.000	2.621	2.379	9.517	9.517	4.759	23.793	5
Cyber Security	4.000	5.000	5.000	3.634	1.366	5.463	6.829	6.829	19.121	8
Blockchain	2.000	4.000	3.000	3.000	2.000	4.000	8.000	6.000	18.000	11
System Integration	2.000	3.000	3.000	2.621	2.379	4.759	7.138	7.138	19.034	10
Internet of Things	3.000	2.000	2.000	3.302	1.698	5.094	3.396	3.396	11.887	18
Digital Twin	3.000	4.000	3.000	2.621	2.379	7.138	9.517	7.138	23.793	5
Simulation	3.000	3.000	4.000	1.442	3.558	10.673	10.673	14.231	35.578	**1**
Big Data Analytics	3.000	3.000	3.000	2.080	2.920	8.760	8.760	8.760	26.279	4
Autonomous Robots	3.000	4.000	2.000	3.420	1.580	4.740	6.320	3.160	14.220	15
Additive Manufacturing	5.000	4.000	4.000	2.884	2.116	10.578	8.462	8.462	27.502	**3**
Andon	3.000	4.000	3.000	3.302	1.698	5.094	6.792	5.094	16.981	12
Gemba	4.000	3.000	3.000	2.621	2.379	9.517	7.138	7.138	23.793	5
Poka Yoke	3.000	3.000	3.000	3.000	2.000	6.000	6.000	6.000	18.000	11
Value Stream Mapping	3.000	4.000	3.000	2.884	2.116	6.347	8.462	6.347	21.155	7
5 Whys	3.000	2.000	3.000	3.634	1.366	4.097	2.732	4.097	10.926	19
Takt Time	2.000	4.000	3.000	3.302	1.698	3.396	6.792	5.094	15.283	13
Genchi Genbutsu	3.000	3.000	3.000	2.884	2.116	6.347	6.347	6.347	19.040	9
Kanban	3.000	3.000	3.000	2.520	2.480	7.440	7.440	7.440	22.321	6
Hoshin Kanri	3.000	3.000	3.000	4.000	1.000	3.000	3.000	3.000	9.000	20
SMED	3.000	4.000	2.000	3.634	1.366	4.097	5.463	2.732	12.292	17
TPM	4.000	4.000	4.000	3.915	1.085	4.341	4.341	4.341	13.022	16
Heijunka	3.000	4.000	3.000	2.000	3.000	9.000	12.000	9.000	30.000	**2**

5. Conclusions and Discussions

The integration of sustainable lean principles with smart-lean tools has the potential to revolutionize manufacturing operations and drive significant improvements in productivity, efficiency, and sustainability. This paper has explored the concept of smart-lean manufacturing readiness and maturity from a sustainability perspective, highlighting the key factors and considerations for successful implementation. By combining sustainable lean principles, which focus on eliminating waste, reducing environmental impact, and promoting social responsibility, with smart-lean tools, such as advanced analytics, automation, and Internet of Things (IoT) technologies, organizations can achieve enhanced operational excellence and competitive advantage. This integration enables real-time data collection, analysis, and decision-making, leading to improved process optimization, resource utilization, and overall performance.

The paper has discussed the importance of organizational readiness for smart-lean manufacturing, emphasizing the need for leadership commitment, and employee engagement. It has also highlighted the significance of technology infrastructure, data governance, and cybersecurity measures to successfully deploy and utilize smart-lean tools. In summary, combining sustainable lean principles with smart lean tools presents a transformative opportunity for the manufacturing industry. By embracing this integrated approach, organizations can enhance their competitiveness, achieve environmental sustainability goals, and contribute to social well-being.

The integration of sustainable lean principles with smart-lean tools holds immense potential for revolutionizing manufacturing operations and fostering substantial improvements in productivity, efficiency, and sustainability. Drawing on insights from the studies conducted by Benkhati et al. (2023), Dahmani et al. (2021), Shahin et al. (2020), and Treviño-Elizondo et al. (2023), this paper has delved into the concept of smart-lean manufacturing readiness and maturity through a sustainability lens. It has underscored the critical factors and considerations essential for the successful implementation of this integrated approach.

The synergy of sustainable lean principles, which center on waste elimination, reduced environmental impact, and social responsibility, with smart-lean tools, encompassing advanced analytics, automation, and Internet of Things (IoT) technologies, opens avenues for organizations to attain heightened operational excellence and competitive advantage (Benkhati et al., 2023; Dahmani et al., 2021; Shahin et al., 2020). The amalgamation facilitates real-time data collection, analysis, and decision-making, thereby fostering improved process optimization, resource utilization, and overall performance.

Throughout this exploration, the paper has emphasized the pivotal role of organizational readiness in smart-lean manufacturing. Leadership commitment, employee engagement, robust technology infrastructure, data governance, and cybersecurity measures have been identified as key prerequisites for the successful deployment and utilization of smart-lean tools. This aligns with the findings of Treviño-Elizondo et al. (2023), who highlight the importance of organizational maturity in becoming a smart organization.

The transformative opportunity presented by combining sustainable lean principles with smart lean tools cannot be overstated. The studies by Benkhati et al. (2023), Dahmani et al. (2021), Shahin et al. (2020), Treviño-Elizondo et al. (2023), Akbal and Doğan (2023), Li (2019), Mahmood and Montagna (2013), and Tripathi et al. (2023) collectively underscore the potential of this integrated approach to enhance competitiveness, achieve environmental sustainability goals, and contribute to social well-being. As organizations in the manufacturing industry embrace this integrated model, they position themselves not only for operational excellence but also as responsible contributors to a sustainable and socially conscious future.

6. Limitations and Future Research Directions

Additionally, in considering future avenues of exploration, it is recommended that researchers delve into industry-specific applications, conduct longitudinal studies on implementation, explore emerging technologies, undertake global comparative studies, employ quantitative analysis of sustainability impact, conduct in-depth case studies, and assess employee perspectives. These recommendations aim to contribute to the evolving field of sustainable smart-lean manufacturing in the context of Industry 4.0.

We acknowledge several limitations in our study. First, our research is primarily focused on the manufacturing industry, limiting the direct applicability of the proposed model to other sectors. The generalization of findings should be approached cautiously, considering the specificities of different organizational contexts. Furthermore, the model's applicability relies on existing literature and conceptual analysis, lacking empirical validation from primary data collection in manufacturing organizations. The dynamic nature of smart manufacturing technologies poses a challenge, requiring periodic updates to incorporate emerging advancements. Additionally, while our model encompasses economic, social, and environmental dimensions, the specific sustainability metrics may need customization based on industry and organizational factors. These limitations highlight areas for future research to enhance the robustness and practicality of the proposed model.

Peer Review: Externally peer-reviewed.

Conflict of Interest: Authors declared no conflict of interest.

Financial Disclosure: Authors declared no financial support.

Author Contributions: Conception/Design of Study- T.P., M.A.G.; Data Acquisition- M.A.G.; Data Analysis/ Interpretation- T.P., M.A.G., S.D.; Drafting Manuscript- S.D., M.A.G.; Critical Revision of Manuscript- T.P.; Final Approval and Accountability- T.P., M.A.G., S.D.

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How cite this article

Gündüz, M.A., Demir, S., & Paksoy, T. (2024). Road-mapping for smart and lean tools with a sustainability perspective: A new model proposal. *Journal of Transportation and Logistics*, XX-XX. https://doi.org/10.26650/JTL.2024.1329972

Appendix

Table 1. Appendix A. Questionnaire of Digital Transformation Maturity from a Sustainability Perspective

Digital Tool	Asset/tool status	Application Status	Adoption Status	Geometric Mean	Gap
Artificial Intelligence	3	3	2	2.621	2.379
Augmented Reality	4	4	4	4.000	1.000
Cloud Computing	3	3	2	2.621	2.379
Cyber Security	4	4	3	3.634	1.366
Blockchain	3	3	3	3.000	2.000
System Integration	3	3	2	2.621	2.379
Internet of Things	4	3	3	3.302	1.698
Digital Twin	3	3	2	2.621	2.379
Simulation	3	1	1	1.442	3.558
Big Data Analytics	3	3	1	2.080	2.920
Autonomous Robots	5	4	2	3.420	1.580
Additive Manufacturing	4	3	2	2.884	2.116

Digital Tool	Environmental Sustainability								Economic Sustainability								Social Sustainability							
	A1	A2	A3	A4	A5	A6	A7	A8	B1	B2	B3	B4	B5	B6	B7	B8	C1	C2	C3	C4	C5	C6	C7	C8
Artificial Intelligence	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4
Augmented Reality	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Cloud Computing	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2
Cyber Security	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Blockchain	2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3
System Integration	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Internet of Things	3	3	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Digital Twin	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3
Simulation	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4
Big Data Analytics	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Autonomous Robots	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2
Additive Manufacturing	5	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	A1. Waste A2. Pollution A3. Emission A4. Land use A5. Energy use A6. Natural resource use A7. Reuse A8. Recycling								B1. Cost B2. MLT B3. OEE B4. Inventory turnover B5. Facility space use B6. Damage and loss B7. Stock-exchange value B8. Sales revenue								C1. Social responsibility C2. Perks and bonuses C3. Positive work environment C4. Occupational health and safety C5. Career development C6. Job satisfaction C7. Job security C8. Flexible work schedule							

0=N/A 1=Very Low 2=Low 3=Moderate 4=High 5=Very High

Table 2. Appendix B. Questionnaire of Lean Manufacturing Maturity from a Sustainability Perspective

Lean Tool	Asset/tool status	Application Status	Adoption Status	Geometric Mean	Gap
Andon	4	3	3	3.302	1.698
Gemba	3	3	2	2.621	2.379
Poka Yoke	3	3	3	3.000	2.000
Value Stream Mapping	4	3	2	2.884	2.116
5 Whys	4	4	3	3.634	1.366
Takt Time	4	3	3	3.302	1.698
Genchi Genbutsu	4	3	2	2.884	2.116
Kanban	4	2	2	2.520	2.480
Hoshin Kanri	4	4	4	4.000	1.000
SMED	4	4	3	3.634	1.366
TPM	5	4	3	3.915	1.085
Heijunka	4	2	1	2.000	3.000

Lean Tool	Environmental Sustainability								Economic Sustainability								Social Sustainability							
	A1	A2	A3	A4	A5	A6	A7	A8	B1	B2	B3	B4	B5	B6	B7	B8	C1	C2	C3	C4	C5	C6	C7	C8
Andon	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3
Gemba	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Poka Yoke	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Value Stream Mapping	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3
5 Whys	3	3	3	3	3	3	3	3	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3
Takt Time	2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3
Genchi Genbutsu	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Kanban	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Hoshin Kanri	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
SMED	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2
TPM	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Heijunka	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3
	A1. Waste A2. Pollution A3. Emission A4. Land use A5. Energy use A6. Natural resource use A7. Reuse A8. Recycling								B1. Cost B2. MLT B3. OEE B4. Inventory turnover B5. Facility space use B6. Damage and loss B7. Stock-exchange value B8. Sales revenue								C1. Social responsibility C2. Perks and bonuses C3. Positive work environment C4. Occupational health and safety C5. Career development C6. Job satisfaction C7. Job security C8. Flexible work schedule							

0=N/A 1=Very Low 2=Low 3=Moderate 4=High 5=Very High