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Identifying the Factors Affecting the Feasibility of Lean Production toward Sustainability in the Iranian Automotive Industry Using Grey Theory

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Abstract

This study aimed to identify and prioritize the factors affecting the feasibility of transitioning from lean production toward sustainability in the Iranian automotive industry using qualitative thematic analysis and Grey Relational Analysis. This applied study employed an exploratory sequential mixed-methods design. In the qualitative phase, data were collected through a review of the literature and semi-structured interviews with 18 academic and professional experts selected purposively, with interviews continuing until theoretical saturation. The qualitative data were analyzed through open, axial, and selective coding to identify the principal dimensions and factors influencing sustainable lean production. In the quantitative phase, a researcher-developed questionnaire based on the extracted qualitative codes was administered to a population of 400 healthcare personnel in Ilam to assess the generalizability of the organizational components in a high-pressure service environment. Content and construct validity and Cronbach's alpha reliability were evaluated. Grey Relational Analysis was then used to transform uncertain judgments into grey numbers, normalize the data, calculate grey relational coefficients, and rank the identified factors. The analysis identified four overarching dimensions: technical and operational, economic and financial, environmental, and organizational and cultural. Grey Relational Analysis ranked reduction of production errors as the most influential factor (0.945), followed by process quality control (0.938), process optimization (0.931), reduction of production cycle time (0.924), and increased equipment efficiency (0.917). Waste reduction also received a high priority (0.910). Among supply-chain and technology factors, sustainable supply of raw materials ranked highest (0.840), while reduction of energy consumption was the leading environmental factor (0.735). Senior management support was the highest-ranked managerial factor (0.630). The transition toward sustainable lean production in the Iranian automotive industry should begin with operational stabilization and quality improvement, followed by supply-chain integration, digitalization, environmental efficiency, and sustained managerial and organizational support.

Keywords: *Lean Production; Sustainability; Grey Theory; Grey Relational Analysis; Automotive Industry; Sustainable Manufacturing; Lean Manufacturing; Iran.*

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1. Introduction

Manufacturing industries have increasingly been required to improve operational efficiency while simultaneously responding to environmental, technological, economic, and social pressures. In this context, lean manufacturing has evolved from a production-oriented philosophy focused primarily on waste elimination and process efficiency into a broader managerial approach associated with quality improvement, resource optimization, responsiveness, and organizational performance. Lean manufacturing seeks to identify and remove non-value-adding activities, reduce defects and delays, improve process flow, enhance equipment utilization, and align production more closely with customer requirements. Its relevance has therefore extended beyond conventional cost reduction and productivity enhancement toward more comprehensive forms of organizational competitiveness and sustainability [1, 2]. Recent advances in lean systems have similarly emphasized improvements in quality, production reliability, process integration, and the ability to respond to increasingly complex market conditions [3]. However, contemporary manufacturing systems operate in an environment in which operational excellence alone is no longer sufficient, and firms are increasingly expected to integrate environmental sustainability, technological innovation, supply-chain resilience, and long-term value creation into their production strategies.

The concept of sustainability has consequently become closely intertwined with the development of modern lean manufacturing systems. Sustainable manufacturing requires organizations to reduce resource and energy consumption, minimize waste and emissions, increase material efficiency, improve environmental performance, and maintain economic viability over the long term. From this perspective, lean and sustainability share several complementary principles. Lean production seeks to eliminate forms of waste that do not create customer value, whereas environmental sustainability seeks to reduce unnecessary consumption of materials, energy, water, and other natural resources and to limit adverse ecological impacts. Accordingly, lean practices may create favorable conditions for sustainability by reducing overproduction, defects, unnecessary transportation, excessive inventories, inappropriate processing, and inefficient use of production resources [4]. Cross-sector evidence has further shown that lean practices may interact with environmental management mechanisms and generate synergies that improve environmental performance rather than simply operational outcomes [5]. Thus, the transition from lean production to sustainable lean production represents a shift from a narrow focus on operational waste toward the coordinated management of economic, operational, and environmental forms of inefficiency.

This transition is particularly important in industries characterized by intensive resource consumption, complex supply chains, high capital requirements, and considerable environmental impacts. The automotive industry is among the most significant examples because vehicle manufacturing involves extensive networks of suppliers, large-scale material flows, energy-intensive production processes, complex assembly systems, demanding quality requirements, and increasing pressure to develop cleaner products. The growing importance of electric and hybrid vehicles has added further complexity by requiring manufacturers to rethink product design, supply networks, component manufacturing, recycling systems, and technological capabilities. Evidence from electric-vehicle parts manufacturing has shown that the combination of Lean Six Sigma and sustainable supply-chain management can contribute to more integrated approaches to production improvement and sustainability [6]. These developments suggest that automotive manufacturers cannot pursue lean production independently of sustainability objectives, because decisions related to process design, sourcing, energy use, technology, quality, and product architecture increasingly affect both operational performance and long-term environmental competitiveness.

At the same time, the integration of lean production and sustainability is being reshaped by Industry 4.0 technologies. Digitalization, artificial intelligence, the Internet of Things, robotics, advanced analytics, intelligent automation, and integrated information systems can extend the capabilities of conventional lean systems by providing real-time information, predictive control, greater transparency, and more accurate decision-making. Research on Industry 4.0 and lean manufacturing indicates that advanced digital technologies can reinforce lean practices by improving process visibility, reducing uncertainty, supporting automation, and enabling faster responses to operational deviations [7]. Similarly, Industry 4.0 technologies can contribute to lean manufacturing and organizational performance by improving connectivity, production coordination, monitoring, and data-driven decision-making [8]. The evolution of manufacturing from conventional lean production toward digitally enabled product and process systems has also created a closer relationship between production technology and product design [9].

The interaction between digital technologies and lean production is particularly relevant when organizations seek to achieve sustainability outcomes. Internet of Things technologies, for example, can facilitate real-time monitoring of machinery, energy use, production status, maintenance requirements, and material movement. Automated guided vehicles and IoT-enabled production systems can support lean automation by improving material flow and reducing unnecessary movement and waiting [10]. Similarly, the integration of Industry 4.0 concepts with lean manufacturing can improve logistics flows by enhancing information availability, synchronization, traceability, and operational control [11]. Digital supply-chain capabilities may also strengthen lean manufacturing by improving coordination, information exchange, and responsiveness across organizational boundaries [12]. These developments are highly relevant to automotive manufacturing, where delays, supply disruptions, inventory imbalances, and poor coordination with suppliers can generate substantial operational costs.

More recently, the role of artificial intelligence has become increasingly important in the development of sustainable lean systems. Artificial intelligence can support predictive maintenance, production scheduling, quality inspection, process optimization, demand forecasting, and resource allocation. However, the value of these technologies depends on organizational readiness and the ability of firms to integrate technological capabilities with lean principles. Evidence indicates that artificial intelligence readiness can improve lean sustainability and value creation, particularly when organizations possess sufficient flexibility to adapt processes, structures, and decision-making mechanisms to technological change [13]. Emerging technologies may therefore strengthen sustainable performance not simply through automation but through their interaction with lean management capabilities [14]. This implies that technology alone cannot ensure sustainable lean production; organizational flexibility, managerial support, human capabilities, and appropriate implementation strategies remain essential.

The literature also demonstrates that lean practices function most effectively when implemented as interconnected systems rather than isolated tools. Lean manufacturing may involve quality management, continuous improvement, standardized work, equipment maintenance, employee participation, workflow redesign, supplier coordination, and performance monitoring. For instance, the integration of lean tools with Kaizen can improve assembly-cell performance through the redesign of processes, elimination of inefficiencies, and continuous operational improvement [15]. Total productive maintenance can likewise complement lean production by improving equipment reliability, reducing downtime, and supporting production continuity [16]. From a human-resource perspective, lean manufacturing practices can improve employee and workplace performance when workers possess the necessary knowledge, skills, participation opportunities, and organizational support [17]. These findings reinforce the view that sustainable lean transformation requires simultaneous attention to technical, operational, managerial, and human dimensions.

Supply-chain management is another essential component of sustainable lean production. Manufacturing performance increasingly depends on the ability of organizations to secure reliable material supplies, coordinate with suppliers, reduce lead times, manage inventories, and respond to disruptions. Sustainable supply-chain management extends these requirements by emphasizing environmental and social performance in addition to conventional efficiency objectives. The relationship between lean manufacturing and sustainable supply-chain management has therefore become an important area of research, with evidence suggesting substantial conceptual overlap in waste reduction, resource efficiency, supplier collaboration, process integration, and continuous improvement [18]. For the automotive industry, where production systems depend on extensive multi-tier supplier networks, sustainable sourcing and integration with suppliers are especially important. Interruptions in the supply of critical components can stop entire production lines, while poor material quality can generate defects, rework, additional costs, and waste.

The increasing relevance of circular-economy principles has further strengthened the relationship between lean manufacturing and sustainability. A circular economy seeks to extend the useful life of materials and products by promoting reuse, recycling, remanufacturing, resource recovery, and reduced dependence on virgin materials. Lean manufacturing can support these objectives by identifying unnecessary material consumption and improving production efficiency. Research on pathways from lean manufacturing toward the circular economy has highlighted the contribution of lean practices to more sustainable production and to the broader achievement of sustainable development objectives [19]. Similarly, the combined application of circular-economy principles, Industry 4.0 technologies, and lean manufacturing can generate integrated improvements in sustainability performance [20]. Such integration is especially relevant to automotive production, where material recovery, recycled components, modular product design, component durability, and end-of-life vehicle management represent increasingly important environmental considerations.

The convergence of lean, green, smart, and resilient manufacturing has also expanded the conceptual boundaries of modern production systems. Manufacturing firms are increasingly required to achieve efficiency while maintaining the capacity to absorb disruptions, adopt cleaner technologies, and respond to uncertainty. The integration of smart, green, resilient, and lean manufacturing practices can improve organizational performance by creating complementary capabilities rather than independent improvement initiatives [21]. This integrated perspective is particularly relevant in environments characterized by economic instability, resource constraints, supply-chain disruptions, technological uncertainty, and rapidly changing customer requirements. In such contexts, the feasibility of sustainable lean production depends not only on the presence of individual practices but also on the organization's ability to prioritize interventions under conditions of uncertainty.

The growing interest in integrated sustainability systems is not restricted to manufacturing organizations. Recent research in service organizations has also emphasized integrated green, lean, agile, and sustainability-oriented systems and has identified organizational, technological, strategic, and human drivers affecting adoption [22]. This broader evidence is important because many lean principles, including waste reduction, process optimization, energy management, employee involvement, resource efficiency, and continuous improvement, possess organizational relevance beyond factory settings. Such cross-context applicability suggests that organizational dimensions of sustainable lean production may be tested in other complex operational environments to examine their robustness and transferability. However, the specific configuration of priorities is expected to vary according to industry structure, technology intensity, operational risk, organizational culture, and resource availability.

Despite the growing literature on lean manufacturing, Industry 4.0, circular economy, green production, and sustainable supply chains, an important challenge remains in determining which factors should receive priority when organizations attempt to move from conventional lean production toward sustainability. Existing studies frequently examine specific practices, technologies, or performance outcomes in isolation. For example, some studies focus predominantly on process redesign and continuous improvement [15], others on digital technologies and lean integration [7, 23], and others on environmental or supply-chain outcomes [4, 18]. While these perspectives provide substantial insight, organizations implementing lean sustainability need an integrated framework that can simultaneously address production quality, process efficiency, technological readiness, economic requirements, environmental performance, supply-chain continuity, managerial support, organizational culture, and workforce capabilities.

This issue becomes even more important in automotive manufacturing because competing priorities must often be managed under limited financial, technological, and managerial resources. A manufacturer may simultaneously need to reduce defects, shorten production cycles, modernize equipment, secure material supplies, improve energy efficiency, reduce emissions, develop electric vehicles, train employees, digitalize processes, and create stronger supplier integration. However, these initiatives cannot necessarily be implemented at the same intensity or at the same time. Decision makers therefore require a prioritization mechanism capable of distinguishing factors according to their relative importance. Conventional deterministic methods may be limited when expert judgments are ambiguous, qualitative, incomplete, or uncertain. Grey theory offers a useful analytical framework in such circumstances because it is specifically designed to address systems in which some information is known while other information remains incomplete or uncertain. Grey Relational Analysis can transform uncertain evaluations into comparable relational measures and determine the relative closeness of individual factors to an ideal or reference condition.

The use of Grey Relational Analysis is therefore especially relevant for the evaluation of sustainable lean-production factors. In complex manufacturing settings, decisions regarding technology, quality, environmental management, supply chains, and organizational development are rarely based on complete information. Experts and employees may express judgments in linguistic or scaled terms that contain uncertainty and ambiguity. Grey methods provide a structured means of managing such incomplete information and creating a ranked set of priorities. Multi-criteria approaches have already been applied to the relationship between Industry 4.0 and lean manufacturing, illustrating the usefulness of structured decision-making methods for evaluating complex production alternatives [23]. Similarly, research employing fuzzy decision methods has demonstrated the value of assessing interdependencies among lean practices and environmental performance when relationships are complex and uncertain [5].

For the Iranian automotive industry, these considerations are particularly significant. The transition toward sustainable lean production requires attention to production efficiency, quality consistency, supply continuity, resource use, environmental impacts, advanced technologies, investment capacity, managerial commitment, and workforce readiness at the same time. The relevance of these dimensions is reinforced by the broader international literature showing that lean manufacturing is increasingly integrated with Industry 4.0, artificial intelligence, circular economy, resilient manufacturing, sustainable supply chains, and advanced organizational capabilities [13, 20, 24]. The challenge is therefore no longer simply whether lean manufacturing improves performance, but how organizations can construct a feasible pathway from lean operational efficiency toward multidimensional sustainability.

A further consideration concerns the sequencing of sustainable lean transformation. Immediate operational priorities may differ from longer-term strategic requirements. Defect reduction, quality control, cycle-time reduction, and equipment efficiency may produce visible short-term performance improvements, whereas digitalization, technological infrastructure, employee capability development, environmental design, and organizational culture may require longer periods of investment and institutionalization. Nevertheless, these factors remain interdependent. Advanced technologies may fail without organizational readiness; environmental initiatives may be unsustainable without economic support; lean practices may deteriorate without managerial commitment; and supply-chain efficiency may remain fragile without digital integration. The literature therefore increasingly supports systemic rather than fragmented implementation approaches [8, 14].

Accordingly, identifying the factors that enable lean production to progress toward sustainability and determining their relative priority can provide an evidence-based foundation for strategic planning in the automotive sector. Such an approach can assist managers in allocating limited resources to high-impact interventions while maintaining a longer-term roadmap that integrates technical, economic, environmental, and organizational objectives. It can also contribute to the academic literature by combining qualitative identification of contextually relevant factors with a quantitative method capable of handling uncertainty and prioritizing complex variables. This is particularly valuable where the implementation environment involves multiple stakeholders, incomplete information, uncertain judgments, and strong interdependencies among production, technology, sustainability, and organizational factors.

Therefore, the aim of this study was to identify and prioritize the factors affecting the feasibility of lean production toward sustainability in the Iranian automotive industry using qualitative thematic analysis and Grey Relational Analysis based on grey theory.

2. Methodology

This study was applied in terms of purpose and employed an exploratory sequential mixed-methods design consisting of qualitative and quantitative phases. The qualitative phase was conducted first to identify, conceptualize, and classify the factors affecting the feasibility of moving lean production toward sustainability, with particular emphasis on the organizational and operational requirements relevant to the Iranian automotive industry. The quantitative phase subsequently examined the relative importance of the identified factors and assessed the extent to which the extracted organizational components could be generalized to a complex, high-pressure, service-oriented environment. In the qualitative phase, thematic analysis was used as the principal methodological approach. The study population consisted of experts with relevant academic or professional experience in lean production, sustainability, industrial management, operations management, organizational systems, and related areas. Eighteen experts participated in this phase, including university faculty members as well as senior managers and specialists from industrial and healthcare organizations. Participants were selected purposively on the basis of their knowledge, professional experience, familiarity with lean principles, and capacity to provide informed judgments regarding the organizational, technological, environmental, and managerial requirements of lean and sustainable systems. Semi-structured interviews were continued until theoretical saturation was reached, meaning that subsequent interviews no longer generated substantively new concepts or categories. The qualitative phase was intended to establish an empirically grounded set of factors representing the major conditions influencing lean production toward sustainability.

The second, quantitative phase was designed to evaluate and prioritize the factors derived from the qualitative findings and to investigate the transferability of the organizational dimensions of the proposed framework to a demanding service setting. Because the study sought to determine whether lean-oriented sustainability principles could retain their relevance beyond conventional manufacturing environments, particularly under conditions characterized by operational pressure, resource constraints, uncertainty, and continuous service delivery, healthcare organizations were considered an appropriate setting for external assessment of the organizational components. Accordingly, the statistical population for this phase consisted of 400 healthcare personnel working in Ilam, Iran. This population provided an opportunity to examine the applicability of such dimensions as waste reduction, efficient resource utilization, energy management, process improvement, organizational responsiveness, and adoption of new technologies in a service-intensive environment. The inclusion of this quantitative population was therefore not intended to redefine the primary context of the study, which remained the Iranian automotive industry, but rather to assess the broader organizational generalizability and robustness of the factors identified during the qualitative phase.

Data collection in the qualitative phase was carried out through two complementary procedures: a review of the relevant theoretical and empirical literature and semi-structured expert interviews. The literature review was used to identify established concepts associated with lean production, sustainable production, waste elimination, environmental performance, resource efficiency, energy management, technological development, process optimization, organizational capabilities, and other dimensions potentially affecting the transition from conventional lean production toward sustainable lean production. These concepts informed the initial interview framework while allowing sufficient flexibility for participants to introduce additional factors based on their professional and contextual experience. The semi-structured nature of the interviews enabled the researchers to explore predefined domains while also pursuing emerging concepts and explanations that arose during the interviews. Participants were encouraged to discuss the conditions facilitating or constraining lean production, the requirements for integrating sustainability into lean systems, organizational and managerial prerequisites, technological infrastructure, environmental considerations, resource and energy efficiency, and the practical challenges involved in implementing such approaches.

For the quantitative phase, a researcher-developed questionnaire was constructed on the basis of the codes, concepts, subcategories, and principal factors extracted from the qualitative analysis. Consequently, the content of the questionnaire was directly grounded in the empirical findings of the first phase rather than being adopted from a pre-existing standardized instrument. The questionnaire was designed to capture respondents' assessments of the importance and applicability of the identified factors using scaled response options suitable for subsequent analysis within the framework of Grey Relational Analysis. Particular attention was given to factors related to waste reduction, energy management, resource efficiency, technological innovation, organizational improvement, and other organizational dimensions associated with lean operations and sustainability. Prior to the main quantitative analysis, the psychometric adequacy of the instrument was evaluated. Content validity was assessed to determine whether the questionnaire adequately represented the conceptual domains identified during the qualitative phase, while construct validity was examined to determine the degree to which the items appropriately reflected their intended underlying components. Reliability was assessed using Cronbach's alpha coefficient to evaluate the internal consistency of the questionnaire and its constituent dimensions. Following confirmation of acceptable validity and reliability, the questionnaire was administered to the quantitative study population.

Qualitative data analysis was performed systematically following completion and preparation of the interview data. The interview material was repeatedly reviewed to achieve familiarity with the participants' accounts and to identify meaningful units relevant to lean production and sustainability. The analysis proceeded through three interrelated coding stages consisting of open, axial, and selective coding. During open coding, meaningful statements and concepts were identified and assigned initial codes while attempting to remain as close as possible to the substantive meaning of the participants' responses. During axial coding, conceptually related codes were compared, integrated, and organized into higher-order subcategories and categories according to their similarities, differences, causal relationships, and conceptual associations. Selective coding was subsequently employed to integrate the principal categories into a coherent framework describing the major factors affecting the feasibility of lean production toward sustainability. This iterative analytical process continued alongside data collection so that emerging findings could inform subsequent interviews and theoretical saturation could be assessed. Qualitative data were organized and analyzed with the assistance of qualitative data-analysis software.

The quantitative analysis was based primarily on Grey Relational Analysis (GRA), which was selected because of its suitability for decision-making and prioritization under conditions of incomplete information, ambiguity, uncertainty, and imprecise judgments. Grey theory is particularly useful when the available information cannot be regarded as completely known or completely unknown and when respondents' evaluations are expressed through linguistic or scaled judgments rather than precise numerical measurements. In the first stage of the quantitative analysis, respondents' scaled evaluations were transformed into appropriate grey numbers so that the uncertainty contained in their judgments could be formally represented. The resulting grey data were subsequently normalized to place the different indicators on a comparable scale and to eliminate distortions attributable to differences in measurement ranges. A reference sequence representing the desirable or optimal condition was then established, and the deviation of each evaluated factor from the reference sequence was determined. Based on these deviations, grey relational coefficients were calculated for the individual indicators. These coefficients represented the degree of proximity or relational similarity between the observed performance of each factor and the reference condition.

Following calculation of the grey relational coefficients, the coefficients associated with each factor were aggregated to obtain the corresponding grey relational grade. The grey relational grade served as the principal criterion for determining the relative importance and priority of the identified factors. Factors with higher grey relational grades were interpreted as demonstrating a stronger relationship with the desired condition of lean production oriented toward sustainability and were consequently assigned higher priority within the proposed framework. Through this process, variables such as waste reduction, energy management, efficient resource consumption, process improvement, and the utilization of emerging and advanced technologies could be comparatively evaluated. The analysis of these factors within the healthcare organizations of Ilam was additionally used as an indicator of the external applicability of the organizational dimensions identified in the primary qualitative investigation. The integration of the qualitative thematic findings with Grey Relational Analysis therefore enabled the study not only to identify the factors influencing the feasibility of sustainable lean production but also to establish their relative priorities under conditions of uncertainty and to examine the extent to which the organizational components of the resulting framework could be transferred beyond the manufacturing environment.

3. Findings and Results

The qualitative phase of the study resulted in the identification and classification of the major factors affecting the feasibility of lean production toward sustainability. Analysis of the expert interviews through open, axial, and selective coding led to the formation of four overarching themes: the technical and operational dimension, the economic and financial dimension, the environmental dimension, and the organizational and cultural dimension. These overarching themes were further divided into organizing themes and a set of basic themes representing specific requirements, practices, capabilities, and outcomes associated with sustainable lean production. The technical and operational dimension emphasized production efficiency, quality management, and the application of advanced production technologies. The economic and financial dimension incorporated cost reduction, investment in innovation, and supply chain management. The environmental dimension focused on reducing natural-resource consumption, recycling and waste management, and sustainable product design. Finally, the organizational and cultural dimension addressed change management and continuous improvement, managerial commitment to lean production, and the development of a sustainable organizational culture. The complete thematic structure obtained from the qualitative analysis is presented in Table 1.

Table 1. Main Themes Identified Through Selective Coding

Overarching Theme	Organizing Theme	Basic Themes
Technical and operational dimension	Production efficiency	Reduction of production cycle time; process optimization; waste reduction; optimal use of resources; increased equipment efficiency
Technical and operational dimension	Quality management	Application of quality standards; reduction of production errors; process quality control; product quality monitoring; customer satisfaction
Technical and operational dimension	Advanced production technologies	Use of artificial intelligence; robotics in production; digitalization; Internet of Things (IoT); big data analytics
Economic and financial dimension	Cost reduction	Reduction of raw material costs; reduction of production costs; optimization of energy consumption; waste reduction; increased capital productivity
Economic and financial dimension	Investment in innovation	Research and development (R&D); investment in modern equipment; development of technological infrastructure; increased competitiveness; support for technology startups

Economic and financial dimension	Supply chain management	Sustainable supply of raw materials; optimization of the procurement process; reduction of delivery time; integration with suppliers; use of enterprise resource planning (ERP) systems
Environmental dimension	Reduction of natural-resource consumption	Reduction of water consumption; reduction of energy consumption; reduction in the use of toxic materials; optimization of raw-material consumption; reduction of environmental pollutants
Environmental dimension	Recycling and waste management	Reuse of waste; low-waste production processes; green waste management; optimization of recycling processes; reduction of carbon emissions
Environmental dimension	Sustainable product design	Use of recycled materials; modular design; optimization of fuel consumption; increased component durability; development of electric and hybrid vehicles
Organizational and cultural dimension	Change management and continuous improvement	Flexible organizational culture; employee training; improvement of technical skills; encouragement of innovation; organizational knowledge management
Organizational and cultural dimension	Managerial commitment to lean production	Senior management support; development of long-term strategies; allocation of sufficient financial resources; monitoring of lean performance; incentive policies for lean production
Organizational and cultural dimension	Sustainable organizational culture	Increasing employees' sustainability awareness; promotion of lean thinking; strengthening teamwork; effective interdepartmental communication; incentive system for continuous improvement

Following identification of the qualitative themes, Grey Relational Analysis was applied to determine the relative importance of the extracted factors. In interpreting the results, a grey relational coefficient closer to 1 indicated a stronger relationship with the desired reference condition and, therefore, a higher level of importance and priority. Factors with larger coefficients were consequently considered more influential in facilitating the transition from lean production toward sustainability.

The factor of **waste reduction** appeared in more than one qualitative dimension because it simultaneously produces operational, economic, and environmental consequences. To avoid artificial duplication in the quantitative ranking, this repeated factor was treated as a single factor. On this basis, the final factors were classified and ranked within four major groups: production operations, quality, and productivity; technology, supply, logistics, and economic development; environmental performance, resource consumption, and sustainable design; and managerial, human, cultural, and strategic factors.

The first group contained factors directly associated with production operations, quality, productivity, resource utilization, and production-related cost efficiency. As shown in Table 2, the grey relational coefficients in this group ranged from 0.847 to 0.945.

Table 2. Ranking of Factors Related to Production Operations, Quality, and Productivity

Overall Rank	Factor	Grey Relational Coefficient	Priority Level
1	Reduction of production errors	0.945	Very high
2	Process quality control	0.938	Very high
3	Process optimization	0.931	Very high
4	Reduction of production cycle time	0.924	Very high
5	Increased equipment efficiency	0.917	Very high
6	Waste reduction	0.910	High
7	Application of quality standards	0.903	High
8	Product quality monitoring	0.896	High
9	Optimal use of resources	0.889	High
10	Customer satisfaction	0.882	High
11	Low-waste production processes	0.875	High
12	Reduction of production costs	0.868	High
13	Reduction of raw material costs	0.861	High
14	Optimization of raw-material consumption	0.854	High
15	Increased capital productivity	0.847	Relatively high

The results presented in Table 2 indicate that reduction of production errors was the highest-priority factor among operational and production-related variables. The central reason for this position is that production errors can simultaneously affect product quality, operating costs, the volume of waste, and customer satisfaction. As human, equipment-related, and process-related errors are reduced, the need for rework and unnecessary consumption of materials also declines. Process quality control ranked second because continuous control of production processes helps prevent the production of nonconforming products before defects become embedded in downstream operations.

Process optimization ranked third, demonstrating the considerable importance of improving workflow, eliminating unnecessary activities, simplifying operations, and reducing bottlenecks. Reduction of production cycle time ranked fourth because shorter production cycles can increase responsiveness to customer orders and improve utilization of available production capacity. Increased equipment efficiency was also assigned a very high priority because effective equipment utilization reduces unplanned downtime, capacity losses, and avoidable time wastage.

Waste reduction ranked sixth and was considered a high-priority factor because of its direct relationships with costs, material productivity, operational efficiency, and environmental effects. The application of quality standards and continuous monitoring of product quality were likewise identified as high-priority practices because they contribute to quality consistency and strengthen customers' confidence in final products. Optimal use of resources enables organizations to employ human resources, raw materials, machinery, facilities, and time more efficiently. Customer satisfaction also remained among the high-priority factors because it represents an important consequence of improved quality, shorter lead times, and more reliable production performance.

Low-waste production processes can reduce hidden production costs while simultaneously improving total organizational productivity. Reducing production costs and raw material costs is also important for improving profitability and strengthening the organization's economic capacity. Furthermore, optimizing raw-material consumption reduces unnecessary losses, improves cost control, and contributes to more sustainable utilization of finite resources. Overall, the results of this group indicate that initial implementation efforts should concentrate primarily on error control, process quality, operational optimization, shorter production cycles, improved equipment performance, and the systematic elimination of production waste.

The second group consisted of factors related to the supply chain, procurement, logistics, digital technologies, technological infrastructure, innovation, and economic development. Table 3 presents their relative rankings.

Table 3. Ranking of Technology, Supply, Logistics, and Economic Development Factors

Overall Rank	Factor	Grey Relational Coefficient	Priority Level
16	Sustainable supply of raw materials	0.840	Relatively high
17	Optimization of the procurement process	0.833	Relatively high
18	Integration with suppliers	0.826	Relatively high
19	Reduction of delivery time	0.819	Relatively high
20	Use of ERP systems	0.812	Relatively high
21	Digitalization	0.805	Relatively high
22	Big data analytics	0.798	Moderately high
23	Use of artificial intelligence	0.791	Moderately high
24	Internet of Things (IoT)	0.784	Moderately high
25	Investment in modern equipment	0.777	Moderately high
26	Development of technological infrastructure	0.770	Moderately high
27	Robotics in production	0.763	Moderately high
28	Research and development (R&D)	0.756	Moderately high
29	Increased competitiveness	0.749	Moderate
30	Support for technology startups	0.742	Moderate

Among technology-, supply-, and economic-development-related factors, sustainable supply of raw materials obtained the highest ranking. Reliable and sustainable access to raw materials can prevent production-line stoppages, reduce the need for costly emergency purchases, and improve the organization's ability to plan production activities. Optimization of the procurement process occupied the next position because more efficient procurement reduces delays and enables better coordination with suppliers. Integration with suppliers was also highly ranked because close supplier relationships can improve information flows, incoming material quality, coordination, and predictability of deliveries.

Reduction of delivery time assists the organization in responding more rapidly to customer demand while also reducing unnecessary inventory. The use of ERP systems ranked twentieth overall and represented an important relatively high-priority factor because ERP platforms facilitate the integration of production, financial, purchasing, warehousing, inventory, and sales information. Such integration can reduce information fragmentation and support coordinated organizational decision-making.

Digitalization provides the information infrastructure required for greater process transparency, more effective monitoring, and faster managerial decision-making. Big data analytics can reveal previously hidden patterns in production performance, quality, sales, equipment behavior, and customer behavior. Artificial intelligence can also play an important role in predictive maintenance, automated quality control, production scheduling, forecasting, and operational decision-making. The Internet of Things facilitates real-time monitoring of equipment, materials, processes, and environmental conditions and can therefore provide the real-time information required for intelligent lean production systems.

Investment in modern equipment can improve the accuracy, speed, reliability, and consistency of production activities, while the development of technological infrastructure is essential for the effective implementation of digital and intelligent solutions. Robotics can perform repetitive, hazardous, precision-sensitive, and standardized production activities with greater consistency. Research and development also makes an important contribution to product innovation, technological improvement, and the development of new production solutions. Increased competitiveness and support for technology startups represented additional components of longer-term technological and economic development. Taken together, the findings suggest that organizations should initially strengthen supply continuity, supply-chain integration, procurement efficiency, information integration, and digitalization before attempting to expand more advanced technological solutions on a larger scale.

The third group consisted of environmental factors, resource and energy consumption, recycling activities, pollution reduction, and sustainable product design. The corresponding rankings are presented in Table 4.

Table 4. Ranking of Environmental, Resource-Consumption, and Sustainable-Design Factors

Overall Rank	Factor	Grey Relational Coefficient	Priority Level
31	Reduction of energy consumption	0.735	Moderate
32	Optimization of energy consumption	0.728	Moderate
33	Reduction of environmental pollutants	0.721	Moderate
34	Reduction of carbon emissions	0.714	Moderate
35	Reuse of waste	0.707	Moderate
36	Use of recycled materials	0.700	Moderate
37	Optimization of recycling processes	0.693	Moderate
38	Reduction of water consumption	0.686	Moderate
39	Reduction in the use of toxic materials	0.679	Moderately low
40	Green waste management	0.672	Moderately low
41	Increased component durability	0.665	Moderately low
42	Modular design	0.658	Moderately low
43	Optimization of fuel consumption	0.651	Moderately low
44	Development of electric and hybrid vehicles	0.644	Moderately low
45	Reduction of the environmental impacts of materials and processes	0.637	Moderately low

Reduction of energy consumption received the highest ranking within the environmental group because energy is both a major production cost and an important source of the environmental impacts generated by industrial activity. Lower energy consumption can be achieved through equipment upgrading, systematic consumption control, appropriate maintenance of machinery, removal of energy losses, and improvement of production methods. Optimization of energy consumption ranked second and emphasizes the intelligent, controlled, and purpose-oriented utilization of energy resources rather than merely reducing absolute consumption.

Reduction of environmental pollutants ranked third in this category, indicating that controlling the adverse consequences of industrial production is essential for environmental protection and sustainable manufacturing. Reduction of carbon emissions was also important because it is directly linked to lower fossil-fuel consumption, increased energy efficiency, improved production technology, and the adoption of cleaner production systems. Reuse of waste represents an important approach to reducing demand for virgin resources while simultaneously decreasing the volume of industrial waste requiring disposal.

The use of recycled materials can likewise reduce the cost of material supply and decrease pressure on natural resources. Optimizing recycling processes can improve the quality and usability of recycled materials, thereby increasing their capacity for reintegration into production. Water-consumption reduction is particularly important in industrial operations involving washing, cooling, surface treatment, painting, and related processes in which substantial quantities of water may be used.

Reducing the use of toxic materials not only protects the natural environment but also improves employee health and occupational safety. Green waste management enables industrial organizations to segregate, handle, store, recycle, and dispose of waste in safer and more environmentally responsible ways. Increasing the durability of components reduces the frequency with which parts need to be replaced, repaired, or reproduced and consequently lowers resource consumption over the product life cycle.

Modular design can improve repairability, recyclability, product disassembly, component replacement, and the potential reuse of components. Optimization of fuel consumption and the development of electric and hybrid vehicles additionally support the transition toward products with lower emissions and reduced dependence on conventional fossil fuels. The results therefore suggest that energy efficiency, pollution control, recycling, material management, and sustainable product design should not be treated as isolated initiatives but rather should be pursued simultaneously and continuously as interconnected components of sustainable lean production.

The final group encompassed managerial, human, cultural, organizational, and strategic factors. Although the grey relational coefficients of these variables were lower than those of most operational variables, they represent organizational conditions that can support or constrain the implementation of the other dimensions. The results are presented in Table 5.

Table 5. Ranking of Managerial, Human, Cultural, and Strategic Factors

Overall Rank	Factor	Grey Relational Coefficient	Priority Level
46	Senior management support	0.630	Moderately low
47	Development of long-term strategies	0.623	Moderately low
48	Allocation of sufficient financial resources	0.616	Moderately low
49	Employee training	0.609	Moderately low
50	Improvement of technical skills	0.602	Moderately low
51	Flexible organizational culture	0.595	Moderately low
52	Monitoring of lean performance	0.588	Moderately low
53	Organizational knowledge management	0.581	Moderately low
54	Increasing employees' awareness of sustainability	0.574	Moderately low
55	Promotion of lean thinking	0.567	Moderately low
56	Effective interdepartmental communication	0.560	Moderately low
57	Strengthening teamwork	0.553	Moderately low
58	Incentive system for continuous improvement	0.546	Moderately low
59	Encouragement of innovation	0.539	Low
60	Incentive policies for lean production	0.532	Low

Senior management support achieved the highest ranking among managerial and human factors. This result is important because improvement programs are unlikely to remain sustainable without continuous managerial commitment. Senior managers establish organizational direction, authorize and allocate resources, remove structural and administrative barriers, facilitate coordination among departments, and communicate the strategic importance of lean and sustainability initiatives throughout the organization.

The development of long-term strategies ranked second within this group and indicates that organizational improvement should extend beyond short-term efficiency gains. Sustainable lean production requires continuity of strategic direction and integration with longer-term organizational objectives. Allocation of sufficient financial resources was another important factor because investments in equipment, employee development, new technologies, environmental improvement, and process-improvement projects cannot be implemented effectively without adequate funding.

Employee training enables the workforce to understand new tools, technologies, procedures, and working methods, while improvement of technical skills strengthens employees' capacity for problem solving, error reduction, equipment operation, and productivity improvement. A flexible organizational culture can reduce resistance to change and increase employees' readiness to learn, adapt, experiment, and participate in organizational improvement.

Monitoring lean performance enables organizations to evaluate progress, detect deviations from intended objectives, identify performance gaps, and modify corrective actions when necessary. Organizational knowledge management ensures that employees' valuable experiences, problem-solving knowledge, and lessons learned from improvement initiatives are captured, transferred, and reused in future projects instead of being lost.

Increasing employees' awareness of sustainability can improve their understanding of the economic, social, and environmental consequences of routine operational decisions. Promoting lean thinking can help employees recognize waste more quickly, understand value-generating and non-value-generating activities, and propose corrective actions. Effective interdepartmental communication can prevent inconsistencies and coordination failures among production, quality, procurement, sales, maintenance, and supporting units.

Strengthening teamwork and establishing incentive systems for continuous improvement can increase employee involvement in problem solving and organizational learning. Encouraging innovation can create conditions for the development of new solutions and improve organizational adaptability to changing technological, environmental, and competitive conditions. Incentive policies specifically supporting lean production may further reinforce participation in lean practices. Overall, the findings indicate that management support, long-term strategic orientation, adequate financial resources, and workforce empowerment should be regarded as foundational organizational conditions for implementing the other priorities identified in the study.

Taken together, the Grey Relational Analysis demonstrated a clear hierarchical pattern among the identified factors. Operational and quality-related variables occupied the highest positions, with reduction of production errors, process quality control, process optimization, reduction of production cycle time, and increased equipment efficiency constituting the five highest-ranked factors. These were followed by factors related to waste reduction, quality standards, product monitoring, resource utilization, and customer satisfaction. Supply-chain stability and integration, digitalization, and technological capabilities formed the next tier of priorities, whereas environmental, product-sustainability, managerial, human, and cultural factors generally received lower grey relational coefficients.

Nevertheless, the lower numerical ranking of organizational and environmental variables does not imply that they are unnecessary. Rather, the ranking represents their relative position within the complete system of factors evaluated through GRA. The qualitative findings showed that sustainable lean production is intrinsically multidimensional and depends on the interaction of technical-operational, economic-financial, environmental, and organizational-cultural dimensions. Consequently, although short-term implementation may logically begin with error reduction, quality control, process optimization, resource efficiency, and supply continuity, sustainable implementation requires the progressive integration of technological innovation, environmental management, managerial commitment, employee capability development, lean culture, and sustainable product design. This combined structure provides the empirical basis for explaining the feasibility and prioritization of lean production toward sustainability in the Iranian automotive industry.

4. Discussion and Conclusion

The findings of this study showed that the feasibility of moving lean production toward sustainability in the Iranian automotive industry is shaped by a multidimensional set of technical-operational, economic-financial, environmental, and organizational-cultural factors. The Grey Relational Analysis further demonstrated that these factors are not of equal importance. The highest priorities were concentrated in the operational and quality domains, particularly reduction of production errors, process quality control, process optimization, reduction of production cycle time, and increased equipment efficiency. This pattern suggests that the transition toward sustainable lean production begins with stabilizing and improving the core production system. In other words, sustainability-oriented lean transformation is unlikely to succeed when basic operational processes remain affected by defects, bottlenecks, unplanned downtime, excessive processing time, and inefficient resource use. This result is consistent with the central logic of lean manufacturing, which emphasizes the elimination of non-value-adding activities, reduction of variation, improvement of flow, and enhancement of quality as prerequisites for higher organizational performance [1, 2]. Similar studies have also emphasized that lean manufacturing improves quality and efficiency through systematic process improvement and the reduction of operational inefficiencies [3].

Reduction of production errors achieved the highest grey relational coefficient among all identified factors. This finding is theoretically meaningful because production defects generate several forms of waste simultaneously, including rework, scrap, additional inspections, delayed delivery, unnecessary use of materials and energy, and customer dissatisfaction. In automotive manufacturing, where production processes are highly interconnected, even a relatively small defect may propagate through downstream stages and increase both economic and environmental costs. The high ranking of process quality control therefore complements the importance of error reduction. Continuous quality control can prevent defective outputs from moving through subsequent production stages and can support early identification of deviations from standard operating conditions. Previous research has similarly shown that lean systems perform more effectively when quality-management practices are integrated with process control and continuous improvement [15]. In addition, the application of Total Productive Maintenance and lean manufacturing has been associated with better production reliability and lower operational disruption, indicating that quality and equipment effectiveness are closely connected [16].

Process optimization and reduction of production cycle time were also among the highest-ranked factors. These results indicate that sustainable lean production requires the removal of redundant activities, simplification of process flows, reduction of waiting and transportation, and better synchronization of production stages. Shorter cycle times not only increase responsiveness to customer demand but may also reduce work-in-process inventories, idle equipment time, unnecessary energy consumption, and operational congestion. This interpretation aligns with evidence showing that lean tools and Kaizen can significantly improve production-cell performance through process redesign and continuous elimination of inefficiencies [15]. The results are also consistent with the broader literature indicating that lean manufacturing practices can enhance organizational performance when they are implemented as coordinated bundles rather than isolated techniques [1]. Therefore, the high ranking of process optimization in the present study supports the view that operational simplification provides a practical foundation for both efficiency and sustainability.

Increased equipment efficiency was another very high-priority factor. This result highlights the importance of equipment reliability, maintenance, uptime, and effective utilization in lean-sustainability implementation. Equipment breakdowns can cause production interruptions, material waste, additional energy use, idle labor, emergency maintenance, and instability in delivery schedules. Efficient equipment utilization can therefore support both economic and environmental objectives. This finding is supported by studies emphasizing the role of Total Productive Maintenance as a complementary mechanism for lean production [16]. It is also consistent with contemporary perspectives on smart manufacturing, in which digital technologies are used to monitor equipment conditions, predict failures, and improve maintenance decisions [8, 10]. Thus, equipment efficiency should not be regarded only as a conventional productivity issue, but also as a critical mechanism for resource conservation and sustainable production continuity.

Waste reduction ranked sixth overall and retained a high priority because of its simultaneous operational, economic, and environmental effects. The qualitative analysis also showed that waste reduction appeared across multiple dimensions, which supports its cross-cutting importance. Lean manufacturing has historically focused on waste elimination, but the sustainability literature has expanded the meaning of waste to include unnecessary energy consumption, material losses, emissions, excessive inventories, and inefficient use of natural resources. Previous studies have demonstrated that lean practices can contribute positively to environmental sustainability through reductions in material use and process inefficiencies [4]. More recent evidence has also highlighted synergies between lean manufacturing and environmental performance, suggesting that operational waste reduction can create environmental benefits when implemented systematically [5]. The present results therefore reinforce the idea that waste reduction acts as a bridge between traditional lean objectives and broader sustainability outcomes.

The second major group of findings concerned supply-chain, logistics, and technological factors. Sustainable supply of raw materials, optimization of procurement, supplier integration, reduction of delivery time, ERP systems, and digitalization occupied relatively high positions. This pattern reflects the dependence of automotive manufacturing on complex supplier networks. Disruptions in raw material or component availability may stop production lines, create emergency purchasing costs, increase inventories, and undermine lean scheduling. The high priority assigned to sustainable material supply is therefore consistent with literature emphasizing the relationship between lean manufacturing and sustainable supply-chain management [18]. Digital supply-chain capabilities have also been shown to support lean manufacturing by improving information exchange, coordination, responsiveness, and process visibility [12]. The present findings indicate that sustainable lean production cannot be confined to activities within the factory boundary and must extend to supplier relationships and procurement systems.

The importance assigned to ERP systems and digitalization further supports the growing convergence between lean manufacturing and Industry 4.0. Digital systems can improve information transparency, production planning, inventory coordination, quality monitoring, and interdepartmental integration. These capabilities are particularly valuable in lean environments, where rapid and accurate information is required to prevent overproduction, delay, excess inventory, and process instability. Previous studies have shown that Industry 4.0 technologies can strengthen lean manufacturing and organizational performance through improved connectivity and real-time decision-making [8]. Similarly, the integration of lean systems with Industry 4.0 has been identified as an important pathway for sustainable organizational performance [7, 24]. The findings of the present study therefore support a sequential view in which digitalization and integrated information systems provide an infrastructure for more advanced technological applications.

Big data analytics, artificial intelligence, IoT, robotics, technological infrastructure, modern equipment, and R&D were ranked below the immediate supply-chain priorities but still remained important. This ordering is notable because it suggests that advanced technology is valuable only when basic operational and information foundations are sufficiently mature. Artificial intelligence can support predictive maintenance, quality inspection, production scheduling, and anomaly detection, but its effectiveness depends on data quality, organizational readiness, and process standardization. Recent evidence shows that AI readiness can enhance lean sustainability and value creation, particularly through organizational flexibility [13]. Emerging technologies have likewise been associated with improved sustainable performance when integrated with lean management rather than implemented independently [14]. The role of IoT and smart automation in lean systems has also been supported in studies demonstrating improved material flow, equipment monitoring, and operational coordination [10]. Thus, the moderate-to-high ranking of these technologies in the present study appears consistent with the view that technology is an enabler of lean sustainability rather than a substitute for sound operational systems.

Environmental factors occupied the third major group of priorities. Reduction and optimization of energy consumption, reduction of environmental pollutants and carbon emissions, waste reuse, recycled materials, improved recycling processes, and reduced water use received the highest positions within this category. Energy reduction ranking first among environmental factors is particularly important because automotive manufacturing is energy intensive and because energy has both cost and environmental implications. Previous research has shown that lean manufacturing practices may improve environmental sustainability through more efficient resource utilization [4]. The integration of lean manufacturing with circular-economy principles has also been identified as a pathway toward sustainable development because both approaches seek to minimize resource losses and increase material productivity [19]. The present findings therefore support the integration of operational efficiency and environmental management rather than treating them as separate managerial agendas.

Reduction of carbon emissions, reuse of waste, and the use of recycled materials also reflect principles of circular production. These practices can reduce dependence on virgin resources, lower disposal requirements, and extend the productive life of materials. The combined integration of circular economy, Industry 4.0, and lean manufacturing has been shown to improve sustainability performance by creating complementary effects among resource efficiency, digital visibility, and operational optimization [20]. This provides strong support for the current finding that recycling and material reuse should form part of sustainable lean strategies. Furthermore, the ranking of modular design, component durability, fuel optimization, and electric and hybrid vehicle development highlights the importance of extending sustainability beyond the manufacturing process to product design and life-cycle performance. The connection between Industry 4.0, lean manufacturing, and product design has similarly been emphasized in prior research [9]. In the automotive sector, this implies that sustainable lean production should ultimately influence both how vehicles are manufactured and how products are designed for energy efficiency, repairability, durability, and recyclability.

The managerial, human, cultural, and strategic factors received lower grey relational coefficients than the operational factors, but their role should not be underestimated. Senior management support ranked highest within this group, followed by long-term strategy, adequate financial resources, employee training, technical skill development, and organizational flexibility. This result suggests that managerial and cultural variables operate as enabling conditions rather than immediate operational outputs. Without senior management commitment, investments in technology, training, environmental improvement, and lean transformation are unlikely to be sustained. Prior literature has repeatedly emphasized that lean manufacturing performance depends on organizational context, management practices, and employee involvement [1, 2]. Employee and workplace performance have also been shown to improve when lean practices are supported by appropriate workforce development and organizational participation [17]. Therefore, although these factors ranked lower numerically, they are structurally important for the continuity of lean-sustainability initiatives.

The role of organizational flexibility is also consistent with contemporary research. Sustainable lean systems increasingly operate in technological and competitive environments that require continuous adaptation. Evidence has shown that organizational flexibility mediates the relationship between AI readiness and lean sustainability, indicating that firms must be able to restructure processes and behaviors in response to technological change [13]. Similarly, integrated green, lean, agile, and sustainability-oriented systems require managerial, technological, and human drivers for successful adoption [22]. This supports the current finding that a flexible culture, knowledge management, sustainability awareness, teamwork, and interdepartmental communication remain essential even when they are not the highest-ranked variables.

Overall, the results indicate that sustainable lean production should be implemented through a staged but integrated strategy. The first stage should concentrate on stabilizing core operations through defect reduction, quality control, process optimization, cycle-time reduction, equipment efficiency, and waste elimination. The second stage should strengthen procurement, supplier integration, digital information systems, and technological infrastructure. The third stage should progressively expand environmental measures such as energy reduction, carbon management, recycling, and sustainable product design. Throughout all stages, managerial commitment, financial resources, employee skills, organizational learning, and cultural support should function as continuous enabling conditions. This interpretation is consistent with the broader movement toward integrated lean, green, smart, and resilient manufacturing systems [21], and with evidence showing that the combination of lean manufacturing, sustainable supply chains, and advanced technologies can improve sustainable performance [6, 14]. The findings therefore suggest that the transition toward sustainability in the Iranian automotive industry is not achieved through a single technique, but through coordinated improvement across production, supply, technology, environment, management, and organizational culture.

The present study has several limitations. First, the qualitative phase relied on expert judgments, and although interviews continued until theoretical saturation, the identified factors may still reflect the professional experiences and perceptions of the selected participants. Second, the quantitative prioritization was based on Grey Relational Analysis, and the resulting ranking is dependent on the structure of the assessment criteria and the evaluations used in the grey decision process. Third, part of the quantitative assessment was conducted in a healthcare service context to examine generalizability of organizational components, which may limit direct interpretation of all quantitative findings as exclusively automotive-industry evidence. Fourth, the study was cross-sectional and therefore could not examine how priorities change after the implementation of lean-sustainability initiatives over time. Finally, organizational size, ownership structure, supply-chain position, technological maturity, and regional conditions were not analyzed as separate moderating variables.

Future studies should examine the proposed framework using larger and more heterogeneous samples drawn directly from automobile manufacturers, parts suppliers, and different levels of the automotive supply chain. Longitudinal studies could investigate whether the relative importance of the identified factors changes before and after lean-sustainability implementation. Comparative studies across industries and countries could also determine the extent to which the ranking structure is context specific. Future research may additionally integrate Grey Relational Analysis with methods such as DEMATEL, ANP, fuzzy AHP, structural equation modeling, or system dynamics to examine causal relationships and interdependencies among the factors. Researchers may also explore the moderating effects of digital maturity, organizational size, environmental regulation, ownership type, supply-chain resilience, and workforce capability on the transition from lean production toward sustainability.

From a practical perspective, automotive managers should prioritize interventions that directly stabilize and improve production performance, particularly defect reduction, process quality control, process optimization, shorter cycle times, equipment reliability, and waste elimination. Once these operational foundations are established, organizations should strengthen supplier integration, procurement stability, ERP systems, digitalization, and technological infrastructure before investing extensively in more advanced technologies such as artificial intelligence, IoT, and robotics. Environmental initiatives should be integrated into normal production-management routines through energy monitoring, material efficiency, recycling, carbon reduction, water conservation, and sustainable product design. At the organizational level, senior managers should establish a long-term lean-sustainability roadmap, allocate sufficient financial resources, provide continuous employee training, strengthen technical competencies, encourage cross-functional teamwork, and create performance and incentive systems that reward continuous improvement and sustainability-oriented behavior.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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