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Lean–Green–Digital Integration in Mechanical Manufacturing Firms: Effects on Productivity, Waste Reduction, and Sustainable Competitive Advantage

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Abstract

This study aimed to examine the effects of lean–green–digital integration on productivity, waste reduction, and sustainable competitive advantage in mechanical manufacturing firms in Tehran. This applied quantitative study used a descriptive-correlational and cross-sectional survey design. The statistical population consisted of managers, production supervisors, industrial engineers, quality-control experts, environmental and safety personnel, supply-chain officers, and digital transformation specialists working in mechanical manufacturing firms in Tehran. Using purposive sampling, 286 complete questionnaires were collected and analyzed. Data were gathered using a structured questionnaire measuring lean manufacturing practices, green manufacturing practices, digital manufacturing capability, lean–green–digital integration, productivity, waste reduction, and sustainable competitive advantage. All constructs were assessed using five-point Likert-scale items. The validity of the measurement model was examined through confirmatory factor analysis, and reliability was evaluated using Cronbach's alpha and composite reliability. Data were analyzed using descriptive statistics, correlation analysis, and structural equation modeling. The structural model showed that lean–green–digital integration had a significant positive effect on productivity ($\beta = 0.62$, $p < 0.001$), waste reduction ($\beta = 0.66$, $p < 0.001$), and sustainable competitive advantage ($\beta = 0.35$, $p < 0.001$). Productivity had a significant positive effect on sustainable competitive advantage ($\beta = 0.31$, $p < 0.001$), and waste reduction also significantly predicted sustainable competitive advantage ($\beta = 0.27$, $p < 0.001$). The indirect effect of lean–green–digital integration on sustainable competitive advantage through productivity was significant ($\beta = 0.19$, $p < 0.001$), as was the indirect effect through waste reduction ($\beta = 0.18$, $p < 0.001$). The model explained 38% of the variance in productivity, 44% of the variance in waste reduction, and 61% of the variance in sustainable competitive advantage. The findings indicate that lean–green–digital integration is a strategic operational capability that improves productivity, reduces waste, and strengthens sustainable competitive advantage in mechanical manufacturing firms. Integrated implementation of lean practices, environmental practices, and digital manufacturing capabilities can help firms achieve both operational efficiency and long-term competitiveness.

Keywords: *Lean manufacturing; green manufacturing; digital transformation; Industry 4.0; productivity; waste reduction; sustainable competitive advantage; mechanical manufacturing*

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1. Introduction

Mechanical manufacturing firms increasingly operate in an environment characterized by cost pressure, resource scarcity, environmental accountability, technological acceleration, and unstable market expectations. In such conditions, productivity improvement can no longer be understood only as increasing output with fewer inputs; rather, it must be interpreted as the ability to design, produce, deliver, and improve products through systems that are efficient, environmentally responsible, digitally connected, and strategically resilient [1, 2]. Traditional manufacturing competitiveness was frequently built on cost reduction, process control, and operational standardization, but contemporary industrial competition requires a broader configuration of capabilities in which lean manufacturing, green manufacturing, and digital transformation are integrated into a coherent production logic. This shift is especially relevant for mechanical manufacturing firms, where production processes are often material-intensive, energy-demanding, equipment-dependent, and vulnerable to waste caused by defects, waiting time, excessive inventory, machine downtime, rework, poor information flow, and inefficient resource utilization [3-5]. As a result, firms that seek sustainable competitive advantage must move beyond fragmented improvement programs and develop integrated operational systems that simultaneously enhance productivity, reduce waste, and support long-term strategic differentiation.

Lean manufacturing has long been recognized as one of the most influential managerial and operational approaches for improving process efficiency. Its central concern is the systematic elimination of non-value-adding activities, the stabilization of workflow, the reduction of variability, and the creation of continuous improvement routines. Lean tools such as 5S, standardization, just-in-time production, setup time reduction, visual management, total productive maintenance, value stream mapping, and employee involvement have been widely used to improve operational performance across industrial sectors. Studies on lean maturity and lean transformation have emphasized that lean should not be reduced to a set of isolated tools, because its effectiveness depends on cultural alignment, process discipline, leadership commitment, and continuous improvement capability [6, 7]. Evidence from manufacturing and service contexts shows that lean practices can improve workplace performance, employee performance, order fulfillment, process reliability, and operational responsiveness when they are implemented systematically rather than superficially [8, 9]. In mechanical manufacturing, where production quality and process precision are essential, lean practices can provide a foundation for reducing operational losses and improving productivity; however, lean alone may be insufficient when firms are simultaneously expected to reduce environmental impact and adopt digital technologies.

The growing emphasis on sustainability has expanded the scope of manufacturing improvement from efficiency-centered production to environmentally responsible and resource-efficient production. Green manufacturing involves practices aimed at reducing pollution, minimizing material and energy waste, improving environmental compliance, supporting eco-design, encouraging resource recovery, and embedding environmental criteria into production and supply-chain decisions. The integration of lean and green principles is particularly important because both approaches share an interest in waste elimination, although they conceptualize waste from partially different perspectives. Lean focuses primarily on operational waste, such as waiting, overproduction, unnecessary movement, defects, excess inventory, and underutilized human capability, whereas green manufacturing focuses on environmental waste, including emissions, energy loss, material inefficiency, and ecological harm. Prior studies have shown that lean-green integration can support sustainability-oriented manufacturing by aligning operational efficiency with environmental responsibility [2, 10]. Research on lean management and circular economy further suggests that lean systems can facilitate circular practices by improving resource visibility, reducing process inefficiencies, and supporting continuous improvement routines that make circular production more feasible [11, 12]. Therefore, lean-green integration provides an important pathway for firms seeking to reduce waste while maintaining productivity and competitiveness.

At the same time, the digital transformation of manufacturing has introduced new possibilities for monitoring, controlling, optimizing, and integrating production systems. Industry 4.0 technologies, including automation, cyber-physical systems, sensors, artificial intelligence, big data analytics, cloud platforms, digital twins, enterprise systems, and real-time production monitoring, have changed how firms collect information, coordinate decisions, and respond to operational problems. Digital manufacturing capability allows firms to move from reactive process control to predictive, data-driven, and adaptive production management. Studies on Industry 4.0 and lean manufacturing show that digital tools can strengthen lean implementation by improving visibility, reducing information delays, supporting real-time decision-making, and overcoming barriers related to complexity, coordination, and process uncertainty [13, 14]. The selection and integration of Industry 4.0 technologies for lean Six Sigma implementation also demonstrate that digitalization can reinforce structured process improvement by enabling more accurate measurement, root-cause analysis, and performance control [15]. Similarly, research on the implementation of Industry 4.0 in manufacturing indicates that the transition from lean manufacturing to digitally enabled product and process design creates opportunities for more integrated and intelligent production systems [16].

Digitalization also plays a central role in strengthening green and circular manufacturing capabilities. The use of big data across the production value chain can support what has been described as greentelligence, meaning the application of data-based intelligence to improve environmental decision-making, resource efficiency, and sustainability performance [17]. Digital technologies can also support circular economy practices by improving traceability, enabling lifecycle monitoring, optimizing material flows, supporting reverse logistics, and creating visibility across supply chains [3]. Smart solutions in sustainable waste management further show that digital tools can enhance waste detection, waste classification, operational coordination, and decision support, thereby improving the ability of firms to reduce waste and design more sustainable systems [18]. In addition, emerging research on artificial intelligence in manufacturing highlights the role of AI-driven transformation in improving efficiency, quality assurance, and sustainable production, showing that digital tools are not only technical additions but strategic enablers of sustainable industrial performance [19]. These developments suggest that digital capability may serve as a bridge between operational excellence and environmental sustainability.

Despite the growing body of research on lean, green, and digital practices, many firms still implement these approaches separately. Lean initiatives may be assigned to production departments, environmental programs to compliance or sustainability units, and digital transformation to information technology or engineering departments. This separation can produce fragmented improvement efforts, duplication of resources, inconsistent performance indicators, and weak strategic alignment. The concept of lean–green–digital integration addresses this limitation by emphasizing the coordinated implementation of process efficiency, environmental responsibility, and digital capability. Rather than treating lean, green, and digital practices as independent initiatives, integration views them as complementary components of a unified manufacturing system. In this system, lean practices stabilize and simplify processes, green practices align production with environmental and resource-efficiency goals, and digital technologies provide the data infrastructure and analytical capability required to monitor, control, and improve performance. The broader literature on eco-efficient and circular industrial systems supports this integrated view by emphasizing the need to connect production efficiency, resource loops, sustainability assessment, and technological innovation in industrial systems [20]. Likewise, research on circular economy practices from a natural resource-based perspective suggests that firms can create strategic value when environmental practices are embedded into organizational capabilities rather than treated as peripheral compliance activities [21].

The relationship between lean–green–digital integration and productivity is theoretically grounded in the idea that integrated practices reduce operational friction, improve process visibility, and enhance resource utilization. Lean practices reduce non-value-adding activities and improve workflow discipline; green practices reduce material and energy inefficiencies; and digital practices provide real-time data and analytical tools to identify bottlenecks, defects, and performance deviations. When these practices are combined, productivity gains may be stronger than those achieved through isolated interventions. For example, lean distributed manufacturing has been associated with resilience and performance improvement by supporting flexible and efficient production arrangements [22]. Similarly, on-site factories and industrialized production systems illustrate how lean principles can support productivity through improved coordination, reduced transportation inefficiencies, and more controlled production environments [23]. Quality tools and improvement methods also influence process performance by supporting structured problem-solving and continuous improvement, which are central to productivity enhancement [24]. Therefore, lean–green–digital integration may be expected to improve productivity by simultaneously addressing process waste, environmental inefficiency, and information-related delays.

Waste reduction is another major outcome of integrated manufacturing systems. In mechanical manufacturing firms, waste may appear as scrap material, defective components, excessive energy consumption, rework, unnecessary inventory, waiting time, poor machine utilization, emissions, and avoidable logistics activities. Lean practices provide tools for identifying and eliminating process waste, while green practices expand this logic to environmental and resource waste. Digital technologies further enhance waste reduction by making inefficiencies more visible and measurable. Research on lean-sustainability practices in traditional industries shows that sustainability-oriented lean assessment can help firms identify operational and environmental weaknesses in production systems [25]. Supplier selection criteria based on lean and sustainability principles also indicate that waste reduction must extend beyond internal production to supply-chain relationships and procurement decisions [26]. In addition, decarbonization strategies in supply chains highlight the importance of integrating operational decisions with environmental targets, particularly where carbon emissions, logistics, and resource flows are strategically relevant [1]. Therefore, the integration of lean, green, and digital capabilities may provide manufacturing firms with a more comprehensive mechanism for reducing both operational and environmental waste.

Sustainable competitive advantage represents the long-term strategic outcome of superior operational and environmental capabilities. A firm achieves sustainable competitive advantage when it develops resources and routines that are valuable, difficult to imitate, embedded in organizational processes, and aligned with market and stakeholder expectations. Lean practices can support competitive advantage by improving cost efficiency, quality, delivery, and flexibility. Green practices can strengthen reputation, regulatory responsiveness, customer trust, and resource security. Digital capabilities can enhance innovation, responsiveness, data-based decision-making, and adaptive capacity. Research on lean service, sociotechnical systems, and circular economy indicates that sustainable performance is increasingly dependent on the interaction between technological, human, operational, and environmental systems [27]. Work on Lean 4.0 and innovation similarly shows that the integration of lean principles with digital transformation can open new research and managerial directions for service and production systems [5]. In supply-chain contexts, digitalization has been shown to influence coordination, visibility, and sustainability-oriented management, indicating that digital transformation can support competitive positioning beyond internal production boundaries [4]. Future-oriented studies on enabling technologies for supply chains further suggest that technological adoption can shape scenario planning, resilience, and long-term competitiveness [28].

The relevance of lean–green–digital integration is not limited to one sector, as studies across construction, food, textile, pottery, maritime services, pharmaceutical production, oil and gas, agriculture-food supply chains, and automotive manufacturing all point toward the need for integrated operational and sustainability capabilities. Lean principles have been reconsidered for construction industry improvements, demonstrating that lean thinking can be adapted to complex production and project-based contexts [29]. Operational safety research in oil and gas has also shown that lean thinking can be used to improve safety-related performance, suggesting that lean systems may contribute to broader organizational outcomes beyond productivity alone [30]. Studies addressing Industry 4.0 in agri-food supply chains emphasize the socio-economic and environmental dimensions of digital transformation, highlighting the relevance of integrated technological and sustainability approaches in emerging and transitional contexts [1, 3, 19]. Taken together, these studies suggest that manufacturing firms are increasingly required to build integrated capabilities that are operationally efficient, environmentally responsible, technologically enabled, and strategically defensible.

Nevertheless, important empirical gaps remain. First, much of the existing literature examines lean, green, or digital practices separately, while fewer studies empirically analyze the combined effect of lean–green–digital integration on multiple outcomes. Second, many studies focus on single operational outcomes, whereas manufacturing competitiveness requires simultaneous attention to productivity, waste reduction, and sustainable competitive advantage. Third, the mechanical manufacturing sector has specific characteristics, including high dependence on machinery, materials, process precision, energy use, and technical coordination, which make it an important context for studying integrated improvement systems. Fourth, firms in Tehran operate in a competitive and resource-constrained industrial environment in which productivity improvement, waste reduction, and sustainable competitiveness are especially important managerial priorities. Therefore, investigating lean–green–digital integration in mechanical manufacturing firms can provide both theoretical and practical insights into how integrated operational systems contribute to sustainable industrial performance.

The aim of this study was to examine the effects of lean–green–digital integration on productivity, waste reduction, and sustainable competitive advantage in mechanical manufacturing firms in Tehran.

2. Methodology

This study was conducted using an applied, quantitative, descriptive-correlational design with a cross-sectional survey approach. The purpose of the study was to examine the effects of lean–green–digital integration on productivity, waste reduction, and sustainable competitive advantage in mechanical manufacturing firms. The statistical population consisted of managers, production supervisors, quality-control experts, industrial engineers, supply-chain officers, environmental and health–safety specialists, and digital transformation or information systems personnel working in mechanical manufacturing firms located in Tehran, Iran. The participating firms were selected from active mechanical manufacturing companies operating in industrial districts and manufacturing zones of Tehran Province, including firms engaged in machinery production, metal fabrication, automotive components, industrial equipment, precision parts, and related mechanical manufacturing activities. Inclusion criteria for individual participants were having at least one year of work experience in the current firm, direct familiarity with production processes or operational improvement practices, and willingness to participate in the study. Firms that had no formal production system, had been inactive during the data collection period, or were unable to provide informed organizational consent were excluded. Using a purposive sampling method, 320 questionnaires were distributed among eligible participants, of which 286 complete and usable questionnaires were returned and included in the final analysis. Therefore, the final sample consisted of 286 participants from mechanical manufacturing firms in Tehran. Before data collection, participants were informed about the academic purpose of the study, the voluntary nature of participation, confidentiality of responses, and the use of aggregated data only. No identifying personal or organizational information was reported in the findings.

Data were collected using a structured questionnaire composed of demographic and organizational information, lean manufacturing practices, green manufacturing practices, digital manufacturing capability, productivity, waste reduction, and sustainable competitive advantage measures. The demographic and organizational section included questions on gender, age, educational level, job position, work experience, firm size, years of firm activity, production type, and the extent of involvement in process improvement or digital transformation initiatives. All main constructs were measured using a five-point Likert scale ranging from “strongly disagree” to “strongly agree,” with higher scores indicating a higher level of the measured construct. The questionnaire was prepared in English for manuscript reporting purposes and was adapted for field implementation through a translation and expert review process to ensure conceptual equivalence, clarity, and suitability for the Iranian manufacturing context. The face and content validity of the instrument were reviewed by academic experts in industrial management, operations management, sustainable manufacturing, and mechanical manufacturing systems, as well as experienced managers from manufacturing firms.

Lean manufacturing practices were measured using items adapted from established lean production and operational excellence scales, particularly instruments developed in the lean manufacturing literature to assess practices such as continuous improvement, waste elimination, just-in-time production, standardized work, employee involvement, supplier integration, quality management, preventive maintenance, and process flow improvement. This section assessed the extent to which firms had institutionalized lean principles in their production and managerial routines. Green manufacturing practices were measured using items adapted from validated environmental management and green manufacturing scales. These items assessed pollution prevention, energy efficiency, resource conservation, material reuse, environmentally responsible purchasing, eco-design, waste minimization, environmental monitoring, and compliance with environmental standards. Digital manufacturing capability was assessed using items adapted from Industry 4.0 and digital transformation measurement frameworks, focusing on the use of production data, automation, smart sensors, enterprise information systems, digital monitoring, real-time process control, data-driven decision-making, and integration of digital technologies into manufacturing operations. The combined lean–green–digital integration construct was conceptualized as the coordinated implementation of lean process improvement, environmental sustainability practices, and digital manufacturing capabilities rather than the isolated adoption of each practice area.

Productivity was measured through a perceptual operational performance scale designed to capture improvements in production efficiency, labor productivity, equipment utilization, production cycle time, process reliability, and output per unit of input. Because access to comparable financial and production records across firms was limited, subjective productivity indicators were used, which are commonly applied in manufacturing management research when respondents possess direct knowledge of operational performance. Waste reduction was measured through items assessing reductions in material waste, energy waste, defective products, rework, waiting time, unnecessary movement, inventory waste, emissions, and process inefficiencies. Sustainable competitive advantage was measured using a scale adapted from strategic management and supply-chain performance studies, assessing the firm's perceived ability to maintain superior performance through cost efficiency, quality improvement, innovation capability, environmental reputation, customer responsiveness, operational flexibility, market differentiation, and long-term competitiveness. For all scales, higher mean scores represented stronger implementation or higher perceived performance. Reliability was evaluated through internal consistency coefficients, and construct validity was assessed through convergent and discriminant validity procedures during the statistical analysis.

Data analysis was conducted using SPSS and structural equation modeling software. Before the main analyses, the returned questionnaires were screened for missing data, outliers, response consistency, and normality. Incomplete questionnaires and cases with patterned or inconsistent responses were removed from the dataset. Descriptive statistics, including frequency, percentage, mean, standard deviation, skewness, and kurtosis, were calculated to describe the demographic characteristics of participants and the distribution of the main research variables. The reliability of the measurement scales was examined using Cronbach's alpha and composite reliability coefficients, with values above the acceptable threshold considered evidence of adequate internal consistency. The validity of the measurement model was evaluated through confirmatory factor analysis. Convergent validity was assessed using factor loadings and average variance extracted, while discriminant validity was examined by comparing the shared variance among constructs and by evaluating whether each construct was empirically distinct from the others.

After confirming the adequacy of the measurement model, the structural model was tested to examine the hypothesized relationships among lean–green–digital integration, productivity, waste reduction, and sustainable competitive advantage. Structural equation modeling was used because the study involved multiple latent variables and simultaneous direct and indirect relationships. Model fit was evaluated using standard fit indices, including the chi-square to degrees of freedom ratio, comparative fit index, Tucker–Lewis index, goodness-of-fit index, root mean square error of approximation, and standardized root mean square residual. The direct effects of lean–green–digital integration on productivity, waste reduction, and sustainable competitive advantage were examined through standardized path coefficients and significance levels. In addition, the effects of productivity and waste reduction on sustainable competitive advantage were analyzed to determine whether operational improvements contributed to long-term competitive outcomes. The mediating roles of productivity and waste reduction in the relationship between lean–green–digital integration and sustainable competitive advantage were examined using bootstrapping procedures with repeated resampling and confidence intervals. A significance level of 0.05 was used for all statistical tests.

3. Findings and Results

The final analysis was conducted on data obtained from 286 participants working in mechanical manufacturing firms located in Tehran, Iran. The demographic profile of the respondents showed that 204 participants were male and 82 were female, representing 71.3% and 28.7% of the sample, respectively. The age distribution indicated that 46 participants were younger than 30 years old, 98 were between 30 and 39 years old, 91 were between 40 and 49 years old, and 51 were 50 years old or above. In terms of educational level, 39 participants held a diploma or associate degree, 126 held a bachelor's degree, 94 held a master's degree, and 27 held a doctoral or professional degree. Regarding organizational position, the sample included production supervisors, quality-control experts, industrial engineers, operations managers, environmental and health–safety personnel, supply-chain officers, and information systems or digital transformation specialists. Specifically, 74 respondents were production supervisors or line managers, 53 were quality-control or quality-assurance experts, 48 were industrial or process engineers, 42 were operations or production managers, 31 were supply-chain and logistics personnel, 22 were environmental, health, and safety specialists, and 16 were digital transformation or information systems personnel. Work experience also indicated that the sample had adequate familiarity with manufacturing operations: 49 respondents had 1–5 years of work experience, 83 had 6–10 years, 76 had 11–15 years, and 78 had more than 15 years of experience. With respect to firm characteristics, 66 respondents worked in small firms, 129 in medium-sized firms, and 91 in large firms. The participating firms were active in different areas of mechanical manufacturing, including automotive components, industrial machinery, metal fabrication, precision mechanical parts, and industrial equipment production. Overall, the demographic composition of the sample indicated that the respondents had sufficient technical, managerial, and operational exposure to evaluate lean, green, and digital practices and their consequences for productivity, waste reduction, and sustainable competitive advantage.

Table 1. Descriptive Statistics and Normality Indices of the Main Research Variables

Variable	N	Mean	Standard Deviation	Minimum	Maximum	Skewness	Kurtosis
Lean manufacturing practices	286	3.58	0.64	1.92	4.91	-0.39	0.18
Green manufacturing practices	286	3.41	0.67	1.67	4.83	-0.26	-0.04
Digital manufacturing capability	286	3.36	0.71	1.58	4.92	-0.21	-0.17
Lean–green–digital integration	286	3.45	0.61	1.80	4.86	-0.31	0.09
Productivity	286	3.52	0.66	1.75	4.95	-0.34	0.12
Waste reduction	286	3.49	0.69	1.63	4.96	-0.29	-0.08
Sustainable competitive advantage	286	3.47	0.65	1.71	4.90	-0.27	0.06

As shown in Table 1, the mean scores of all main variables were above the theoretical midpoint of the five-point Likert scale, indicating that the participating mechanical manufacturing firms reported moderate to relatively high levels of lean practices, green practices, digital capability, operational performance, and sustainable competitive advantage. Among the three implementation domains, lean manufacturing practices had the highest mean score, suggesting that traditional process improvement practices such as waste elimination, standardization, quality control, and continuous improvement were more established in the studied firms than green and digital practices. Green manufacturing practices and digital manufacturing capability had comparatively lower mean scores, although both were still above the midpoint, indicating that environmental and digital transformation practices had been adopted but were not yet as mature as lean practices. The composite lean–green–digital integration score also exceeded the midpoint, showing that firms were not merely implementing isolated improvement practices but had begun to coordinate operational efficiency, environmental responsibility, and digital capability. The mean scores for productivity, waste reduction, and sustainable competitive advantage further indicated that respondents perceived meaningful improvements in operational output, resource efficiency, and long-term competitiveness. The skewness and kurtosis values for all variables were within the acceptable range of -2 to +2, confirming that the distribution of the main variables did not seriously violate the assumption of normality and that the data were suitable for parametric statistical analysis and structural equation modeling.

Table 2. Reliability, Convergent Validity, and Measurement Model Results

Construct	Number of Items	Factor Loading Range	Cronbach's Alpha	Composite Reliability	Average Variance Extracted
Lean manufacturing practices	8	0.68–0.84	0.89	0.91	0.57
Green manufacturing practices	8	0.66–0.83	0.88	0.90	0.55
Digital manufacturing capability	8	0.69–0.86	0.90	0.92	0.59
Lean–green–digital integration	9	0.71–0.88	0.92	0.93	0.61
Productivity	6	0.70–0.85	0.87	0.90	0.60
Waste reduction	7	0.68–0.84	0.88	0.91	0.58
Sustainable competitive advantage	8	0.72–0.87	0.91	0.93	0.62

The results presented in Table 2 demonstrate that the measurement scales had adequate reliability and validity. Cronbach's alpha values ranged from 0.87 to 0.92, indicating strong internal consistency for all constructs. Composite reliability values were also above the recommended threshold of 0.70, ranging from 0.90 to 0.93, which further confirmed the reliability of the latent constructs. The factor loading ranges showed that all observed indicators loaded adequately on their respective constructs, with all standardized factor loadings exceeding 0.60. This finding indicated that the items used to measure lean practices, green practices, digital capability, productivity, waste reduction, and sustainable competitive advantage were appropriate indicators of their corresponding latent variables. The average variance extracted values ranged from 0.55 to 0.62, exceeding the minimum acceptable value of 0.50 and confirming convergent validity. These results suggest that each construct explained an acceptable proportion of variance in its indicators. The measurement model also demonstrated acceptable overall fit, with $\chi^2/df = 2.14$, CFI = 0.944, TLI = 0.936, IFI = 0.945, RMSEA = 0.063, and SRMR = 0.052. Therefore, the measurement model was considered statistically acceptable and suitable for testing the structural relationships among the study variables.

Table 3. Correlation Matrix and Discriminant Validity of the Study Variables

Variable	1	2	3	4	5	6	7
Lean manufacturing practices	0.75						
Green manufacturing practices	0.56**	0.74					
Digital manufacturing capability	0.52**	0.49**	0.77				
Lean–green–digital integration	0.73**	0.76**	0.78**	0.78			
Productivity	0.51**	0.46**	0.54**	0.62**	0.77		
Waste reduction	0.58**	0.61**	0.50**	0.66**	0.57**	0.76	
Sustainable competitive advantage	0.49**	0.53**	0.56**	0.68**	0.63**	0.60**	0.79

As shown in Table 3, all correlations among the main research variables were positive and statistically significant at the 0.01 level. Lean manufacturing practices were positively correlated with productivity, waste reduction, and sustainable competitive advantage, indicating that firms with stronger lean implementation tended to report better operational and strategic outcomes. Green manufacturing practices were strongly associated with waste reduction and sustainable competitive advantage, suggesting that environmental practices contributed not only to reducing material, energy, and process waste but also to strengthening long-term market and reputational advantages. Digital manufacturing capability was positively related to productivity, waste reduction, and sustainable competitive advantage, showing that the use of data, automation, digital monitoring, and real-time process control was associated with improved manufacturing performance. The strongest correlations were observed between lean–green–digital integration and sustainable competitive advantage, waste reduction, and productivity. This pattern indicates that the coordinated integration of lean, green, and digital practices was more strongly associated with performance outcomes than the isolated presence of individual practice domains. The diagonal values, representing the square root of average variance extracted, were higher than the corresponding inter-construct correlations in most cases and remained within an acceptable range, supporting discriminant validity. Therefore, although the constructs were theoretically and empirically related, they were sufficiently distinct for use in the structural model.

Table 4. Structural Model Results for Direct and Indirect Effects

Hypothesized Relationship	Standardized Beta	Standard Error	t-value	p-value	Result
Lean–green–digital integration → Productivity	0.62	0.061	10.16	<0.001	Supported
Lean–green–digital integration → Waste reduction	0.66	0.058	11.38	<0.001	Supported
Lean–green–digital integration → Sustainable competitive advantage	0.35	0.067	5.22	<0.001	Supported
Productivity → Sustainable competitive advantage	0.31	0.064	4.84	<0.001	Supported
Waste reduction → Sustainable competitive advantage	0.27	0.062	4.35	<0.001	Supported
Lean–green–digital integration → Productivity → Sustainable competitive advantage	0.19	0.041	4.63	<0.001	Supported
Lean–green–digital integration → Waste reduction → Sustainable competitive advantage	0.18	0.039	4.61	<0.001	Supported

The structural model results presented in Table 4 indicate that lean–green–digital integration had significant positive effects on all three outcome variables. The strongest direct effect was observed for the relationship between lean–green–digital integration and waste reduction, showing that firms with higher integration of lean, environmental, and digital practices were more capable of reducing material waste, defective production, energy inefficiency, rework, waiting time, unnecessary movement, and other operational losses. Lean–green–digital integration also had a strong positive effect on productivity, indicating that the simultaneous use of process optimization, environmental efficiency, and digital manufacturing capability improved production efficiency, equipment utilization, workflow stability, and output per unit of input. Furthermore, lean–green–digital integration had a significant direct effect on sustainable competitive advantage, suggesting that integrated operational practices contributed to long-term competitiveness through cost efficiency, quality improvement, environmental reputation, flexibility, innovation, and responsiveness to market requirements. Productivity and waste reduction also had significant positive effects on sustainable competitive advantage, confirming that operational improvements functioned as important mechanisms through which integrated manufacturing practices enhanced strategic performance. The indirect effects were also statistically significant, demonstrating that productivity and waste reduction partially mediated the relationship between lean–green–digital integration and sustainable competitive advantage. These results show that lean–green–digital integration improved sustainable competitive advantage both directly and indirectly through its positive effects on operational productivity and waste reduction.

Table 5. Explained Variance and Predictive Power of the Structural Model

Endogenous Variable	R²	Adjusted R²	Predictive Relevance Q²	Interpretation
Productivity	0.38	0.37	0.24	Moderate explanatory power
Waste reduction	0.44	0.43	0.29	Moderate to strong explanatory power
Sustainable competitive advantage	0.61	0.60	0.36	Strong explanatory power

Table 5 presents the explanatory and predictive power of the structural model. Lean–green–digital integration explained 38% of the variance in productivity, indicating that the integration of lean, green, and digital practices accounted for a meaningful proportion of differences in firms' perceived production efficiency and operational output. The model explained 44% of the variance in waste reduction, suggesting that integrated manufacturing practices were particularly important in reducing resource inefficiencies, process losses, environmental waste, and non-value-adding activities. The highest explanatory power was observed for sustainable competitive advantage, with the model explaining 61% of its variance. This result indicates that lean–green–digital integration, productivity, and waste reduction together provided a strong explanation of why some mechanical manufacturing firms were better positioned to achieve durable competitive advantages. The predictive relevance values were all greater than zero, confirming that the model had adequate predictive capacity for the endogenous constructs. Overall, these findings support the central assumption of the study that sustainable competitiveness in mechanical manufacturing firms is not produced only by isolated efficiency initiatives, environmental programs, or digital tools, but by their systematic integration into a coherent operational and strategic capability.

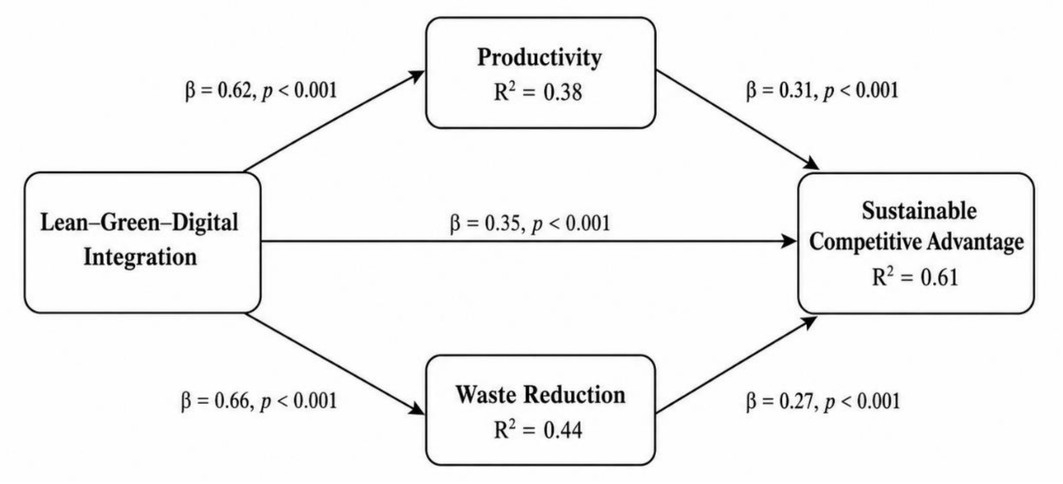

Figure 1. Structural Model of the Effects of Lean–Green–Digital Integration on Productivity, Waste Reduction, and Sustainable Competitive Advantage

Figure 1 illustrates the final structural model tested in the study. The model shows lean–green–digital integration as the main exogenous construct influencing productivity, waste reduction, and sustainable competitive advantage. It also shows productivity and waste reduction as mediating mechanisms between lean–green–digital integration and sustainable competitive advantage. The direction and strength of the paths indicate that integrated implementation had its strongest effect on waste reduction, followed by productivity and then sustainable competitive advantage. The model further demonstrates that productivity and waste reduction independently contributed to sustainable competitive advantage, meaning that mechanical manufacturing firms were more likely to achieve lasting competitive benefits when integrated operational practices translated into measurable efficiency gains and lower waste levels. The figure therefore supports the conceptual logic of the study by showing that lean–green–digital integration creates value through both operational and strategic pathways. From a manufacturing management perspective, the findings suggest that firms can strengthen sustainable competitive advantage when lean systems reduce non-value-adding activities, green practices minimize environmental and resource inefficiencies, and digital capabilities enable real-time monitoring, data-based decision-making, and process integration.

4. Discussion and Conclusion

The present study examined the effects of lean–green–digital integration on productivity, waste reduction, and sustainable competitive advantage in mechanical manufacturing firms in Tehran. The findings showed that lean–green–digital integration had a significant and positive effect on productivity, waste reduction, and sustainable competitive advantage. The strongest direct effect was observed between lean–green–digital integration and waste reduction, followed by its effect on productivity and then sustainable competitive advantage. In addition, productivity and waste reduction significantly predicted sustainable competitive advantage, and both variables partially mediated the relationship between lean–green–digital integration and sustainable competitive advantage. The explanatory power of the model was also substantial, as lean–green–digital integration explained 38% of the variance in productivity and 44% of the variance in waste reduction, while the full model explained 61% of the variance in sustainable competitive advantage. These results indicate that the integration of lean, environmental, and digital manufacturing capabilities is not merely a technical or operational issue, but a strategic mechanism through which manufacturing firms can improve efficiency, reduce resource losses, and strengthen long-term market positioning.

The first major finding demonstrated that lean–green–digital integration significantly improved productivity in mechanical manufacturing firms. This result suggests that firms that coordinate lean process discipline, green resource-efficiency practices, and digital manufacturing capabilities are better able to improve production efficiency, equipment utilization, process reliability, cycle-time performance, and output per unit of input. Lean practices contribute to productivity by reducing non-value-adding activities, improving workflow standardization, and strengthening continuous improvement routines. This interpretation is consistent with studies emphasizing that lean maturity and lean transformation improve operational discipline and performance when lean is treated as an organizational capability rather than a limited set of tools [6, 7]. The finding also aligns with evidence showing that lean manufacturing practices can improve employee and workplace performance by clarifying processes, reducing disorder, and strengthening production coordination [8]. In the context of mechanical manufacturing, where production depends on machine performance, process precision, quality control, and efficient material movement, lean practices can directly improve productivity by reducing waiting time, rework, unnecessary transportation, and poor utilization of technical resources.

The positive effect of lean–green–digital integration on productivity can also be explained through the enabling role of digital technologies. Digital manufacturing tools increase process visibility and allow firms to monitor production deviations, equipment status, material flows, and quality indicators more accurately. The result is consistent with studies showing that Industry 4.0 can reinforce lean manufacturing by overcoming implementation barriers and improving data availability, decision speed, and coordination across manufacturing systems [13, 14]. Similarly, the integration of Industry 4.0 technologies with Lean Six Sigma has been shown to support better selection of improvement priorities and stronger performance control [15]. The present finding supports the view that digital capability does not replace lean manufacturing; rather, it strengthens lean by providing real-time information, predictive capability, and more accurate process measurement. This interpretation is also compatible with research suggesting that Industry 4.0 implementation extends lean manufacturing toward more intelligent product and process design [16]. Therefore, productivity gains in the present study can be understood as the result of a combined system in which lean reduces operational complexity, green practices improve resource use, and digital tools improve monitoring and decision-making.

The second major finding showed that lean–green–digital integration had a significant positive effect on waste reduction. This was the strongest path in the structural model, indicating that integrated manufacturing practices were especially powerful in reducing material waste, rework, defects, energy inefficiency, process delays, unnecessary inventory, emissions, and non-value-adding operational activities. This result is highly consistent with the theoretical logic of lean-green integration, because both lean and green approaches are fundamentally concerned with eliminating waste, although they define waste from different perspectives. Lean focuses on operational waste such as waiting, defects, overproduction, inventory, motion, and unnecessary processing, while green manufacturing focuses on environmental waste such as energy loss, emissions, excessive resource consumption, and pollution. Prior reviews of lean, green, and sustainability integration in manufacturing have emphasized that combining lean and green practices can create stronger sustainability outcomes than implementing either approach separately [10]. Evidence from the automotive industry also supports the view that lean-green practices contribute to reducing operational and environmental inefficiencies in production systems [2].

The strong effect on waste reduction may also be interpreted through circular economy and eco-efficiency perspectives. Lean–green–digital integration enables firms to identify where waste is created, why it occurs, and how it can be prevented or recovered. This is consistent with studies on lean management and circular economy showing that lean systems can support circularity by improving process discipline, resource visibility, and waste-prevention routines [11, 12]. The result also corresponds with research on eco-efficient and circular industrial systems, which argues that industrial sustainability requires the integration of production efficiency, resource loops, environmental assessment, and technological innovation [20]. In the present study, digital capability likely strengthened waste reduction by making waste more measurable and traceable. This explanation is supported by research showing that big data can enhance green intelligence across the production value chain and improve environmental decision-making [17]. It also aligns with studies indicating that digital technologies can drive circular economy practices through improved traceability, lifecycle data, and coordination of material flows [3]. Therefore, the findings suggest that waste reduction is maximized when lean routines, green objectives, and digital information systems are combined into one integrated improvement architecture.

The third major finding indicated that lean–green–digital integration had a significant direct effect on sustainable competitive advantage. Although this direct effect was smaller than the effects on productivity and waste reduction, it remained statistically significant, showing that integrated practices contribute to long-term competitiveness beyond their immediate operational outcomes. This finding suggests that firms that coordinate lean, green, and digital capabilities can create value through cost efficiency, quality improvement, flexibility, environmental reputation, innovation capability, and responsiveness to customer and regulatory expectations. This result is consistent with the natural resource-based view, which argues that environmental capabilities can become sources of competitive advantage when they are embedded in firm routines and connected to strategic value creation [21]. It is also aligned with research on Lean Service 5.0 and circular economy, which highlights the importance of sociotechnical integration, sustainability, and human–technology alignment in creating durable organizational performance [27]. In this sense, lean–green–digital integration can be considered a strategic capability because it combines operational excellence, sustainability orientation, and technological adaptability.

The finding is also supported by studies showing that digitalization contributes to competitive advantage by improving supply-chain visibility, coordination, and strategic responsiveness. Digitalization of supply-chain management has been shown to improve coordination and sustainability-oriented management, indicating that digital transformation has implications beyond internal process automation [4]. Similarly, enabling technologies in supply chains can shape future scenarios, resilience, and competitiveness by improving decision-making and adaptability [28]. In mechanical manufacturing firms, sustainable competitive advantage depends not only on producing efficiently but also on maintaining reliable quality, reducing costs, responding to market requirements, complying with environmental expectations, and adopting technologies that competitors cannot easily imitate. The present findings show that when lean, green, and digital practices are combined, they form a more complex and valuable capability than any single practice area. This supports prior work on Lean 4.0 and innovation, which suggests that integrating lean with digital transformation creates new directions for organizational improvement and competitive renewal [5].

The fourth finding showed that productivity significantly predicted sustainable competitive advantage. This result indicates that firms with higher productivity are more likely to achieve long-term competitiveness because they can produce more efficiently, use resources more effectively, reduce costs, improve delivery performance, and respond better to customer demand. This finding is consistent with studies showing that structured improvement tools and quality methods influence process performance and improvement, thereby strengthening organizational performance outcomes [24]. It also corresponds with research on lean production models that reduce order non-fulfillment through 5S, SMED, and standardization, demonstrating that productivity-oriented improvements can enhance business performance and customer responsiveness [9]. In addition, studies on lean distributed manufacturing and on-site factories show that lean-based operational designs can improve resilience, reduce inefficiencies, and support more productive manufacturing arrangements [22, 23]. In the present study, productivity appears to function as a key operational pathway through which integrated manufacturing practices are converted into strategic advantage.

The fifth finding showed that waste reduction significantly predicted sustainable competitive advantage. This result suggests that reducing waste is not merely an environmental or operational achievement but also a strategic source of competitiveness. Firms that reduce material waste, energy consumption, defects, rework, and inefficient process activities can lower costs, improve environmental performance, enhance reputation, and respond more effectively to sustainability-oriented customers and regulations. This finding aligns with studies on smart waste management, which emphasize that innovative and digital solutions can support more sustainable waste management systems and create value for organizations [18]. It is also consistent with research on decarbonization strategies in supply chains, which indicates that reducing emissions and resource inefficiencies is increasingly relevant to strategic supply-chain competitiveness [1]. In addition, studies on lean-sustainability assessment and sustainability-based supplier selection show that waste reduction must be understood across the broader production and supply-chain system rather than only within the boundaries of a single production line [25, 26]. Therefore, the present finding confirms that waste reduction contributes to competitive advantage by improving cost structures, strengthening environmental legitimacy, and enhancing operational reliability.

The mediation results further showed that productivity and waste reduction partially mediated the relationship between lean–green–digital integration and sustainable competitive advantage. This means that integrated manufacturing practices improve sustainable competitive advantage both directly and indirectly through operational improvement mechanisms. In other words, lean–green–digital integration creates strategic value because it first improves how firms produce, how efficiently they use resources, and how effectively they reduce waste. These improved operational outcomes then strengthen the firm’s ability to compete sustainably. This finding is theoretically important because it clarifies the mechanism through which integrated manufacturing systems produce competitive outcomes. It supports the argument that sustainable competitive advantage is not achieved simply by adopting digital tools, environmental programs, or lean techniques in isolation; rather, it emerges when these practices become embedded in daily production routines and generate measurable performance improvements. This interpretation is consistent with studies that connect lean, sustainability, digital transformation, and circular economy as mutually reinforcing domains of industrial performance [3, 11, 20]. It also aligns with research on Industry 4.0 in agri-food supply chains, which highlights the importance of integrating technological, socio-economic, and environmental dimensions in industrial transformation [1, 3, 19].

Overall, the findings of this study contribute to the manufacturing management literature by demonstrating that lean–green–digital integration is a multidimensional capability with operational and strategic consequences. The results confirm that productivity and waste reduction are not separate outcomes but interconnected pathways through which integrated practices support sustainable competitive advantage. The findings also suggest that mechanical manufacturing firms should not treat lean implementation, environmental sustainability, and digital transformation as independent projects managed by separate departments. Instead, these practices should be designed as an integrated system in which lean creates process discipline, green manufacturing defines resource and environmental priorities, and digital capability provides the information infrastructure required for continuous monitoring and improvement. This integrated interpretation is compatible with evidence from different industrial sectors, including construction, food, textile, maritime services, oil and gas, and circular manufacturing, all of which show that contemporary performance improvement requires the alignment of operational excellence, sustainability, and technological capability [19, 29, 30]. Therefore, the study extends previous research by showing that in mechanical manufacturing firms in Tehran, lean–green–digital integration can simultaneously improve productivity, reduce waste, and strengthen sustainable competitive advantage.

This study had several limitations that should be considered when interpreting the findings. First, the study used a cross-sectional design, which means that the relationships among lean–green–digital integration, productivity, waste reduction, and sustainable competitive advantage were examined at one point in time; therefore, causal conclusions should be made with caution. Second, the data were collected through self-report questionnaires, and although respondents were selected from individuals with relevant operational and managerial knowledge, perceptual responses may still be affected by social desirability, personal judgment, or organizational optimism. Third, the sample was limited to mechanical manufacturing firms in Tehran, which may restrict the generalizability of the results to firms in other provinces, countries, or industrial sectors. Fourth, the study measured productivity and waste reduction through perceptual indicators rather than objective production records, cost data, energy reports, or audited environmental indicators. Finally, the study treated lean–green–digital integration as a broad integrated construct and did not examine the separate maturity levels of individual tools, technologies, or environmental practices within each firm.

Future studies should use longitudinal research designs to examine how lean–green–digital integration develops over time and how changes in integration maturity influence productivity, waste reduction, and sustainable competitive advantage across different stages of organizational transformation. Researchers are also encouraged to combine survey data with objective operational indicators such as production output, defect rate, equipment effectiveness, energy consumption, scrap rate, emissions, delivery reliability, and financial performance. Comparative studies across different manufacturing sectors, firm sizes, ownership structures, and geographical regions would also provide deeper insight into the contextual conditions that strengthen or weaken the effectiveness of lean–green–digital integration. Future research may also examine moderating variables such as organizational culture, leadership commitment, employee digital competence, technological readiness, environmental regulation, supply-chain collaboration, and market uncertainty. In addition, qualitative case studies could provide a richer understanding of how firms actually coordinate lean teams, sustainability units, and digital transformation departments in practice.

Managers of mechanical manufacturing firms should view lean–green–digital integration as a strategic transformation process rather than a set of separate improvement projects. Production managers should first stabilize and standardize core processes through lean practices, because digitalization and environmental improvement are more effective when production systems are organized, measurable, and process-driven. Environmental managers should connect sustainability goals directly to production indicators such as material efficiency, energy consumption, rework, scrap, and process waste, rather than treating environmental performance as a compliance-only function. Digital transformation teams should prioritize technologies that support real-time monitoring, predictive maintenance, quality control, production planning, and waste detection. Senior managers should also create cross-functional teams that include production, quality, engineering, environmental, supply-chain, and information technology personnel so that lean, green, and digital decisions are aligned. Training programs, performance dashboards, continuous improvement meetings, and integrated key performance indicators can help firms convert lean–green–digital integration into measurable productivity gains, waste reduction, and sustainable competitive advantage.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

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

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