Achieving tractable and reliable agriculture supply chain operations through Industry 4.0 tools to support Lean Six Sigma application

International Journal of Industrial Engineering and Operations Management

Received 29 May 2024
Revised 19 July 2024
Accepted 12 August 2024

Fatma Betül Yeni
Department of Industrial Engineering, Karadeniz Technical University, Trabzon, Turkey
Beren Gürsoy Yılmaz
Department of Industrial Engineering, Karadeniz Technical University, Trabzon, Turkey and
Department of Industrial and System Engineering, University of Florida, Gainesville, Florida, USA
Behice Meltem Kayhan and Gökhan Özçelik
Department of Industrial Engineering, Karadeniz Technical University, Trabzon, Turkey, and
Ömer Faruk Yılmaz
Department of Industrial Engineering, Karadeniz Technical University, Trabzon, Turkey and
Department of Industrial and System Engineering, University of Florida, Gainesville, Florida, USA

Abstract

Purpose – This study aims to address challenges related to long lead time within a hazelnut company, primarily attributed to product quality issues. The purpose is to propose an integrated lean-based methodology incorporating a continuous improvement cycle, drawing on Lean Six Sigma (LSS) and Industry 4.0 applications.

Design/methodology/approach – The research adopts a systematic approach, commencing with a current state analysis using VSM and fishbone analysis to identify underlying problems causing long lead time. A Pareto analysis categorizes these problems, distinguishing between supplier-related issues and deficiencies in lean applications. Lean tools are initially implemented, followed by a future state VSM. Supplier-related issues are then addressed, employing root cause analyses and Industry 4.0-based countermeasures, including a proposed supplier selection model.

Findings – The study reveals that, despite initial lean implementations, lead times remain high. Addressing supplier-related issues, particularly through the proposed supplier selection model, significantly reduces the number of suppliers and contributes to lead time reduction. Industry 4.0-based countermeasures ensure traceability and strengthen supplier relationships.

Declaration of interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

International Journal of Industrial Engineering and Operations Management
Emerald Publishing Limited
e-ISSN: 2690-6104
p-ISSN: 2690-6090
DOI 10.1108/IJIEOM-05-2024-0029

Originality/value – This research introduces a comprehensive LSS methodology, practically demonstrating the application of various tools and providing managerial insights for practitioners and policymakers. The study contributes theoretically by addressing challenges comprehensively, practically by showcasing tool applications and managerially by offering guidance for system performance enhancement.

Keywords Lean Six Sigma, Industry 4.0, Axiomatic design, Supplier selection, Food industry

Paper type Case study

1. Introduction

Lean manufacturing is a production system developed to eliminate the seven types of waste through continuous improvement, with a primary focus on delivering customer-defined value (Wilson, 2010). Implementing lean manufacturing involves waste reduction in various business domains, whether manufacturing or services, and adherence to the fundamental principles of lean, as stated by Liker (2004). Furthermore, lean manufacturing necessitates the organization-wide application of lean tools, aiming to minimize unused human mind/potential and skills (Yılmaz *et al.*, 2023; Pakdil and Leonard, 2014). Given that lean implementation is an ongoing process, active participation of all stakeholders in the organization is critical for sustaining the continuous improvement cycle.

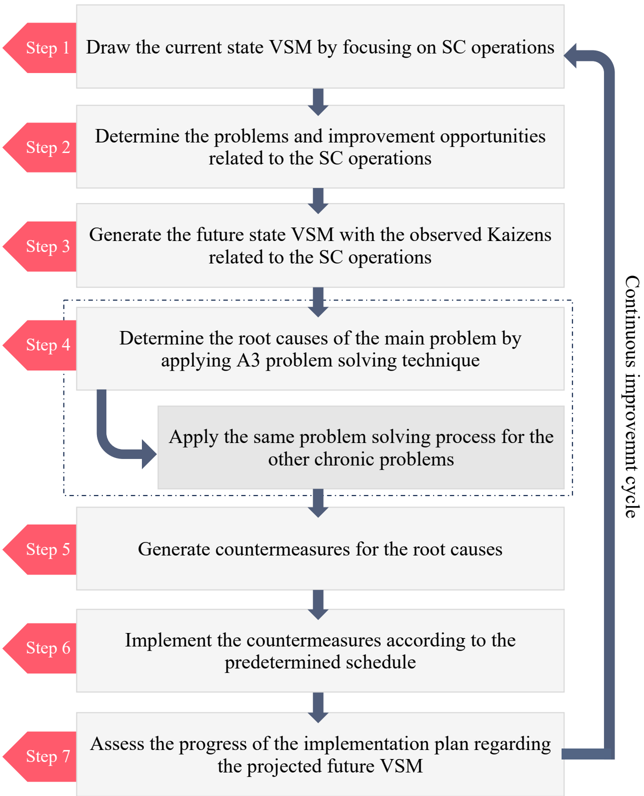
On the other hand, Six Sigma is a quality management methodology that focuses on enhancing quality by reducing process variation through the use of standardized tools (Bilgin Turna, 2023). These two distinct approaches are often combined under the umbrella of operational excellence, creating what is known as Lean Six Sigma (LSS). LSS is applied when there is a pressing need for continuous improvement through waste reduction and improved quality (Pakdil *et al.*, 2020). When LSS is effectively implemented, it results in a continuous and smooth flow through processes, reduced variability, and the ability to identify and address problem sources through Kaizen activities over the planning horizon. Thus motivated, this combined methodology has been extensively and efficiently applied in manufacturing enterprises over the past decades to enhance customer satisfaction levels (Guarraia *et al.*, 2008; Prashar, 2018; Thomas *et al.*, 2016; Rane *et al.*, 2023).

Sustaining efficient manufacturing operations begins with establishing a reliable supply chain structure for an organization that adheres to lean manufacturing principles in combination with the Six Sigma approach, or in other words, employing LSS (Yılmaz and Pardalos, 2017). The rationale behind this lies in the fact that supply chain operations directly impact product quality, process variation, and ultimately, customer satisfaction. Therefore, in order to fully utilize the benefits of LSS implementation, it is crucial to consider supply chain operations during LSS application in manufacturing enterprises (Praharsi *et al.*, 2021). By doing so, reduced variability, fewer defects, shorter lead times, increased efficiency gains, and higher product quality can be achieved. Achieving this integration of supply chain processes with LSS within the operational excellence framework is a challenging yet crucial task.

To achieve effective outcomes through the integration of supply chain operations with LSS tools, Industry 4.0 emerges as a new paradigm for enterprises. Industry 4.0 transforms the way companies carry out their operations by equipping factories and supply chains with advanced sensors and fully adapted software to monitor real-time data for effective decision-making (Pozzi *et al.*, 2023). In recent years, Industry 4.0 has been recognized as a strategic model for realizing improvement opportunities in terms of overall cost, production efficiency, quality, and lead times (Malik *et al.*, 2023). As Industry 4.0 effectively incorporates various new technologies such as the Internet of Things (IoT), cloud computing, and artificial intelligence, it can also be employed to integrate supply chain operations with LSS techniques, as explored in this study (Chiarini and Kumar, 2021).

In this study, a case is examined from a hazelnut company where lean manufacturing principles are combined with the Six Sigma quality management approach under the LSS operational excellence methodology. The company faces extended lead times in responding to customer requests due to ineffective supply chain operations, which can be traced back to its suppliers. Despite implementing the LSS methodology within its production process, the company has experienced product returns from customers due to low product quality, directly impacting lead times. Hence, ensuring real-time visibility of operations conducted by suppliers becomes imperative for effective decision-making and quality improvement by reducing variability, not only in the production process but also within the supply chain.

To address this challenge, the objective of this study is to evaluate the impact of LSS implementation on system performance from various perspectives, identify the primary reasons for high lead time, and propose actions to mitigate it. This study also explores how LSS implementation can support the quality improvement process and develop effective countermeasures to alleviate high lead time. Consequently, the key LSS tools that contribute significantly to enhancing the performance of the production system will be determined. A comprehensive methodology, as depicted in Figure 1, is proposed to illustrate how LSS methodology and supply chain operations can be integrated through the Industry 4.0 concept, with a specific focus on reducing waste, defects, and process variations through a continuous improvement cycle and standardization. In the application of this methodology, we consider a set of critical metrics for hazelnuts and utilize statistical quality control tools to visualize potential shifts through real-time data collected from suppliers.



Source(s): Figure created by authors

Figure 1. The procedural steps of the proposed methodology

In this study, the following research questions are considered to reveal important managerial insights from this research.

RQ1. What is the impact of LSS implementation on system performance and the quality improvement process from various perspectives?

RQ2. What are the primary reasons for high lead time, and how can effective countermeasures be implemented to alleviate high lead time?

RQ3. Which key LSS tools contribute significantly to enhancing the performance of the production system?

The rest of the study is organized as follows: In Section 2, a comprehensive literature review is conducted, examining studies that integrate Industry 4.0 applications with lean techniques from a methodological perspective. The information on the real case application is provided in Section 3. Lean Six Sigma applications and supplier improvement initiatives conducted within the framework of the developed methodology are detailed in Sections 4 and 5, respectively. While the detailed discussions and managerial insights are provided in Section 6, the results and evaluations are presented in Section 7.

2. Literature review

Nowadays, implementing lean manufacturing systems has become essential for organizations. Many companies adapt lean principles to reduce waste, improve processes quality, transition to a one-piece flow, and enhance their competitive advantages (Chugani *et al.*, 2017). Numerous studies in the literature emphasize the philosophy of the lean manufacturing system and its beneficial impact on enterprises (Mostafa *et al.*, 2013; Neves *et al.*, 2018). On the other hand, the concept of LSS, which aims to improve quality processes, has gained prominence in recent lean applications (Patel and Patel, 2021). Scheller *et al.* (2021) conducted a situational analysis by implementing LSS in a manufacturing company. They demonstrated that LSS reduces variability in quality processes and improves the feasibility of lean practices.

The application of LSS in the food industry is also particularly noteworthy due to the sector's unique challenges, such as stringent safety standards, high perishability, and complex supply chains. By adopting LSS methodologies, food industry enterprises can significantly improve process efficiency, and ensure product quality and safety (Costa *et al.*, 2018; McDermott *et al.*, 2024). For instance, Costa *et al.* (2021) identified the best LSS practices for effectively managing operations in the food industry. Azalanzazllay *et al.* (2022) proposed a multi-method qualitative approach to identify LSS readiness dimensions and their attributes. By providing a structured framework, organizations can evaluate and enhance their preparedness for LSS adoption in the food manufacturing industry. Widiwati *et al.* (2024) examined the application of the DMAIC and LSS approaches to reduce waste in the production process of a food manufacturing industry. They demonstrated how these methodologies could systematically identify inefficiencies, implement corrective measures, and sustain improvements over time.

Notwithstanding companies can reduce waste and enhance various performance dimensions through lean principles, completing the lean transformation remains a significant challenge for organizations (Buer *et al.*, 2018). To address this challenge, lean practices, particularly LSS, are increasingly integrating with Industry 4.0 technologies, which offer substantial benefits in terms of traceability and management during the transition to lean manufacturing (Mayr *et al.*, 2018).

In recent years, numerous studies have examined the relationship between Industry 4.0 and lean tools (Sony, 2018; Rossini *et al.*, 2019; Rosin *et al.*, 2020). To demonstrate the position of this subject in the literature, searches are conducted in the "title, abstract, keywords" section of the Scopus database using the terms "Industry 4.0", "Lean management", and

"Lean Six Sigma (LSS)". Following this, essential lean techniques such as "kaizen", "six sigma", and "value stream mapping" are searched in combination with "Industry 4.0 and Lean management" within the same database section. Additionally, Industry 4.0 technologies like "smart machines", "image processing", and "Internet of Things" are also searched in conjunction with these terms. From the 137 studies identified through the search, the relevant studies are categorized in Table 1 according to their methodologies, the Industry 4.0 and lean techniques employed, and their respective contributions to the literature.

Most literature reviews emphasize the insufficient attention given to the integration of LSS application and Industry 4.0 (Taghavi and Beauregard, 2020; Pagliosa *et al.*, 2021; Lobo Mesquita *et al.*, 2022; Rossini *et al.*, 2023). While some studies combine lean techniques and Industry 4.0 applications in the manufacturing industry, there are limited instances of LSS implementation (Kamble *et al.*, 2020; Narula *et al.*, 2023). For instance, Ahmed *et al.* (2020), demonstrated three simulations compare within a LSS project. Jayaram (2016), designed a supply chain management model utilizing Industry 4.0 techniques to minimize waste and enhance quality. Ahmed *et al.* (2023), proposed a framework that combines LSS and simulation applications to enhance efficiency and reduce waste in an LED manufacturing company. Rathi *et al.* (2024) provided guidelines for enterprises to integrate the LSS approach with blockchain technology. They present a model aimed at resolving real-time challenges in information sharing, transparency, and traceability throughout every stage of an LSS project. Vazquez Hernandez and Elizondo Rojas (2024) suggested a methodology that incorporates LSS and data mining processes. This methodology aimed to improve spare parts inventory management policies following the COVID-19 pandemic. Kumar *et al.* (2024) developed a model to determine and examine the critical success factors for integrating LSS implementation with Industry 4.0. Their model offers a framework that ensures efficient management within these two areas for Indian manufacturing industries. Alsaadi (2024) investigated the challenges of integrating LSS practices with Industry 4.0 technologies in enterprises and recommended strategies to mitigate these barriers.

Upon examination of the literature, it becomes apparent that there is a significant gap regarding the connection between LSS implementation and Industry 4.0 in the food industry. Despite the transformative potential of both concepts in the manufacturing industry, their integration remains largely unexplored in the food industry. In this regard, this paper aims to address this gap by presenting a comprehensive methodology for integrating LSS implementation and supply chain operations within the framework of the Industry 4.0 concept. This approach is demonstrated through a real case study of a hazelnut company.

3. The implementation of the proposed methodology through a real case study

In this study, a case from a hazelnut company in Turkey is considered. The application of the LSS methodology within the context of operational excellence has already been initiated by the company. In this regard, the current value stream map (VSM) has been created to visualize the current situation of the production system, as shown in Figure 2. VSM, a widely used lean tool, serves the purpose of visual control, also known in Japanese as Mieruka. The existing academic literature features a numerous VSM applications, including supply chain mapping by Yılmaz *et al.* (2023) and Mubarik *et al.* (2023), visualization of industrial waste flows by Schoeman *et al.* (2020), stock level visualization by Midilli and Elevli (2020), and new product development projects by Baysan *et al.* (2017), Yilmaz *et al.* (2020), and Durmusoglu and Aglan (2024). Moreover, VSM has been extensively applied in various manufacturing systems, as demonstrated by McDonald *et al.* (2002), Abdulmalek and Rajgopal (2007), Rahani and Al-Ashraf (2012), Mudgal *et al.* (2020), Bega *et al.* (2023), and Wang *et al.* (2024).

Three different types of products are produced and packaged for customers in the plant: (1) roasted hazelnut, (2) diced hazelnut, and (3) hazelnut puree. Since all these product types

Table 1.
The relevant studies in the existing literature

Authors	Research type	Contribution	Industry 4.0 technologies	Lean techniques	Methodology
Sanders *et al.* (2016)	Empirical	Identifying the specific aspects of Industry 4.0 that contribute to various dimensions of lean manufacturing	Internet of things, Smart machines, Monitoring, Machine learning, Cloud Computing	JIT, SMED, Pull Production, TPM, Continuous Flow	Reviewing the literature and determining appropriate solution principles
Jayaram (2016)	Conceptual	Designing a supply chain management model utilizing Industry 4.0 techniques to minimize waste and enhance quality	Internet of things, Smart machines, Monitoring, Cloud Computing	Lean Six Sigma	Logistic model
Wagner *et al.* (2017)	Conceptual	Developing a framework to assess the impact of Industry 4.0 on lean production systems for industrial companies	Big Data, Internet of things, Cyber–physical System	5S, Kaizen, JIT, Jidoka, Heijunka, Standardization, Pull System	Statistic research and design framework
Tortorella and Fettermann (2018)	Empirical	Exploring the correlation between lean production practices and the adoption of Industry 4.0 in Brazilian manufacturing companies	Big Data, Cloud Computing, Internet of Things, Simulation	JIT, Pull System, One piece flow, Supplier feedback	Questionnaire development and data collection, clustering of data statistical analysis
Varela *et al.* (2019)	Empirical	Suggesting a structural equation model for the quantitative measurement of the effects of Lean Manufacturing and Industry 4.0 on sustainability	Big Data, Cloud Computing, Digitalization, Autonomous Robots	Pull Production, Poka-Yoke, Jidoka	A questionnaire-based survey and statistical analysis
Rossini *et al.* (2019)	Empirical	Exploring the influence of the relation between the adoption of Industry 4.0 technologies and the implementation of lean production practices on the enhancement of operational performance in European manufacturing companies	Big Data, Cloud Computing, Digitalization, Artificial Intelligent, Augmented Reality, Cyber–physical System, Internet of Things, Simulation	VSM, Kaizen, Kanban, JIT, SMED, Poka-Yoke, Jidoka, TPM, Standardization, Continuous flow, PDCA, Hoshin Kanri	A questionnaire-based survey and statistical analysis
Ahmed *et al.* (2020)	Empirical	To demonstrate three simulations, compare within a Lean Six Sigma project	Simulation, Agent-based Model	Lean Six Sigma	Discrete-event simulation

(*continued*)

Authors	Research type	Contribution	Industry 4.0 technologies	Lean techniques	Methodology
Rosin *et al.* (2020)	Conceptual	Investigating the impact of Industry 4.0 principles on lean techniques while considering their effects in relation to capability levels	Cloud Computing, Big Data, Simulation, Autonomous Robots, System integration	JIT, Jidoka	Classification
Kamble *et al.* (2020)	Empirical	Investigating the effects of Industry 4.0 and lean manufacturing practices on sustainable organizational performance	Cloud Computing, Big Data, Internet of Things, Augmented Reality, Robotics System	Supplier Feedback, JIT, Pull systems, Continuous Flow, SMED, TPM	A questionnaire-based survey and statistical analysis
Taghavi and Beauregard (2020)	Literature Review	Identifying significant gaps in the association between lean and Industry 4.0. in the literature	Big Data, Cloud Computing, Digitalization, Artificial Intelligent, Augmented Reality, Cyber–physical System, Internet of Things, Simulation	VSM, Kaizen, Kanban, JIT, SMED, Poka-Yoke, Jidoka, TPM, Standardization, Continuous Flow, PDCA, Hoshin Kanri	Systematic literature review
Pagliosa *et al.* (2021)	Literature Review	Carrying out a literature review to define the relationships between Industry 4.0 and lean manufacturing	Cyber Physical System, Smart Factory, Internet of Things	VSM, Kaizen, Kanban, JIT, SMED, Poka-Yoke, Jidoka, TPM, Standardization, Continuous Flow, PDCA, Hoshin Kanri	Systematic literature review
Florescu and Barabas (2022)	Conceptual	Analyzing the compatibility of Lean tools and Industry 4.0 technologies to create a framework model for their development and integration in manufacturing systems	Big Data, Cloud Computing, Digital Twin, Artificial Intelligent, Augmented Reality, Cyber–physical System, Internet of Things	VSM, Kaizen, Kanban, JIT, SMED, Poka-Yoke, Jidoka, TPM	Framework model
Lobo Mesquita *et al.* (2022)	Literature Review	Establishing a framework for research endeavors that incorporate Industry 4.0, lean practices, and environmental sustainability	Big Data, Smart Machines, Artificial Intelligent, Augmented Reality, Internet of Things	JIT, TPM, VSM, Autonomation, 5S, Kanban	Systematic literature review

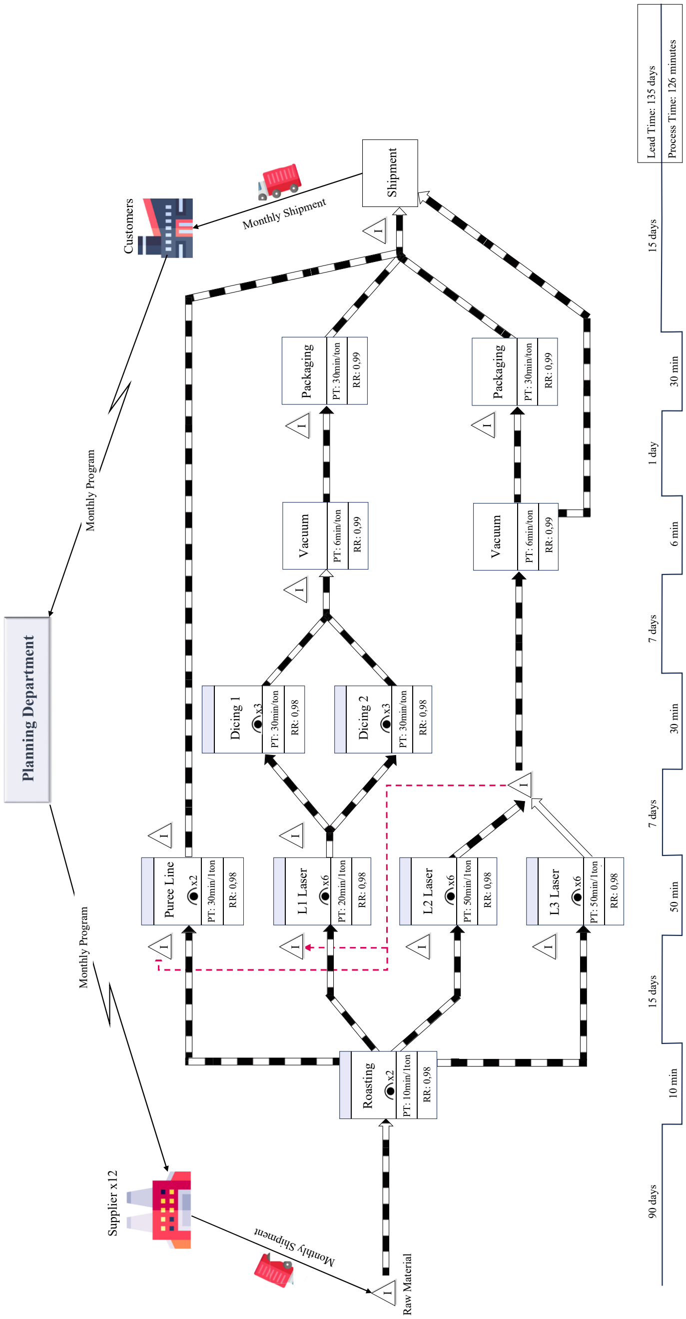
(*continued*)

Table 1.

Table 1.

Authors	Research type	Contribution	Industry 4.0 technologies	Lean techniques	Methodology
Ahmed *et al.* (2023)	Empirical	Proposing a framework that combines Lean Six Sigma and simulation applications to enhance efficiency and reduce waste in an LED manufacturing company	Simulation, Agent-based Model	Lean Six Sigma	DMAIC and DMADV
Narula *et al.* (2023)	Empirical	Introducing a conceptual model that illustrates the influence of Industry 4.0 technologies on lean tools	Internet of Things, Simulation, Big Data, Cloud Computing, Augmented Reality	VSM, Kaizen, Kanban, JIT, SMED, Poka-Yoke, Jidoka, TPM, Standardization, Continuous flow, PDCA, Hoshin Kanri	A questionnaire-based survey, Statistical analysis and BWM
Rossini *et al.* (2023)	Literature Review	Engaging in a literature review focused on the integration of Industry 4.0 and lean supply chain management	Smart machines, Digitalization, Internet of Things	JIT	Systematic literature review
Singhal *et al.* (2024)	Literature Review	Conducting a literature review on lean practices and TQM approaches for creating a sustainable supply chain within the context of Industry 4.0	Big Data, Internet of Things, Cloud Computing	JIT, TQM	Systematic literature review
Rathi *et al.* (2024)	Empirical	Providing guidelines for enterprises to integrate the LSS approach with blockchain technology	Blockchain	Lean Six Sigma	Literature Review and BLSS model
Kumar *et al.* (2024)	Empirical	Determining the critical success factors for integrating LSS implementation with Industry 4.0 in Indian manufacturing industry	Big Data, Internet of Things	Lean Six Sigma	Interpretive structural modeling and MICMAC
This study	Empirical	Integrating LSS implementation and supply chain operations within the framework of the Industry 4.0 concept	Smart machine, Image processing, Internet of things, Blockchain	Lean Six Sigma, VSM, 5S, Kaizen, A3 problem solving, CONWIP	ANP + Goal Programming, Axiomatic Design, Framework model

Note(s): JIT: Just-in-time, VSM: Value Stream Mapping, TPM: Total Productive Maintenance, PDCA: Plan-Do-Check-Act, SMED: Single-Minute Exchange of Die, DMAIC: Define-Measure-Analyze-Improve- Control, DMADV: Define- Measure- Analyze- Design- Verify, BWM: Best-Worst Method, ANP: Analytic Network Process, TQM: Total Quality Management, BLSS: Blockchain and Lean Six Sigma
Source(s): Table created by authors



Source(s): Figure created by authors

Figure 2.
The current VSM

undergo the same processes at certain production stages, they are considered as a product family, and a value stream map is designed to encompass all of them. Initially, all products undergo a roasting process before being separated according to their respective types. As illustrated in the figure, a push production control mechanism is implemented, and inventory levels at each stage are merely observed without being actively controlled. The red dotted line in the figure represents the feeding process, where semi-finished products after the L2 and L3 laser processes can supply both the Puree line and the L3 laser processes.

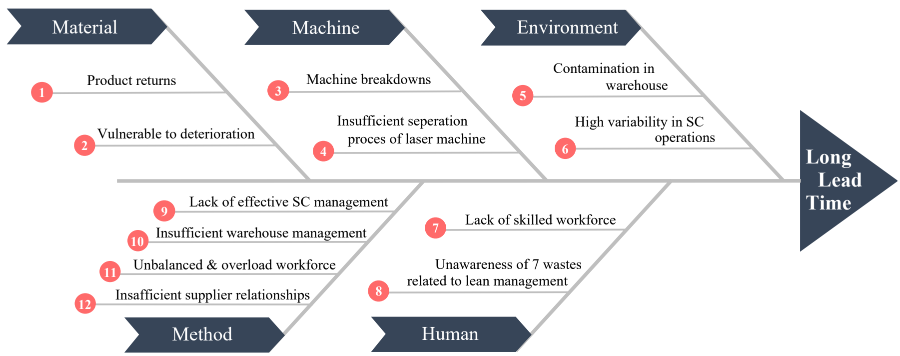
The total lead time, which represents the time taken to produce a new customer order, is currently 135 days. In contrast, the total process time is 126 min to produce a new order when the inventories of raw materials, semi-finished, and finished products are at minimum levels. The current value stream map shows that the lead time is significant and needs reduction. Additionally, there are several improvement opportunities to facilitate Kaizen activities, including implementing a pull production control mechanism and enhancing relationships with suppliers to improve overall product quality.

As observed in the current VSM, the long lead time poses a significant challenge for the company. While the primary issue appears to be the long lead time, it’s essential to recognize that there could be various underlying reasons for this challenge. To identify these potential problems, the Ishikawa Diagram, a problem-solving technique commonly employed in A3 studies, has been utilized. Through the application of this approach, 12 sub-problems, causing the long lead times, have been identified under the main headings of Material, Machine, Environment, Method, and Human, as illustrated in Figure 3.

A Pareto analysis has been conducted to prioritize these sub-problems, grouping them into four categories: supplier-related, lack of lean application, material-related, and machine-related. Figure 4 shows that five sub-problems are supplier-related, four are due to a lack of lean application, two are material-related, and one is machine-related. Notably, 80% of the issues stem from supplier-related problems and a lack of lean application. Therefore, the primary focus is on improving lean implementation, followed by addressing supplier-related issues.

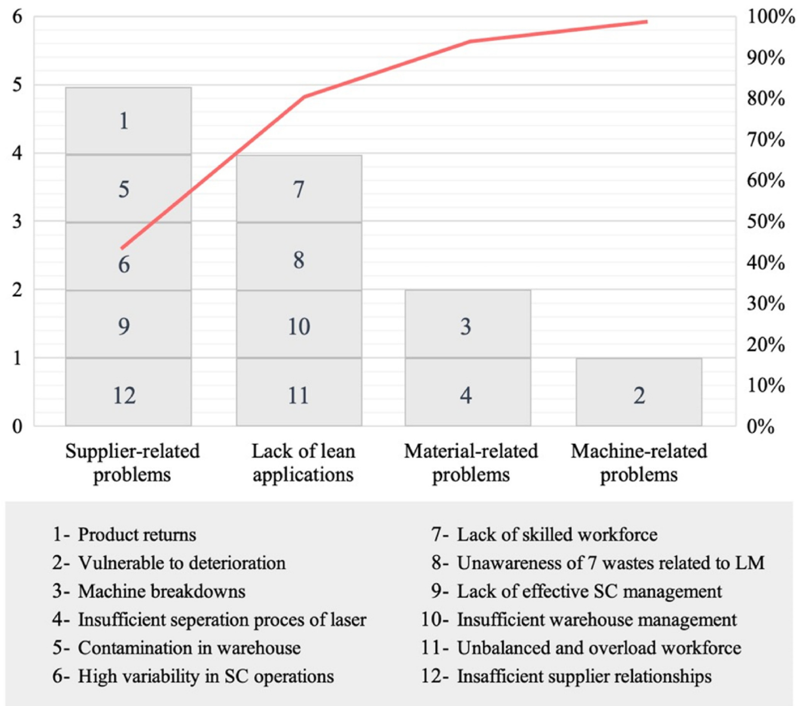
4. Lean Six Sigma applications

In this study, a case study is conducted on a hazelnut company that produces three different product types within the same facility. The initiation of LSS implementation at the facility aims to enhance system performance, specifically focusing on reducing lead time and improving various lean metrics. Subsequently, significant improvements have been achieved through the application of LSS tools. To illustrate the application process, examples of these



Source(s): Figure created by authors

Figure 3.
The Ishikawa diagram



Source(s): Figure created by authors

Figure 4.
Pareto analysis

tools are provided in the following sections. The implementation has resulted in a substantial reduction in lead time, along with additional improvements.

Nevertheless, recognizing that improvement opportunities extend beyond the confines of the focused facility, consideration is given to enhancing supplier quality. Motivated by this, a methodology is proposed within the broader context of integrating operational excellence and supply chain management. The 5S application (Sort, Straighten, Shine, Standardize, and Sustain) and the transformation to cellular manufacturing for one-piece flow have already been conducted. Some of the applications carried out within the scope of 5S and Occupational safety and health (OHS) are presented in Figure 5.

The A3 problem-solving technique has been used to facilitate group-based Kaizen activities. An Asakai area has been designed to visualize the daily data collected from the production system, and daily meetings are organized in this area (Figure 6). Statistical quality control tools are effectively employed both for problem-solving purposes and within the Asakai area.

It is also important to state that due to the confidentiality agreements with the company involved in this study, specific data and detailed outcomes from the statistical quality control tools implemented are not disclosed. This restriction is essential to protect sensitive proprietary information that is integral to the company's competitive position. While this limits the detail of empirical results that can be shared, the study still outlines the types of statistical tools employed and their general impact on quality control efforts, providing valuable insights into the application of these methodologies within the constraints of industry-specific data policies.

Emphasis has been placed on work standardization, resulting in the reduction of process variability. Inventory levels for raw materials are determined according to the continuous review inventory policy, and Kanbans are employed to control inventories within the facility

The state of the warehouse before 5s operation
(a)

The state of the warehouse after 5s operation
(b)

OHS and 5S activities in the facility
(c)

Source(s): Figure created by authors

Figure 5.
Some examples of 5S and OHS applications

Source(s): Figure created by authors

Figure 6.
Asakai area

through supermarkets. The pull production control mechanism has been applied, along with production leveling and smoothing (Heijunka) principles. In this regard, the CONWIP production control mechanism is preferred due to its applicability for the considered company. In the context of the never-ending process of continuous improvement, predetermined key performance indicators (KPIs) are *reviewed* weekly and monthly to assess the development in the production system over time. It has been observed that the implemented LSS methodology has improved the system's performance with respect to some performance metrics. Figure 7 visualize the implementation of the LSS methodology for some tools.

The future value stream map (FVSM), which outlines the expected state of the production system after completing the LSS implementations, has been crafted. The FVSM is depicted in Figure 7 and incorporates a hybrid push-pull production control mechanism known as CONWIP. With this mechanism, all production processes are systematically managed through Kanbans. Inventory levels are now actively controlled via supermarkets rather than merely observed. Additionally, a focus on the one-piece flow principle has highlighted that only the vacuum and packaging operations can be combined.

Upon the introduction of weekly production programs, shipments and replenishments are now conducted weekly rather than monthly. Complementing this approach, various LSS tools, including 5S, A3 problem-solving, and other Kaizens, aim to reduce lead time from 135 days to 67 days. Additionally, the total process time has been reduced from 126 to 115 min.

Nonetheless, the company still suffers from customers' negative feedback and product returns due to low quality, leading to high lead times for the relevant products. To address this issue, the A3 problem-solving tool has been utilized to determine the root cause of this main problem, as shown in Figure 1. Since customers base their return decisions on metrics such as Aflatoxin-B1, Aflatoxin-Total, Acidity, Moisture, and Sifter bottom/top, the company has focused on improving these metrics to enhance product quality and, consequently, customer service levels.

5. Supplier improvement

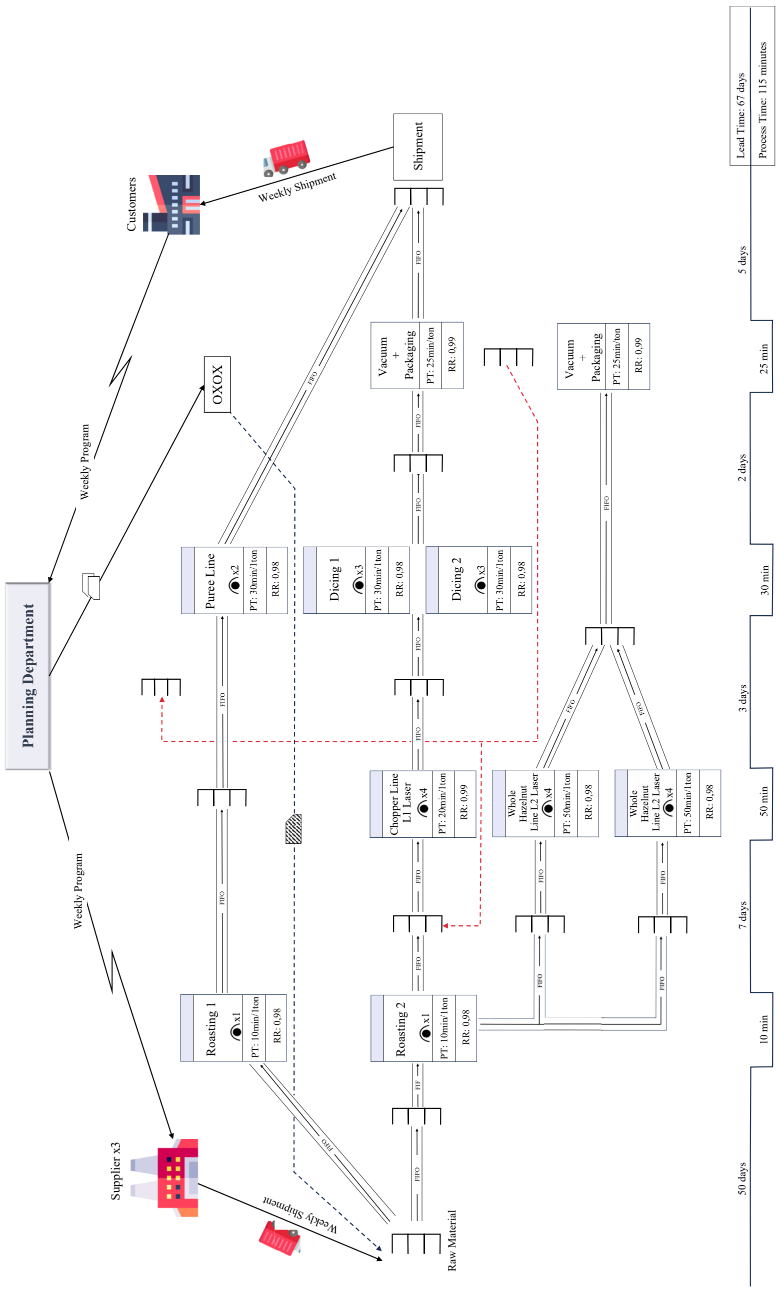
As previously stated, a substantial portion of the challenges contributing to the long lead times within the company are directly associated with suppliers. In this section, focusing on supplier-related fundamental issues, the root causes of these problems have been identified, and countermeasures have been developed to address these root causes. This analysis is presented in Figure 8.

The company currently maintains affiliations with 12 suppliers. This extensive supplier base deteriorates communication with suppliers, complicates the monitoring of supply processes, makes it challenging to track product quality, and consequently leads to an increase in product returns. Therefore, as the primary step to tackle these supplier-related challenges, supplier selection has been undertaken, reducing the number of suppliers to 3. Following this, countermeasures in the form of Industry 4.0-supported solution proposals have been introduced to address the root causes of each identified problem, and a road map has been developed for the implementation of Industry 4.0 based solutions using the methodology of Axiomatic Design (AD).

The Functional Requirements (FRs) determined as countermeasures for each root cause are presented in Figure 8 and outlined as follows: Assess environmental conditions automatically (FR1), Detect contamination sources (FR2), Monitor and control the process of the suppliers (FR3), Ensure transparency, compliance, and traceability of the supply processes (FR4), Predict aflatoxin, acidity, and moisture level of the product (FR5). The proposed methodology and the roadmap for their implementation are detailed in Section 5.2.

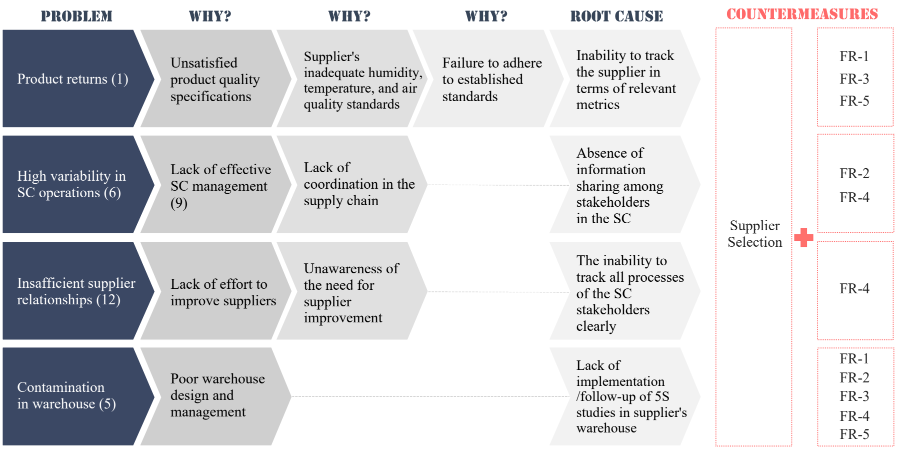
5.1 Supplier selection

Supplier selection is the initial countermeasure that will support and facilitate the applicability of Industry 4.0 technologies in the suppliers. As known, the lean perspective also recommends establishing robust relationships with a limited number of suppliers. In this



Source(s): Figure created by authors

Figure 7.
The future state VSM



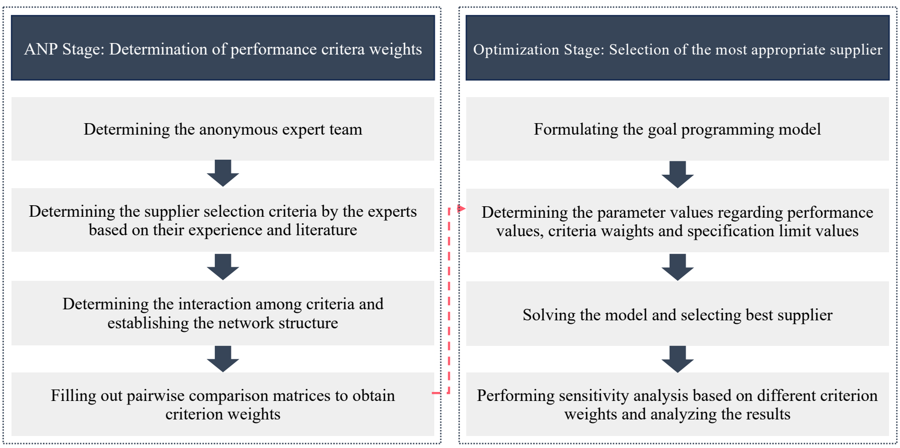
Source(s): Figure created by authors

Figure 8. Root cause analysis and countermeasures

context, the aim is not only to build strong relationships with fewer suppliers through supplier selection but also to ensure supplier traceability by employing Industry 4.0 technologies in the determined suppliers. To this end, a supplier selection model is proposed with the aim of selecting the top 3 suppliers from the company's existing 12 suppliers.

5.1.1 Supplier selection model. In this subsection, the proposed supplier selection model based on ANP (Analytic Network Process), and goal programming is presented. The flow diagram of the proposed supplier selection model is illustrated in Figure 9.

[ANP Stage]: In this stage, first, the performance criteria are established by consulting an expert team and reviewing the literature. The expert team consists of two engineers working in a hazelnut factory in Turkey and an academician conducting research in this field. Accordingly, the explanations for the determined criteria are summarized in Table 2. It should be noted that all the criteria are cost-based. In other words, the minimum performance value for each criterion represents the optimal value for that criterion.



Source(s): Figure created by authors

Figure 9. The flow diagram of the proposed supplier selection model

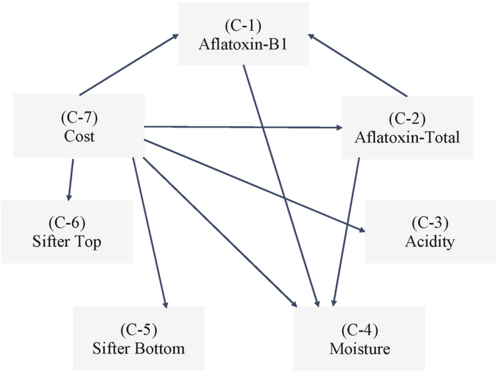
Table 2. The brief explanations of performance criteria

Performance criterion	Abb.	Unit	Explanation	Reference
Aflatoxin-B1	C-1	$\mu g/kg$	The Aflatoxin-B1 criterion is crucial in hazelnut procurement because elevated levels of Aflatoxin-B1 can jeopardize product safety, pose health risks, and lead to trade restrictions. This criterion considers the Aflatoxin-B1 level in the purchased product from suppliers	Aycicek *et al.* (2005) Bacaloni *et al.* (2008) Baltaci *et al.* (2012) Kabak (2016)
Aflatoxin-Total	C-2	$\mu g/kg$	The Aflatoxin-Total criterion plays a critical role in hazelnut procurement because it assesses the total Aflatoxin levels, particularly including Aflatoxin-B1. Elevated Aflatoxin levels can jeopardize product safety, pose health risks, and lead to trade restrictions. This criterion considers the Aflatoxin-Total level in the purchased product from suppliers	Aycicek *et al.* (2005) Bacaloni *et al.* (2008) Baltaci *et al.* (2012) Kabak (2016)
Acidity	C-3	$\%/kg$	The acidity criterion is critical in hazelnut procurement to determine product quality. High acidity can adversely affect the taste and quality of the product, shorten shelf life, and lead to undesirable characteristics in processed goods. This criterion considers the acidity level in the purchased product from suppliers	Ghirardello *et al.* (2013) Ghirardello *et al.* (2014) Silvestri *et al.* (2021)
Moisture	C-4	$\%/kg$	This criterion is essential for determining product quality. High moisture levels can diminish quality, lead to mold, and shorten storage duration. This criterion considers the moisture level in the purchased product from suppliers	Kibar and Öztürk (2009) Kaya *et al.* (2011) Turan and Karaosmanoğlu (2019)
Sifter bottom	C-5	$\%/kg$	It is important that the purchased hazelnuts are in the desired size physically. This criterion pertains to the percentage of purchased hazelnuts that remain under the sifter	Expert team
Sifter top	C-6	$\%/kg$	It is important that the purchased hazelnuts are in the desired size physically. This criterion pertains to the percentage of purchased hazelnuts that remain on the sifter	Expert team
Cost	C-7	\$/kg	This criterion is related to the purchase cost of the hazelnut	Expert team

Source(s): Table created by authors

Due to the interaction between criteria, the ANP method introduced by Saaty in 1996 is employed to determine the performance criterion weights (Saaty, 1996, 2001). To achieve this, an expert panel is consulted to establish the network structure illustrating the interactions of the criteria. The network structure, which visualizes the relationship between the criteria, is provided in Figure 10. As an example, as depicted in Figure 10, the (C-4) criterion influences the (C-1) criterion, and the (C-1) criterion affects the (C-2) criterion. Subsequently, pairwise comparisons based on the created network structure were conducted using the "*superdecision*" software package. The consistency ratio (CR) of all pairwise comparisons was examined ($CR < 0.1$), and the criteria's importance weights were obtained as presented in Figure 10.

[Optimization Stage]: The following section provides general information on the indices, sets, and parameters of the proposed supplier selection model based on goal programming. The model is then formulated using the criteria weights obtained from the ANP stage and the performance values obtained from the suppliers.



Criterion	Priorities (Weights)
(C-1) Aflatoxin-B1	0.32397
(C-2) Aflatoxin-Total	0.12563
(C-3) Acidity	0.10465
(C-4) Moisture	0.39275
(C-5) Sifter Bottom	0.02004
(C-6) Sifter Cost	0.02004
(C-7) Cost	0.01392

Source(s): Figure created by authors

Figure 10. The network structure summarizing the relationships between the criteria and the importance weights

Indices and sets:

i: the index of suppliers, $(i \in I)\ i = 1, \ldots, n$

j: the index of selection criteria, $(j \in J)\ j = 1, \ldots, m$

I: the set of suppliers

J: the set of criteria

Decision and deviation variables:

$$x_i = \begin{cases} 1, \textit{If the } i^{th} \textit{ supplier is selected} \\ 0, \textit{otherwise} \end{cases}$$

d_j^-: the negative deviation variable from the target value in the constraint related to the j^{th} criterion

d_j^+: the positive deviation variable from the target value in the constraint related to the j^{th} criterion

Parameters:

a_{ij}: the normalized performance value of the i^{th} supplier under the j^{th} criterion

w_j: the importance weight of the j^{th} criterion

δ_j^{upper}: normalized upper specification limit related to the j^{th} criterion

δ_j^{lower}: normalized lower specification limit related to the j^{th} criterion

In the selection model, the objective function (1) minimizes the total weighted negative deviation amount from the goal values regarding criterion. Constraint (2) represents the goal constraints formulated for each criterion. In this constraint, the goal value for each criterion is set to 1 since the best performance value is 1 after the normalization process. Accordingly, in each criterion constraint, the weighted negative deviation from the target value is primarily minimized in the objective function. The model, by simultaneously considering all constraints, aims to select the supplier that is closest to the target appropriateness value of 1 for each criterion. Constraints (3) and (4) ensure that the selected supplier's products meet the quality criteria within lower and upper specification limits. Here, if no lower limit is specified, it is considered as 0. Constraint (5) guarantees the selection of the most suitable supplier. Constraints (6) and (7) represent constraints for binary decision variables and deviation variables, respectively.

$$Min\, Z = \sum_{j \in J} w_j d_j^- \tag{1}$$

$$s.t.$$

$$\left(\sum_{i \in I} a_{ij} x_i \right) + d_j^- - d_j^+ = 1;\ \forall j \tag{2}$$

$$a_{ij} x_i \leq \delta_j^{upper};\ \forall i, j \tag{3}$$

$$a_{ij} x_i \geq \delta_j^{lower};\ \forall i, j \tag{4}$$

$$\sum_{i \in I} \mathrm{x}_i = 1 \tag{5}$$

$$x_i \in \{0, 1\};\ \forall i, j \tag{6}$$

$$d_j^-, d_j^+ \geq 0;\ \forall j \tag{7}$$

Table 3 presents the performance values of the suppliers according to the performance criteria and the acceptable upper bound levels. Before formulating the goal programming model, these values are normalized. Since all determined performance criteria are cost-based, the following Eq. (8) is employed for each criterion.

$$r_{ij} = \frac{\min_j x_{ij}}{x_{ij}};\ j = 1, 2, \ldots, n \tag{8}$$

Table 3. The information of the performance values of the suppliers

	Performance criteria						
Alternative suppliers	Aflatoxin B1 C-1	Aflatoxin total C-2	Acidity C-3	Moisture C-4	Sifter bottom C-5	Sifter top C-6	Cost C-7
A-1	4.21	7.92	0.04	4.41	2.22	1.33	3.99
A-2	4.32	7.75	0.05	3.92	3.63	0.61	3.56
A-3	3.73	6.64	0.09	5.13	3.04	1.02	3.55
A-4	3.83	6.53	0.12	5.35	3.91	0.23	3.57
A-5	3.92	7.02	0.17	4.74	2.25	1.24	3.65
A-6	3.71	7.82	0.14	5.83	2.41	2.42	3.87
A-7	4.24	8.01	0.34	6.25	4.75	1.75	2.99
A-8	4.55	8.23	0.08	6.04	4.26	0.23	2.98
A-9	5.12	7.23	0.25	5.73	3.97	0.96	2.87
A-10	4.91	6.94	0.22	5.34	3.02	0.81	3.50
A-11	2.94	5.65	0.28	4.11	3.04	1.01	3.70
A-12	3.9	6.44	0.22	5.30	4.02	0.89	3.52
Unit	$\mu g/kg$	$\mu g/kg$	$\%/kg$	$\%/kg$	$\%/kg$	$\%/kg$	$/kg
(Acceptable bound levels)	≤5	≤10	≤ 1	≤ 6 (for natural)	≤5 (for 13–15 mm)	≤5 (for 13–15 mm)	–

Source(s): Table created by authors

where x_{ij} represents the performance value of the i^{th} supplier under the j^{th} criterion, r_{ij} indicates the normalized value of the x_{ij}. The normalized performance values are given in Table 4.

The optimization model is coded by using GAMS® 23.6/CPLEX solver on a personal computer with 2.4 GHz Intel(R) Core™ i7-3630QM CPU and 16 GB of RAM. By running the coded optimization model, the most appropriate supplier is identified as A-11. Subsequently, the A-11 alternative is extracted from the model, and the model is re-run. As the second alternative, the top supplier is identified as A-2. Similarly, after extracting the A-11 and A-2 alternatives from the model, it is re-run. As the third alternative, the top supplier is determined to be A-1. Consequently, the top three suppliers to work with are identified in the following order: A-11 > A-2 > A-1.

5.1.2 Sensitivity analysis. The scenarios generated based on varying criterion weights are presented in Table 5. Here, S-0 corresponds to the scenario that considers the weights determined by the experts, while S-1 is associated with the scenario in which the criterion weights are equal. Starting from S-2, in each of the scenarios, the weight of one criterion is significantly greater than the weight of the other criteria. Observing closely, the generated scenarios overlap in terms of patterns. For instance, in scenarios S-2, S-9, and S-16, the importance weight of C-1 is significantly higher compared to the importance weights of other criteria.

The optimization model is run with varying parameter values for sensitivity analysis to assess the variability in the results. In total, 23 runs are performed using the CPLEX solver, and all optimal results are obtained within seconds. The computational results are summarized in Table 6.

As seen in Table 6, starting from S-2, on a row-by-row basis, each scenario exhibits the same pattern. In this context, when considering S-2, S-9, and S-16, it becomes evident that in S-2, the importance weight of Aflatoxin-B1 criterion is greater than that of Aflatoxin-B1 criterion in S-9 and S-16. Similarly, in S-9, the importance weight of Aflatoxin-B1 criterion exceeds that of Aflatoxin-B1 criterion in S-16. Accordingly, the following insights can be provided:

(1) As the criterion weights converge, the significance of supplier-1 (A-1) increases.

Alternative suppliers	Performance criteria C-1	C-2	C-3	C-4	C-5	C-6	C-7
A-1	0.6983372	0.7133838	1	0.8888888	1	0.1729323	0.7192982
A-2	0.6805555	0.7290322	0.8000000	1	0.6115702	0.3770491	0.8061797
A-3	0.7882037	0.8509036	0.4444444	0.7641325	0.7302631	0.2254902	0.808450
A-4	0.7676240	0.8652373	0.3333333	0.7327102	0.5677749	1	0.8039217
A-5	0.750000	0.8048430	0.2352941	0.8270042	0.9866666	0.1854838	0.7863013
A-6	0.7924528	0.7225063	0.2857142	0.6723842	0.9211618	0.0950413	0.7416020
A-7	0.6933962	0.7053682	0.1176470	0.6272000	0.4673684	0.1314285	0.9598662
A-8	0.6461538	0.6865127	0.5000000	0.6490066	0.5211267	1	0.9630872
A-9	0.5742187	0.7814661	0.1600000	0.6841186	0.5591939	0.2395833	1
A-10	0.5987780	0.8141210	0.1818181	0.734082	0.7350993	0.2839506	0.8200000
A-11	1	1	0.1428571	0.9537712	0.7302631	0.2277227	0.7756756
A-12	0.7538461	0.8773291	0.1818181	0.7396226	0.5522388	0.2584269	0.8153409
Normalized acceptable bound levels	≥ 0.588	≥ 0.565	≥ 0.04	≥ 0.653	≥ 0.444	≥ 0.046	–

Source(s): Table created by authors

Table 4. The normalized performance values of the suppliers related to the addressed criteria

Table 5. The scenarios regarding distribution of the performance criteria weights

Scenarios	C-1	C-2	C-3	C-4	C-5	C-6	C-7
S-0	*0.32297*	*0.12563*	*0.10465*	*0.39275*	*0.02004*	*0.02004*	*0.01392*
S-1	0.14185	0.14185	0.14185	0.14185	0.14185	0.14185	0.14185
S-2	*0.70*	0.05	0.05	0.05	0.05	0.05	0.05
S-3	0.05	*0.70*	0.05	0.05	0.05	0.05	0.05
S-4	0.05	0.05	*0.70*	0.05	0.05	0.05	0.05
S-5	0.05	0.05	0.05	*0.70*	0.05	0.05	0.05
S-6	0.05	0.05	0.05	0.05	*0.70*	0.05	0.05
S-7	0.05	0.05	0.05	0.05	0.05	*0.70*	0.05
S-8	0.05	0.05	0.05	0.05	0.05	0.05	*0.70*
S-9	*0.40*	0.10	0.10	0.10	0.10	0.10	0.10
S-10	0.10	*0.40*	0.10	0.10	0.10	0.10	0.10
S-11	0.10	0.10	*0.40*	0.10	0.10	0.10	0.10
S-12	0.10	0.10	0.10	*0.40*	0.10	0.10	0.10
S-13	0.10	0.10	0.10	0.10	*0.40*	0.10	0.10
S-14	0.10	0.10	0.10	0.10	0.10	*0.40*	0.10
S-15	0.10	0.10	0.10	0.10	0.10	0.10	*0.40*
S-16	*0.25*	0.15	0.15	0.15	0.15	0.15	0.15
S-17	0.15	*0.25*	0.15	0.15	0.15	0.15	0.15
S-18	0.15	0.15	*0.25*	0.15	0.15	0.15	0.15
S-19	0.15	0.15	0.15	*0.25*	0.15	0.15	0.15
S-20	0.15	0.15	0.15	0.15	*0.25*	0.15	0.15
S-21	0.15	0.15	0.15	0.15	0.15	*0.25*	0.15
S-22	0.15	0.15	0.15	0.15	0.15	0.15	*0.25*

Source(s): Table created by authors

Table 6. The list of selected suppliers with respect to scenarios

Scenarios	Selected supplier	z^*	Scenarios	Selected supplier	z^*	Scenarios	Selected supplier	z^*
S-0	*A-11*	*0.131861*						
S-1	A-1	0.256346						
S-2	A-11	0.108485	S-9	A-11	0.216971	S-16	A-1	0.301240
S-3	A-11	0.108485	S-10	A-11	0.216971	S-17	A-1	0.299736
S-4	A-1	0.090358	S-11	A-1	0.180716	S-18	A-1	0.271074
S-5	A-2	0.099781	S-12	A-2	0.199561	S-19	A-1	0.282185
S-6	A-1	0.090358	S-13	A-1	0.180716	S-20	A-1	0.271074
S-7	A-4	0.096470	S-14	A-4	0.192940	S-21	A-4	0.289410
S-8	A-8	0.125699	S-15	A-8	0.214485	S-22	A-1	0.299144

Source(s): z^* corresponds to the objective function value representing the total weighted sum of negative deviations
Source(s): Table created by authors

(2) With the increase in the weight of the Sifter top criterion, supplier-4 (A-4) gains importance.

(3) The significant weight of the Aflatoxin-B1 and Aflatoxin-Total criteria supports the selection of supplier-11 (A-11).

(4) The greater importance of the Moisture criterion supports the selection of supplier-2 (A-2).

(5) Taking the Cost criterion into significant consideration supports the selection of supplier-8 (A-8).

5.2 Supplier improvements based on Industry 4.0

In this section, axiomatic design is presented as a roadmap for the developed countermeasures addressing the root causes of supplier-related problems. First, the fundamentals of AD are introduced in the following subsection, and then the AD methodology developed for the problem is presented. Detailed explanations of functional requirements (FRs) and design parameters (DPs) are also provided.

5.2.1 Axiomatic design fundamentals. Nam P. Suh developed Axiomatic Design (AD) methodology with the objective of simplifying design processes of product, software, and production systems. This approach facilitates effective decision-making at various levels, ultimately reducing overall complexity (Suh, 1998; Kulak *et al.*, 2010). AD generates integrated solutions through mapping between Functional Requirements (FRs) and Design Parameters (DPs). FRs are described as the essential set of requirements that the design needs to satisfy while the DPs specify the methods through which we intend to meet these functional requirements (Suh, 1998; Cochran *et al.*, 2000).

During the mapping process, there are two main axioms that the design should satisfy to produce a robust design (Suh, 1998). They are stated as follows:

Axiom 1: The Independence Axiom

Axiom 2: The Information Axiom

The independence axiom states that the ideal design requires maintaining the independence of functional requirements. In other words, it states that in the presence of two or more FRs, the design solution should be structured in a way that each FR can be fulfilled independently, without influencing the others (Suh, 1998; Kulak *et al.*, 2010).

The information axiom suggests minimizing the information content. It emphasizes the idea that achieving functional requirements with the least information is optimal (Suh, 1998; Rauch *et al.*, 2015).

As a consequence of the Independence Axiom and the Information Axiom, the number of FRs and DPs should be equal, and the relationship between FRs and DPs is expressed mathematically as follows:

$$\{FR\} = [A]\{DP\} \tag{9}$$

$$[A] = \begin{bmatrix} A11 & A12 & A13 \\ A21 & A22 & A23 \\ A31 & A32 & A33 \end{bmatrix}$$

Where $\{FR\}$ is the functional requirement vector, $\{DP\}$ is the design parameter vector, and $[A]$ is the design matrix that characterizes the design and each A_{ij} of $[A]$ relates the *ith* FR to *jth* DP.

To fulfill the independence axiom, the design matrix should take the form of either a diagonal or triangular matrix, signifying uncoupled or decoupled designs, respectively. An uncoupled design implies that each of the FRs can be satisfied independently by means of one DP. Conversely, a decoupled design signifies that the independence of FRs is ensured only if the DPs are altered in the correct sequence. All designs, except those featuring a diagonal or triangular design matrix, infringe upon the Independence Axiom and are referred to as coupled designs. Consequently, when multiple functional requirements need fulfillment, designers must craft designs adhering to a diagonal or triangular matrix structure (Suh, 1998).

5.2.2 Axiomatic design methodology for Industry 4.0 implementation. A significant portion of the issues contributing to prolonged lead times within the company has been directly attributed to factors related to suppliers. By concentrating on these factors, the root causes of these problems have been identified as follows: (1) Inability to track suppliers in terms of relevant metrics; (2) Lack of information sharing among stakeholders in the supply chain; (3) The inability to clearly track all processes of supply chain stakeholders; (4) Lack of implementation/follow-up of 5S studies in the supplier's warehouse. Examining these issues reveals that the central challenge related to supplier-related problems is the lack of traceability and reliability in the supply process. Consequently, the primary FR for the system is defined as achieving a traceable and reliable supply process. To meet this FR, the decision is made to implement Industry 4.0 tools coupled with statistical methods. The overall view of the AD of the implementation is presented in Figure 11.

The FRs of implementing Industry 4.0 tools coupled with statistical methods are as follows:

FR1: Assess environmental conditions automatically

FR2: Detect contamination sources

FR3: Monitor and control the process of the suppliers

FR4: Ensure transparency, compliance, and traceability of the supply process

FR5: Predict aflatoxin, acidity, and moisture levels of the products

Corresponding DPs are as follows:

DP1: Establish the sensors (mold, humidity, etc.) and cameras for real-time monitoring

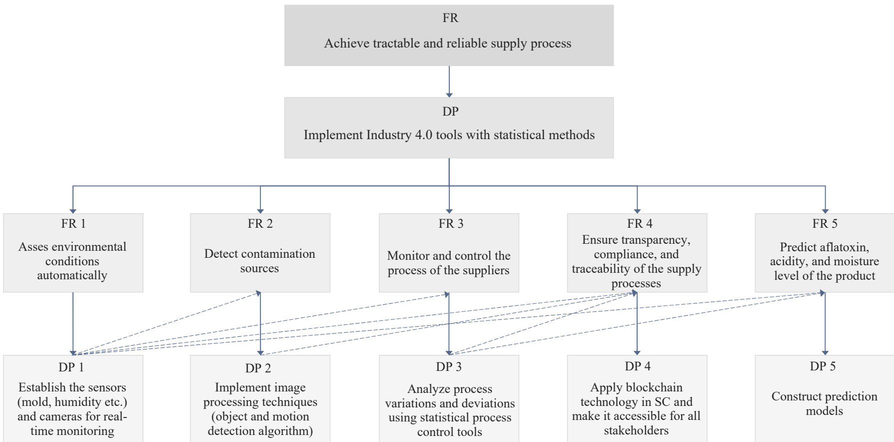
DP2: Implement image processing techniques (object and motion detection algorithm)

DP3: Analyze process variations and deviations using statistical process control tools

DP4: Apply blockchain technology in SC and make it accessible for all stakeholders

DP5: Construct prediction models

The design matrix of the proposed system can be written as in Equation (9):



Source(s): Figure created by authors

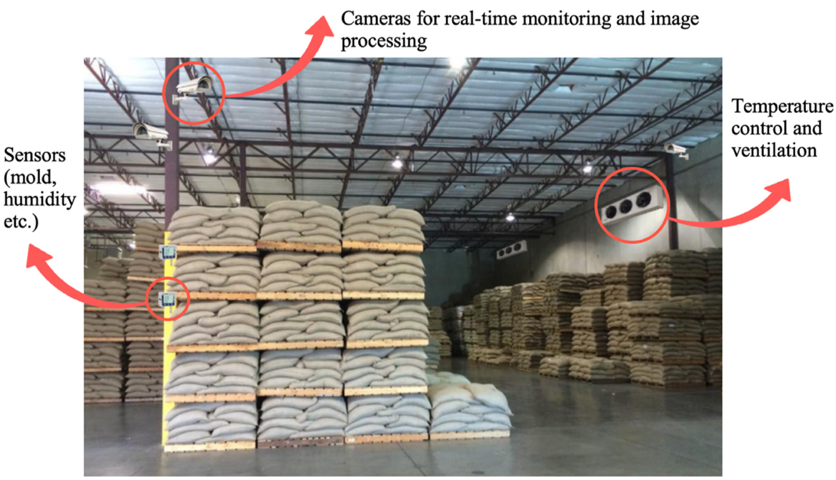
Figure 11. Axiomatic design for Industry 4.0 implementation

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ DP5 \end{bmatrix}$$

As previously indicated, maintaining an optimal humidity level within the supplier warehouse is crucial due to its impact on increasing the moisture content of hazelnut products, thereby creating conditions conducive to mold formation—an unacceptable product defect in the hazelnut industry. In order to assess environmental conditions automatically (FR1) and to mitigate the risk of product returns and contamination, the implementation of sensors and cameras for real-time monitoring (DP1) becomes essential. Furthermore, the implementation of DP1 not only satisfies FR1 but also significantly influences the fulfillment of the remaining FRs. The proposed system is illustrated in Figure 12.

To ensure the quality of the products and the reliability of the suppliers, it is imperative for the company to detect contamination sources (FR2) within the supplier warehouse. Meeting FR2 necessitates the implementation of image processing techniques (DP2) specifically designed for the detection of undesirable foreign substances and animals. The establishment of DP2 not only fulfills FR2 but also significantly contributes to the satisfaction of FR4.

DP3 involves the analysis of process variations and deviations through statistical process control tools. The implementation of DP3 serves a dual purpose. Firstly, it directly addresses FR3 by facilitating the real-time monitoring and control of supplier processes. Secondly, DP3 plays a crucial role in aligning with FR4, which emphasizes the importance of ensuring transparency, compliance, and traceability throughout the supply chain. By strategically implementing DP3, the company not only fulfills immediate functional requirements but also establishes a foundation for enhanced supply chain transparency and compliance, ultimately contributing to the overall reliability and quality of the hazelnut products. Additionally, DP3 plays a crucial role in meeting the requirements of FR5 by providing a foundation for predicting aflatoxin, acidity, and moisture levels in hazelnut products, thereby bolstering the overall quality control measures within the supply chain.



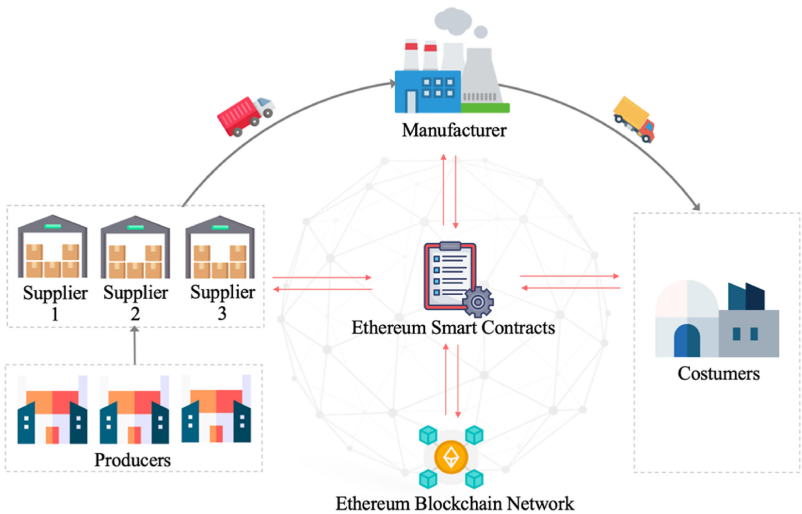
Source(s): Figure created by authors

Figure 12.
IoT applications in the supplier warehouses

As mentioned in DP4, the use of the blockchain technology is planned to maintain transparency and traceability in the SC network. Processes involving the flow of products, information, and funds will be executed using Ethereum smart contracts coded in the Solidity programming language on the Ethereum platform. The selection of the Ethereum blockchain is motivated by its use of the Proof of Stake (PoS) consensus mechanism, which ensures a fast approval process for transactions (Bottoni *et al.*, 2020). Furthermore, Ethereum smart contracts are highly flexible and programmable, allowing for the easy development of various applications and services. Additionally, Ethereum, being a globally distributed blockchain network, provides global accessibility for smart contracts, facilitating future establishment of new supplier relationships (Abdallah and Nizamuddin, 2023). The proposed blockchain-based SC network is illustrated in Figure 13. Each participant in this network, including suppliers, customers, and the manufacturer, will have an Ethereum account containing an address, public key, and private key. According to the contract, stakeholders will conduct product shipments, tracking, and payment processes through this network.

As stated in Section 5.1.1, acidity, aflatoxin, and moisture levels are pivotal performance criteria significantly impacting product quality and safety, with potential implications for health risks and trade restrictions. Consequently, the control and prevention of undesired levels in these criteria are paramount. Predicting aflatoxin, acidity, and moisture levels in hazelnut products (FR5) is identified as a critical requirement. To fulfill FR5, the objective is to develop robust prediction models (DP5), aligning with the overarching aim of constructing reliable models to foresee and manage these crucial performance indicators effectively.

Overall, the implementation of sensors (DP1) includes advanced environmental monitoring sensors capable of detecting temperature, humidity, and mold spores in real-time. These sensors provide critical data that helps maintain optimal storage conditions, thus preventing product spoilage and reducing waste. For instance, temperature and humidity sensors continuously monitor the environment, and if conditions deviate from the optimal range, alerts are generated, prompting immediate corrective actions. This real-time monitoring ensures that the storage conditions are always ideal, significantly reducing the risk of mold formation and ensuring the quality of the hazelnuts.



Source(s): Figure created by authors

Figure 13. Proposed blockchain-based supply chain network

For DP2, image processing techniques involve the use of high-resolution cameras combined with machine learning algorithms to identify and classify foreign objects and contaminants. This technology ensures that any contamination is detected early, allowing for immediate corrective actions and ensuring product safety and quality. For example, high-resolution cameras capture detailed images of the hazelnuts, and machine learning algorithms analyze these images to detect and classify contaminants such as foreign objects or mold. This early detection system minimizes the risk of contaminated products reaching the customers, enhancing overall product safety.

DP3 incorporates statistical process control tools to monitor process stability and detect variations that could lead to defects. This proactive approach allows for timely interventions, maintaining consistent quality and reducing variability in production processes. For example, statistical process control tools can track and analyze data from various stages of the production process, identifying any deviations from the standard process. By addressing these deviations promptly, the company can ensure that the production process remains stable, and that the final product meets the desired quality standards.

In DP4, blockchain technology not only ensures traceability and transparency but also enhances the security of transactions and data integrity within the supply chain. This technology builds trust among stakeholders and streamlines supply chain operations by providing a tamper-proof record of all transactions. For instance, every transaction, from raw material procurement to final product delivery, is recorded on the blockchain. This transparent record-keeping ensures that all parties can verify the authenticity and integrity of the product and its journey through the supply chain, fostering trust and reliability.

Lastly, DP5 involves the development of prediction models using machine learning techniques. These models analyze historical and real-time data to predict aflatoxin, acidity, and moisture levels, enabling preventive measures and quality control to ensure the final product meets safety and quality standards. For example, by analyzing patterns and trends in historical data, machine learning models can forecast potential quality issues before they occur. This predictive capability allows the company to implement preventive measures, ensuring that the hazelnuts meet the required safety and quality standards consistently.

6. Discussion and managerial insights

As previously mentioned, this study focuses on a real case from a hazelnut plant within a company. Initially, Lean Six Sigma (LSS) tools are applied as part of operational excellence in the plant, resulting in significant improvements in both Kaizen activities and lead time. However, there is still a need for further enhancements in supply chain integration. Therefore, a comprehensive methodology is proposed to address limitations arising from supplier-related challenges.

In the subsequent section, managerial insights are provided based on the applied methodology:

(1) LSS implementation markedly reduces lead time in responding to customer expectations, unveiling additional improvement opportunities. (Response to RQ1)

(2) Quality improvements by suppliers should prioritize moisture and aflatoxin-B1 criteria, followed by consideration of other relevant criteria. (Response to RQ1 and RQ2)

(3) Countermeasures to root causes of supplier-related issues are proposed, including a supplier selection method. Moisture emerges as a critical performance criterion, underscoring its significance in the supplier selection process. Additionally, aflatoxin-B1 is identified as an important criterion for supplier evaluation. (Response to RQ1 and RQ2)

(4) Real-time monitoring, essential for traceability, is proposed through the integration of Industry 4.0 tools within the suggested methodology. (Response to RQ1 and RQ2)

(5) The hybrid push-pull production control mechanism, implemented as CONstant work in process (CONWIP), simplifies the managerial processes of the production system. This mechanism enables comprehensive control through the implementation of Kanban. (Response to RQ1 and RQ3)

(6) Production leveling and smoothing are ensured via Heijunka to reduce unevenness (Mura) and overburden (Muri), allowing identification and elimination of waste in the production system. (Response to RQ1 and RQ3)

(7) Given the demonstrated effectiveness of the A3 problem-solving tool in identifying root causes and proposing solutions, it is recommended to apply this technique to address supplier-related problems as well. (Response to RQ1 and RQ3)

(8) The active involvement of the entire organization in LSS implementation is deemed crucial to minimize untapped human potential and skills. This collective participation facilitates the identification of improvement opportunities and enables swift actions to be taken. (Response to RQ1 and RQ3)

(9) High lead time is identified as a consequence of low product quality and subsequent product returns, highlighting the importance of implementing a supplier development process. It is recommended to support LSS implementation with supplier development within the operational excellence framework. (Response to RQ2)

(10) Application of AD principles is advised for the seamless implementation of proposed countermeasures. (Response to RQ2)

(11) Enhanced quality is facilitated by having fewer suppliers, as it allows the establishment of a strong relationship between producers and suppliers. (Response to RQ2 and RQ3)

(12) The application of the 5S methodology is instrumental in achieving the projected goals by eliminating significant wastes and streamlining system management. (Response to RQ3)

Overall, this study demonstrates the substantial benefits of LSS implementation in a hazelnut plant, particularly in reducing lead times and improving operational excellence, which aligns with the results of Srinivasan *et al.* (2024), Normand and Bradley (2024), and Sordan *et al.* (2023), who observed similar reductions in lead times in their studies of LSS across different industries. Additionally, a supplier selection model is proposed with the aim of selecting the top 3 suppliers from the company's existing suppliers. The ANP method is employed to determine the performance criterion weights, by consulting an expert team and reviewing the literature. As a result, it is found that the most important criteria in supplier evaluation are moisture and aflatoxin-B1. The results correspond with the findings of Aycicek *et al.* (2005), Bacaloni *et al.* (2008), Kibar and Öztürk (2009), and Kaya *et al.* (2011), who identified these factors as critical in ensuring product safety and quality in food supply chains. Moreover, the study highlights the necessity of real-time monitoring for traceability through Industry 4.0 tools and the effectiveness of hybrid push-pull production control mechanisms like CONWIP and Heijunka in streamlining production processes. Furthermore, the study underscores the value of the A3 problem-solving tool and the 5S methodology in identifying and eliminating waste, as well as the critical role of supplier development and the involvement of the entire organization in achieving continuous improvement. These insights provide a comprehensive framework for addressing supplier-related challenges and enhancing overall supply chain integration, ultimately leading to improved product quality and reduced lead times.

7. Concluding remarks

This study addresses challenges related to long lead times in responding to customers, which are primarily due to product quality issues linked to suppliers. To overcome these challenges, an integrated lean-based methodology is proposed, adopting a continuous improvement cycle that incorporates principles from lean manufacturing, Six Sigma, and Industry 4.0 applications.

To achieve this, a VSM is drawn for the current state analysis in the company, revealing an excessively long lead time for customer response. Subsequently, 12 underlying problems causing the extended lead time are identified through a fishbone analysis. A Pareto analysis is then conducted to categorize these problems into two main groups: (1) related to suppliers and (2) related to the lack of lean applications. Within this scope, based on the Pareto analysis, it is observed that out of the 12 identified problems, 5 are related to suppliers, and 4 are related to the lack of lean applications. Accordingly, lean applications are initially implemented in the company. A future state VSM is then developed, revealing that the lead time is still high. To further reduce the lead time, issues related to suppliers are addressed. Root cause analyses are conducted for the supplier-related problems categorized in the Pareto analysis, and Industry 4.0-based countermeasures are developed for each root cause. The primary countermeasure is identified as “supplier selection,” aimed at reducing the number of suppliers. To achieve this, a supplier selection model is proposed, resulting in a reduction from 12 to 3 suppliers. Following this, an axiomatic design is constructed to illustrate how other Industry 4.0-based countermeasures, ensuring supplier traceability, can be implemented.

The study’s contributions are delineated through three perspectives as follows:

(1) *Theoretical Contribution:* This research extends the traditional LSS framework by integrating it with Industry 4.0 technologies, offering a novel approach to addressing supplier-related quality issues. This adaptation provides a valuable reference for academia, particularly in understanding how digital transformation can complement lean practices. By applying lean principles to the agricultural sector, this study contributes to the relatively sparse literature on lean applications outside of traditional manufacturing environments. It also explores the potential of LSS to improve not just manufacturing efficiency but also the reliability and quality of agricultural supply chains. Additionally, the study showcases how continuous improvement efforts can be systematically documented and analyzed using modern technologies, providing a theoretical framework that can be tested and refined in other sectors.

(2) *Practical Contribution:* The proposed methodology for a hazelnut company is systematically implemented, showcasing the practical application of various LSS tools such as VSM, Kaizen, 5S, A3 problem-solving technique, CONWIP, among others. Similarly, by concentrating on the root causes of the problem, solutions are provided for the identified problems. Within this scope, a supplier selection model is introduced, followed by recommendations for utilizing Industry 4.0 applications to strengthen supplier relationships and ensure traceability. It is anticipated that the visually demonstrated step-by-step methodology in this context will serve as a guide for many organizations. Accordingly, this methodology is readily characterized by its adaptability to various system.

(3) *Managerial Contribution:* The findings from this study offer strategic insights for managers on how to effectively integrate lean and digital technologies. This can lead to more informed decision-making, especially in industries where supply chain operations significantly impact product quality and customer satisfaction. The adoption of Industry 4.0 technologies, such as real-time monitoring and data analytics, empowers managers to make more precise decisions based on up-to-date information, enhancing operational efficiency and responsiveness. Additionally, the step-by-step approach illustrated in this study serves as a practical guide for other organizations looking to implement similar transformations. Its adaptability to various systems makes it a valuable model for managers seeking to reduce lead times and improve quality.

This study outlines several promising avenues for extending the research on the integration of LSS with Industry 4.0 technologies. Firstly, improving supplier relationships, executing effective data management, and ensuring traceability can be achieved by incorporating advanced Industry 4.0 applications such as digital twins, big data analytics, and machine learning. These technologies hold the potential to significantly enhance operational traceability and strategic flexibility in supply chain management. Additionally, due to the inherent variability in operations, adopting techniques such as fuzzy VSM can offer a robust method to manage time uncertainty in supply chains. This approach allows for more adaptable and responsive system modeling. Similarly, developing a fuzzy-based supplier selection model could address the imprecision and variability in supplier evaluation, providing a stronger, data-driven foundation for decision-making. Exploring these technologies and methodologies within the LSS framework could yield substantial improvements in operational efficiency and contribute to the evolving landscape of industrial management research.

References

Abdallah, S. and Nizamuddin, N. (2023), "Blockchain-based solution for pharma supply chain industry", *Computers and Industrial Engineering*, Vol. 177, 108997, doi: 10.1016/j.cie.2023.108997.

Abdulmalek, F.A. and Rajgopal, J. (2007), "Analyzing the benefits of lean manufacturing and value stream mapping via simulation: a process sector case study", *International Journal of Production Economics*, Vol. 107 No. 1, pp. 223-236, doi: 10.1016/j.ijpe.2006.09.009.

Ahmed, A., Page, J. and Olsen, J. (2020), "A comparison of three simulation methodologies for a Lean Six Sigma manufacturing project–a business case study", *International Journal of Lean Six Sigma*, Vol. 11 No. 3, pp. 405-427, doi: 10.1108/ijlss-03-2018-0025.

Ahmed, A., Olsen, J. and Page, J. (2023), "Integration of Six Sigma and simulations in real production factory to improve performance–a case study analysis", *International Journal of Lean Six Sigma*, Vol. 14 No. 2, pp. 451-482, doi: 10.1108/ijlss-06-2021-0104.

Alsaadi, N. (2024), "Roadblocks in integrating Lean Six Sigma and Industry 4.0 in small and medium enterprises", *Systems*, Vol. 12 No. 4, p. 125, doi: 10.3390/systems12040125.

Aycicek, H., Aksoy, A. and Saygi, S. (2005), "Determination of aflatoxin levels in some dairy and food products which consumed in Ankara, Turkey", *Food Control*, Vol. 16 No. 3, pp. 263-266, doi: 10.1016/j.foodcont.2004.03.004.

Azalanzazllay, N.N., Lim, S.A.H., Abidin, U.F.U.Z. and Anass, C. (2022), "Uncovering readiness factors influencing the Lean Six Sigma pre-implementation phase in the food industry", *Sustainability*, Vol. 14 No. 14, p. 8941, doi: 10.3390/su14148941.

Bacaloni, A., Cavaliere, C., Cucci, F., Foglia, P., Samperi, R. and Laganà, A. (2008), "Determination of aflatoxins in hazelnuts by various sample preparation methods and liquid chromatography–tandem mass spectrometry", *Journal of Chromatography A*, Vol. 1179 No. 2, pp. 182-189, doi: 10.1016/j.chroma.2007.11.081.

Baltaci, C., İlyasoğlu, H. and Cavrar, S. (2012), "Aflatoxin levels in raw and processed hazelnuts in Turkey", *Food Additives and Contaminants: Part B*, Vol. 5 No. 2, pp. 83-86, doi: 10.1080/19393210.2012.656146.

Baysan, S., Durmusoglu, M.B. and Cinar, D. (2017), "Team based labour assignment methodology for new product development projects", *Computers and Industrial Engineering*, Vol. 106, pp. 83-104, doi: 10.1016/j.cie.2016.11.032.

Bega, M., Sapel, P., Ercan, F., Schramm, T., Spitz, M., Kuhlenkötter, B. and Hopmann, C. (2023), "Extension of value stream mapping 4.0 for comprehensive identification of data and information flows within the manufacturing domain", *Production Engineering*, Vol. 17 No. 6, pp. 915-927, doi: 10.1007/s11740-023-01207-5.

Bilgin Turna, G. (2023), "Application of Lean Six Sigma for yield improvement in the stainless-steel industry: a recipe from Türkiye", *International Journal of Lean Six Sigma*, Vol. 14 No. 3, pp. 534-554, doi: 10.1108/ijlss-02-2022-0049.

Bottoni, P., Gessa, N., Massa, G., Pareschi, R., Selim, H. and Arcuri, E. (2020), "Intelligent smart contracts for innovative supply chain management", *Frontiers in Blockchain*, Vol. 3, p. 52, doi: 10.3389/fbloc.2020.535787.

Buer, S.V., Strandhagen, J.O. and Chan, F.T. (2018), "The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2924-2940, doi: 10.1080/00207543.2018.1442945.

Chiarini, A. and Kumar, M. (2021), "Lean Six Sigma and Industry 4.0 integration for operational excellence: evidence from Italian manufacturing companies", *Production Planning and Control*, Vol. 32 No. 13, pp. 1084-1101, doi: 10.1080/09537287.2020.1784485.

Chugani, N., Kumar, V., Garza-Reyes, J.A., Rocha-Lona, L. and Upadhyay, A. (2017), "Investigating the green impact of lean, six sigma and Lean Six Sigma: a systematic literature review", *International Journal of Lean Six Sigma*, Vol. 8 No. 1, pp. 7-32, doi: 10.1108/ijlss-11-2015-0043.

Cochran, D.S., Eversheim, W., Kubin, G. and Sesterhenn, M.L. (2000), "The application of axiomatic design and lean management principles in the scope of production system segmentation", *International Journal of Production Research*, Vol. 38 No. 6, pp. 1377-1396, doi: 10.1080/002075400188906.

Costa, L.B.M., Godinho Filho, M., Fredendall, L.D. and Paredes, F.J.G. (2018), "Lean, six sigma and Lean Six Sigma in the food industry: a systematic literature review", *Trends in Food Science and Technology*, Vol. 82, pp. 122-133, doi: 10.1016/j.tifs.2018.10.002.

Costa, L.B.M., Godinho Filho, M., Fredendall, L.D. and Ganga, G.M.D. (2021), "Lean Six Sigma in the food industry: construct development and measurement validation", *International Journal of Production Economics*, Vol. 231, 107843, doi: 10.1016/j.ijpe.2020.107843.

Durmusoglu, M.B. and Aglan, C. (2024), "A complete lean system design for team-oriented product development projects", *International Journal of Lean Six Sigma*. doi: 10.1108/ijlss-07-2023-0124.

Florescu, A. and Barabas, S. (2022), "Development trends of production systems through the integration of lean management and Industry 4.0", *Applied Sciences*, Vol. 12 No. 10, p. 4885, doi: 10.3390/app12104885.

Ghirardello, D., Contessa, C., Valentini, N., Zeppa, G., Rolle, L., Gerbi, V. and Botta, R. (2013), "Effect of storage conditions on chemical and physical characteristics of hazelnut (Corylus avellana L.)", *Postharvest Biology and Technology*, Vol. 81, pp. 37-43, doi: 10.1016/j.postharvbio.2013.02.014.

Ghirardello, D., Zeppa, G., Rolle, L.G.C., Gerbi, V., Contessa, C., Valentini, N., Botta, R. and Griseri, G. (2014), "Effect of different storage conditions on hazelnut quality", *Acta Horticulturae*, Vol. 1052, pp. 315-318, doi: 10.17660/actahortic.2014.1052.44.

Guarraia, P., Carey, G., Corbett, A. and Neuhaus, K. (2008), *Lean Six Sigma for Manufacturing*, Bain & Company, Mexico City.

Jayaram, A. (2016), "Lean Six Sigma approach for global supply chain management using Industry 4.0 and IIoT", *2016 2nd International Conference on Contemporary Computing and Informatics (IC3I)*, IEEE, pp. 89-94.

Kabak, B. (2016), "Aflatoxins in hazelnuts and dried figs: occurrence and exposure assessment", *Food Chemistry*, Vol. 211, pp. 8-16, doi: 10.1016/j.foodchem.2016.04.141.

Kamble, S., Gunasekaran, A. and Dhone, N.C. (2020), "Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies", *International Journal of Production Research*, Vol. 58 No. 5, pp. 1319-1337, doi: 10.1080/00207543.2019.1630772.

Kaya, A., Aydin, O. and Akgun, M. (2011), "Drying kinetics and moisture transfer parameters of hazelnut", *Journal of Food Processing and Preservation*, Vol. 35 No. 5, pp. 714-721, doi: 10.1111/j.1745-4549.2011.00522.x.

Kibar, H. and Öztürk, T. (2009), "The effect of moisture content on the physico-mechanical properties of some hazelnut varieties", *Journal of Stored Products Research*, Vol. 45 No. 1, pp. 14-18, doi: 10.1016/j.jspr.2008.06.005.

Kulak, O., Cebi, S. and Kahraman, C. (2010), "Applications of axiomatic design principles: a literature review", *Expert Systems with Applications*, Vol. 37 No. 9, pp. 6705-6717, doi: 10.1016/j.eswa.2010.03.061.

Kumar, P., Bhamu, J., Goel, S. and Singh, D. (2024), "Interpretive structural modeling of Lean Six Sigma critical success factors in perspective of Industry 4.0 for Indian manufacturing industries", *International Journal of System Assurance Engineering and Management*, Vol. 15 No. 8, pp. 1-18, doi: 10.1007/s13198-024-02375-y.

Liker, J.K. (2004), *Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*, McGraw-Hill Education, New York, NY.

Lobo Mesquita, L., Lizarelli, F.L., Duarte, S. and Oprime, P.C. (2022), "Exploring relationships for integrating lean, environmental sustainability and Industry 4.0", *International Journal of Lean Six Sigma*, Vol. 13 No. 4, pp. 863-896, doi: 10.1108/ijlss-09-2020-0145.

Malik, A., Sharma, S., Batra, I., Sharma, C., Kaswan, M.S. and Garza-Reyes, J.A. (2023), "Industrial revolution and environmental sustainability: an analytical interpretation of research constituents in Industry 4.0", *International Journal of Lean Six Sigma*, Vol. 15 No. 1, pp. 22-49, doi: 10.1108/ijlss-02-2023-0030.

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

McDermott, O., Moloney, C., Noonan, J. and Rosa, A. (2024), "Green Lean Six Sigma in the food industry: a systematic literature review", *British Food Journal*, Vol. 126 No. 13, pp. 455-469, doi: 10.1108/bfj-01-2024-0100.

McDonald, T., Van Aken, E.M. and Rentes, A.F. (2002), "Utilising simulation to enhance value stream mapping: a manufacturing case application", *International Journal of Logistics*, Vol. 5 No. 2, pp. 213-232, doi: 10.1080/13675560210148696.

Midilli, Y.E. and Elevli, B. (2020), "Value stream mapping with simulation to optimize stock levels: case study", *Jordan Journal of Mechanical and Industrial Engineering*, Vol. 14 No. 3, pp. 295-302.

Mostafa, S., Dumrak, J. and Soltan, H. (2013), "A framework for lean manufacturing implementation", *Production and Manufacturing Research*, Vol. 1 No. 1, pp. 44-64, doi: 10.1080/21693277.2013.862159.

Mubarik, M.S., Kusi-Sarpong, S., Govindan, K., Khan, S.A. and Oyedijo, A. (2023), "Supply chain mapping: a proposed construct", *International Journal of Production Research*, Vol. 61 No. 8, pp. 2653-2669, doi: 10.1080/00207543.2021.1944390.

Mudgal, D., Pagone, E. and Salonitis, K. (2020), "Approach to value stream mapping for make-to-order manufacturing", *Procedia Cirp*, Vol. 93, pp. 826-831, doi: 10.1016/j.procir.2020.04.084.

Narula, S., Puppala, H., Kumar, A., Luthra, S., Dwivedy, M., Prakash, S. and Talwar, V. (2023), "Are Industry 4.0 technologies enablers of lean? Evidence from manufacturing industries", *International Journal of Lean Six Sigma*, Vol. 14 No. 1, pp. 115-138, doi: 10.1108/ijlss-04-2021-0085.

Neves, P., Silva, F.J.G., Ferreira, L.P., Pereira, T., Gouveia, A. and Pimentel, C. (2018), "Implementing lean tools in the manufacturing process of trimmings products", *Procedia Manufacturing*, Vol. 17, pp. 696-704, doi: 10.1016/j.promfg.2018.10.119.

Normand, A. and Bradley, T.H. (2024), "An experimental investigation of Lean Six Sigma philosophies in a high-mix low-volume manufacturing environment", *PLoS One*, Vol. 19 No. 5, e0299498, doi: 10.1371/journal.pone.0299498.

Pagliosa, M., Tortorella, G. and Ferreira, J.C.E. (2021), "Industry 4.0 and Lean Manufacturing: a systematic literature review and future research directions", *Journal of Manufacturing Technology Management*, Vol. 32 No. 3, pp. 543-569, doi: 10.1108/jmtm-12-2018-0446.

Pakdil, F. and Leonard, K.M. (2014), "Criteria for a lean organization: development of a lean assessment tool", *International Journal of Production Research*, Vol. 52 No. 15, pp. 4587-4607, doi: 10.1080/00207543.2013.879614.

Pakdil, F., Toktaş, P. and Can, G.F. (2020), "Six sigma project prioritization and selection: a multi-criteria decision-making approach in healthcare industry", *International Journal of Lean Six Sigma*, Vol. 12 No. 3, pp. 553-578, doi: 10.1108/ijlss-04-2020-0054.

Patel, A.S. and Patel, K.M. (2021), "Critical review of literature on Lean Six Sigma methodology", *International Journal of Lean Six Sigma*, Vol. 12 No. 3, pp. 627-674, doi: 10.1108/ijlss-04-2020-0043.

Pozzi, R., Rossi, T. and Secchi, R. (2023), "Industry 4.0 technologies: critical success factors for implementation and improvements in manufacturing companies", *Production Planning and Control*, Vol. 34 No. 2, pp. 139-158, doi: 10.1080/09537287.2021.1891481.

Praharsi, Y., Jami'in, M.A., Suhardjito, G. and Wee, H.M. (2021), "The application of Lean Six Sigma and supply chain resilience in maritime industry during the era of COVID-19", *International Journal of Lean Six Sigma*, Vol. 12 No. 4, pp. 800-834, doi: 10.1108/ijlss-11-2020-0196.

Prashar, A. (2018), "Toward cycle time reduction in manufacturing SMEs: proposal and evaluation", *Quality Engineering*, Vol. 30 No. 3, pp. 469-484, doi: 10.1080/08982112.2018.1460669.

Rahani, A.R. and Al-Ashraf, M. (2012), "Production flow analysis through value stream mapping: a lean manufacturing process case study", *Procedia Engineering*, Vol. 41, pp. 1727-1734, doi: 10.1016/j.proeng.2012.07.375.

Rane, S.B., Wavhal, S. and Potdar, P.R. (2023), "Integration of Lean Six Sigma with Internet of Things (IoT) for productivity improvement: a case study of contactor manufacturing industry", *International Journal of System Assurance Engineering and Management*, Vol. 14 No. 5, pp. 1990-2018, doi: 10.1007/s13198-023-01980-7.

Rathi, R., Singh, M., Antony, J., Garza-Reyes, J.A., Goyat, R. and Shokri, A. (2024), "Integration of blockchain and Lean Six Sigma approach for operational excellence: a proposed model", *International Journal of Lean Six Sigma*. doi: 10.1108/ijlss-07-2022-0148.

Rauch, E., Dallasega, P. and Matt, D.T. (2015), "Axiomatic design-based guidelines for the design of a lean product development process", *Procedia Cirp*, Vol. 34, pp. 112-118, doi: 10.1016/j.procir.2015.07.005.

Rosin, F., Forget, P., Lamouri, S. and Pellerin, R. (2020), "Impacts of Industry 4.0 technologies on lean principles", *International Journal of Production Research*, Vol. 58 No. 6, pp. 1644-1661, doi: 10.1080/00207543.2019.1672902.

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

Rossini, M., Powell, D.J. and Kundu, K. (2023), "Lean supply chain management and Industry 4.0: a systematic literature review", *International Journal of Lean Six Sigma*, Vol. 14 No. 2, pp. 253-276, doi: 10.1108/ijlss-05-2021-0092.

Saaty, T.L. (1996), *Decision Making with Dependence and Feedback: The Analytic Network Process*, Vol. 4922 No. 2, RWS Publications. Pittsburgh.

Saaty, T.L. (2001), *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World*, RWS Publications, Pittsburgh, PA.

Sanders, A., Elangeswaran, C. and Wulfsberg, J.P. (2016), "Industry 4.0 implies lean manufacturing: research activities in Industry 4.0 function as enablers for lean manufacturing", *Journal of Industrial Engineering and Management*, Vol. 9 No. 3, pp. 811-833, doi: 10.3926/jiem.1940.

Scheller, A.C., Sousa-Zomer, T.T. and Cauchick-Miguel, P.A. (2021), "Lean Six Sigma in developing countries: evidence from a large Brazilian manufacturing firm", *International Journal of Lean Six Sigma*, Vol. 12 No. 1, pp. 3-22, doi: 10.1108/ijlss-09-2016-0047.

Schoeman, Y., Oberholster, P. and Somerset, V. (2020), "Value stream mapping as a supporting management tool to identify the flow of industrial waste: a case study", *Sustainability*, Vol. 13 No. 1, p. 91, doi: 10.3390/su13010091.

Silvestri, C., Bacchetta, L., Bellincontro, A. and Cristofori, V. (2021), "Advances in cultivar choice, hazelnut orchard management, and nut storage to enhance product quality and safety: an overview", *Journal of the Science of Food and Agriculture*, Vol. 101 No. 1, pp. 27-43, doi: 10.1002/jsfa.10557.

Singhal, V., Maiyar, L.M. and Roy, I. (2024), "Environmental sustainability consideration with just-in-time practices in Industry 4.0 era–a state of the art", *Operations Management Research*, pp. 1-24, doi: 10.1007/s12063-024-00478-0.

Sony, M. (2018), "Industry 4.0 and lean management: a proposed integration model and research propositions", *Production and Manufacturing Research*, Vol. 6 No. 1, pp. 416-432, doi: 10.1080/21693277.2018.1540949.

Sordan, J.E., Marinho, C.A., Oprime, P.C., Pimenta, M.L. and Andersson, R. (2023), "Characterization of Lean Six Sigma projects in healthcare settings: empirical research", *Benchmarking: An International Journal*, Vol. 30 No. 10, pp. 4058-4075, doi: 10.1108/bij-03-2022-0183.

Srinivasan, K., Sarulkar, P. and Yadav, V.K. (2024), "Operational excellence of the steel industry using the Lean Six Sigma approach: a case study", *International Journal of Quality and Reliability Management*, Vol. 41 No. 3, pp. 826-849, doi: 10.1108/ijqrm-08-2022-0250.

Suh, N.P. (1998), "Axiomatic design theory for systems", *Research in Engineering Design*, Vol. 10 No. 4, pp. 189-209, doi: 10.1007/s001639870001.

Taghavi, V. and Beauregard, Y. (2020), "The relationship between lean and Industry 4.0: literature review", *Proceedings of the 5th North American Conference on Industrial Engineering and Operations Management*, Detroit, MI, USA, pp. 10-14.

Thomas, A.J., Francis, M., Fisher, R. and Byard, P. (2016), "Implementing Lean Six Sigma to overcome the production challenges in an aerospace company", *Production Planning and Control*, Vol. 27 Nos 7-8, pp. 591-603, doi: 10.1080/09537287.2016.1165300.

Tortorella, G.L. and Fettermann, D. (2018), "Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2975-2987, doi: 10.1080/00207543.2017.1391420.

Turan, A. and Karaosmanoğlu, H. (2019), "Effect of drying methods on long term storage of hazelnut", *Food Science and Technology*, Vol. 39 suppl 2, pp. 406-412, doi: 10.1590/fst.20518.

Varela, L., Araújo, A., Ávila, P., Castro, H. and Putnik, G. (2019), "Evaluation of the relation between lean manufacturing, Industry 4.0, and sustainability", *Sustainability*, Vol. 11 No. 5, p. 1439, doi: 10.3390/su11051439.

Vazquez Hernandez, J. and Elizondo Rojas, M.D. (2024), "Improving spare parts (MRO) inventory management policies after COVID-19 pandemic: a Lean Six Sigma 4.0 project", *The TQM Journal*, Vol. 36 No. 6, pp. 1627-1650, doi: 10.1108/tqm-08-2023-0245.

Wagner, T., Herrmann, C. and Thiede, S. (2017), "Industry 4.0 impacts on lean production systems", *Procedia Cirp*, Vol. 63, pp. 125-131, doi: 10.1016/j.procir.2017.02.041.

Wang, C.N., Vo, T.T.B.C., Chung, Y.C., Amer, Y. and Truc Doan, L.T. (2024), "Improvement of manufacturing process based on value stream mapping: a case study", *Engineering Management Journal*, Vol. 36 No. 3, pp. 300-318, doi: 10.1080/10429247.2023.2265793.

Widiwati, I.T.B., Liman, S.D. and Nurprihatin, F. (2024), "The implementation of Lean Six Sigma approach to minimize waste at a food manufacturing industry", *Journal of Engineering Research*, doi: 10.1016/j.jer.2024.01.022.

Wilson, L. (2010), *How to Implement Lean Manufacturing*, McGraw-Hill Education, New York, NY.

Yılmaz, Ö.F. and Pardalos, P.M. (2017), "Minimizing average lead time for the coordinated scheduling problem in a two-stage supply chain with multiple customers and multiple manufacturers", *Computers and Industrial Engineering*, Vol. 114, pp. 244-257, doi: 10.1016/j.cie.2017.10.018.

Yilmaz, O.F., Ozcelik, G. and Yeni, F.B. (2020), "Lean holistic fuzzy methodology employing cross-functional worker teams for new product development projects: a real case study from high-tech industry", *European Journal of Operational Research*, Vol. 282 No. 3, pp. 989-1010, doi: 10.1016/j.ejor.2019.09.048.

Yılmaz, Ö.F., Yeni, F.B., Yılmaz, B.G. and Özçelik, G. (2023), "An optimization-based methodology equipped with lean tools to strengthen medical supply chain resilience during a pandemic: a case study from Turkey", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 173, 103089, doi: 10.1016/j.tre.2023.103089.

Corresponding author
Gökhan Özçelik can be contacted at: gozcelik@ktu.edu.tr