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Effects of lean and green supply chain management practices on the performance of Hungarian manufacturing companies

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Abstract

Ensuring long-term sustainability and maintaining competitiveness are critical challenges for manufacturing enterprises. In this study the authors investigated the hypothesis that the adoption of Lean and GSCM practices affects corporate performance across environmental, economic, and operational dimensions. The data consisted of a sample of 125 Hungarian manufacturing firms that had adopted Lean management principles. To the authors' knowledge, no comparable large-scale empirical investigation has been conducted in Hungary, thus the research is unique in the national literature. The study employed Partial Least Squares Path Modelling (PLS-PM) as the analytical approach to the analysis. The findings indicate that Lean practices as side effects independently yield notable efficiency improvements, primarily in waste reduction and process optimisation what are coincides with GSCM initiatives too. However, the results also demonstrate that GSCM alone cannot produce such results on corporate performance only when it combined with Lean. A strong positive relationship was found between the two approaches: Lean fosters the adoption of GSCM elements—such as green procurement and eco-design—which in turn indirectly enhance both economic and operational performance. The practical implication of the research is that it revealed that the manufacturing firms may gain measurable competitive advantage through the strategic integration of green initiatives built on a Lean foundation.

Keywords Lean, Green supply chain management, Lean and green, Environmental performance, Operational performance, Economic performance, PLS-PM

1 Introduction

Lean management is a well-known approach that can be interpreted in various ways. It can be considered as a philosophy, a strategy, or a set of methods and tools. This variety of approaches can sometimes result in terminological conflicts [1]. There are several definitions in the lean literature [2, 3], one of the most widespread of which emphasises the lean approach's role in optimising resources to enhance both economic and environmental performance [4–6]. This multifaceted nature of lean management necessitates a clear understanding to effectively implement its principles across different organizational



contexts [7]. According to the latest definition, LEAN management is an organizational operational model that, through continuous improvements (e.g., Kaizen), reduces waste and, with the support of digital tools (enabled by Industry 4.0 technologies), increases process transparency, flexibility, reliability, and acceptance of change [8].

Many people see lean as a value-creating approach that can reduce loss through continuous improvement, increases operational excellence, thus contributes to increasing customer satisfaction.

This is supported by a recent 2025 case study, which states that the application of Lean Six Sigma techniques is closely and significantly related to improvements in customer satisfaction and customer retention [9]. This customer-centric philosophy applies across industries and company sizes, as the goal remains efficient operations coupled with high customer satisfaction [1] and strives to continuously improve operational processes and products [10]. Strategic lean leadership emphasizes the crucial role of leaders in fostering collaboration, optimizing the use of resources, and cultivating a culture of continuous improvement, thereby supporting the successful implementation and long-term sustainability of lean practices [11]. Implementing lean management effectively requires a commitment to fostering a culture of continuous improvement and shared responsibility among all employees. This cultural shift is essential for sustaining the benefits of lean management and ensuring that all employees are engaged in the pursuit of efficiency and value creation [12]. These improvements can significantly raise company's competitiveness [13], although the implementation of the lean methods can be challenging, as not all companies possess the same capabilities, resources, and capacity [14–18].

Nevertheless, despite these challenges, vast majority of authors have concluded that lean practices or packages have a positive effect on performance indicators [19–23]; several also recommend examining their impact on the financial, operational, and market outcomes [19, 24].

Unlike the performance indicators identified in the research of Panwar et al. [25] and Godinho Filho et al. [26], Valente et al. [27] also examined financial and market performance indicators. Valente's model demonstrated that introducing lean practices significantly impacts business performance, including customer involvement, statistical processes, continuous flow, and total productive maintenance. It is also important to recognise that implementing lean methods can lead to substantial market improvements, such as increased market share and increased sales. Additionally, positive changes may occur in financial performance indicators (e.g. ROA and net income) and operational performance indicators (production costs, cycle time and number of errors) [28, 29].

In connection with these findings, it is essential to mention some organizational culture researches. The organizational culture's formal definition the organizational culture is the pattern of basic assumptions that a given group has invented, discovered, or developed in learning to cope with its problems of external adaptation and internal integration, and that have worked well enough to be considered valid, and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems [30]. In this manner philosophy and ideology what can be change or able to causing changes in the organizational thinking method what closely influent the problem solving methods and behave what are may help and develop the operational and business efficiency. Because the thinking method fundamentally influent the operational areas of organizational culture e.g. work methods and operational behave, in this

manner the thinking method and its development is a kind of system organizing tool for to achieve the organizational goals. One such goal could be to create a healthy and effective organizational culture and in one a successful and competitive corporation [31]. In 1992, Kotter and Heskett [32] published an 11-year evaluation of corporate cultures. They found that over an 11-year period, companies with healthy cultures increased sales by an average of 682%, compared to a 166% increase for similar companies without such healthy cultures. It can be rightly assumed that the organizational performance comprises the actual results when compared with the intended result or objectives. One of the major reasons to unravel the relationship existing between the organizational culture and organizational performance is that there are assumptions that the development of organizational culture could enhances organizations' performance [33]. Based on these findings we are close to a truth statement that LEAN management methods and thinking method or philosophy directly affect the development of organizational culture. At the same time, as a corporate political element and strategic aspiration, it can be a conscious and effective means of development for the leadership [34].

1.1 Lean and sustainability

Today, sustainability is closely linked to the success of lean companies [35]. Increasing productivity while reducing costs is essential for the economic survival of organisations and can now be achieved in a much more sustainable way, thereby increasing companies' social impact [36, 37]. This alignment of lean management with sustainability principles not only enhances operational efficiency but also fosters a more responsible approach to resource utilization and environmental stewardship.

Ng et al. [38] argued that lean management (LM) reduces environmental impact and increases environmental benefits. According to Yang et al. [39], who examined the relationship between LM practices, environmental management, and business performance. Their research suggested that lean management experiences are positively associated with environmental management practices.

The essence of the lean approach is economical and efficient operation that strives to optimise the use of raw materials and energy. However, traditional lean concepts are increasingly being pushed into the background, with so-called "lean and green" approaches coming to the fore [40]. These approaches focused on environmentally friendly operations, within sustainability aspects are integrated into the lean management system to minimise environmental impacts and strengthen social responsibility. Sustainability-oriented innovation involves transforming an organisation's philosophy, values, products, and processes, to achieve environmental and social goals alongside economic outcomes [41, 42]. This includes considering the interests of local communities, treating employees fairly and favouring sustainable products that also bring economic benefits [43].

Figure 1 illustrates that green lean and sustainability are closely linked and that the two approaches have many areas in common that cannot be sharply separated.

1.2 Lean tools

Although the JIT system is questionable from a sustainability point of view, several methods are widely used in the lean approach. These include the ISO initiative (International Organization for Standardization), in which many companies implement environmental



Fig. 1 Venn-diagram of lean green and sustainability. *Source* [43]

management systems (ISO14001), social responsibility (ISO 26001), Energy Management (ISO 50001) and certified environmental management system (EMAS), as well as corporate social responsibility (CSR) reports, which help organisations address sustainability at a strategic level [44, 45]. In many cases, however, it is questionable whether the use of these tools and methods contributes to the company's financial results, as it is often not supported by the company itself and it is not even necessary to demonstrate how much of the company's revenue such expenses constitute [46]. However, there are several activities whose environmental impact is indisputable [47], as they result in energy savings and reduced energy consumption. Overall, the impact of sustainable operating policies implemented by companies can also be seen at the financial/economic level [48]. Various lean methods can be important within corporate sustainability, for example, to increase energy and resource efficiency [49, 50].

Csapó [51] and Brunner [52] agreed that companies, regardless of whether they are manufacturing or service companies, need to define their lean framework. According to Renström and Niss [53], although almost all companies have heard of the lean philosophy and many have attempted to implement it, only a few have been able to successfully implement it into their daily operational processes. In his research, he found that only 10% of companies that start a lean transformation manage to implement it successfully. Several researchers have investigated the reason for this; the authors' primary objective is to examine its impact on economic, environmental and operational factors [54].

Based on the above-mentioned issues the authors believe that it is necessary to examine the relationship between lean management practices, GSCM and company performance with respect to the environment, operations and finance in Hungary among manufacturing companies. According to the authors' knowledge no similar survey has been made in Hungary on a larger scale, so it fills a really significant gap within this field.

2 Methodology

In order to analyze the impact of Lean and GSCM on company performance (environmental, economic and operational) Partial Least Squares Path Modelling (called PLS-PM) was applied. PLS-PM aims to study the relationship between blocks of observed variables (items) which can be described by latent variables (LVs) (called the measurement model). The structural model represents the linear relationships between the (LVs)

and their items. LVs can also be grouped into superblocks (SB) and their relationships can be studied too. PLS-PM process is the part of the Structural Equation Modelling problems (SEM) and was founded by [55]. The first PLS analytical tool was developed by [56] and the entire algorithm was published in the 80 s [57, 58]. Further developments were made by [59, 60] and [61]. From a methodological point of view, the concept of PLS and SEM differ entirely. The SEM estimation procedure is based on the classical covariances and maximum likelihood (ML) estimation, whereas the PLS approach is a variance-based procedure with fewer assumptions. In the SEM framework variables must obey a normal distribution and there must be over 200 observations. However, PLS allows one to work with small sample sizes and does not require the data to be normally distributed [62]. PLS can handle complex relationships between a large number of LVs, SBs and items [63, 64]. In PLS, relationships can be treated flexibly and be modelled in formative or reflective ways. Both approaches are supported by the literature [65, 66]. In the present study, the authors fitted a reflective-reflective higher order model type, which means casual relations are directed from SBs to LVs at the second level and from LVs to its items at the first level. The rationale for this modelling approach based on theoretical causality as lean and performances are reflective in nature in similar studies [3, 27, 67]. Before the construction of the model, an Explanatory Factor Analysis (EFA) was applied using principal axis extraction and Varimax rotation to each of the original variables that were studied, and a single component created for this purpose for each separate block of variables. EFA was performed by JAMOVI 2.6 [68], while PLS-PM was performed by R statistics 4.2.3. [69] using SEMinR package.

2.1 Hypothesis testing and theoretical model

The study examined the relationship between the Lean management practices, GSCM and company performance with respect to the environment, operations and finance. Four hypotheses are formulated in line with previous studies in this field by scholars such as Shah and Ward [3, 22], Zhu, Sarkis and Lai [70] and Inman and Green [71] among others. The first hypothesis tests the mediation effect of GSCM on company performance. The other hypotheses (H2-H4) are formed to test the effect of either lean management practices (a) or GSCM (b) on company performance. The following hypotheses are tested in the investigation:

H1: There is a direct relationship between lean management practices and GSCM. Lean positively influences GSCM. If H1 is true together with another hypothesis (H2-H4) for GSCM, this would suggest a mediating effect of GSCM on company performance.

H2: Lean (a) and GSCM (b) directly stimulate the company's economic performance by reducing costs and increasing profitability.

H3: Lean (a) and GSCM (b) directly improve the operational performance of the company by facilitating inventory management and optimising stock levels and managing waste.

H4: Lean (a) and GSCM (b) directly enhance the environmental performance by reducing environmental pollution and the company's harmful effects.

Figure 2 explains the exogenous role of lean in relation to company performance as an endogenous variable, with GSCM acting as a moderating factor. The model is divided into two parts, the construct validity and reliability for the “measurement” model and the regression “structural” model between the SBs.

2.2 Mathematical formulation of the model

In the path model (Fig. 2), the relationships between Lean, Green Supply Chain Management (GSCM), and company performance (environmental, economic and operational) are assessed quantitatively through latent variables (LVs) and their direct and indirect effects. A particular type of models in PLS-PM modelling is called hierarchical models. These models consist of several higher-order constructs. Latent variables (LVs) are the first order constructs representing items conceptually related to them. However, sometimes the researcher needs to create second-order constructs which represents other LVs in the model. These are also called a superblock (SBs), as they consist of similar theoretically or conceptually related LVs.

Lean, GSCM, and the economic, operational latent constructs are treated as superblocks (SBs) within the model. The SBs (lean and GSCM) are formulated as follows:

$$LEAN = \lambda_1 \text{Supplier} + \lambda_2 \text{Clients} + \lambda_3 \text{Workers} + \lambda_4 \text{Equipment} \tag{1}$$

$$GSCM = \lambda_5 \text{Green Procurement} + \lambda_6 \text{Eco Design} + \lambda_7 \text{Cooperation Clients} \tag{2}$$

where λ_i is the so-called loading for each LV. The lean superblock includes the LVs of suppliers, clients, workers and equipment, which are formed from observed items. Meanwhile, the GSCM superblock is formed through green procurement, eco-design and cooperation with clients. The relationships between the superblocks are studied in the structural model. This captures the impact of lean and GSCM on economic performance (perfecon), operational performance (perfooper), and environmental factors:

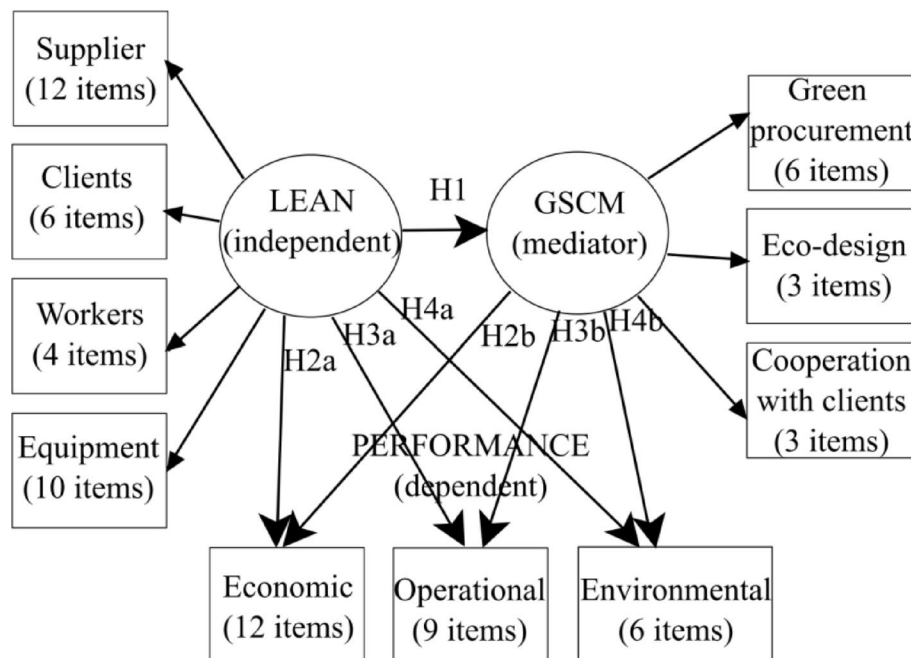


Fig. 2 Framework of the hypothetical model

$$H2 : \text{perfecon} = \beta_1 \text{Lean} + \beta_2 \text{GSCM} + \varepsilon_1 \quad (3)$$

$$H3 : \text{perfoper} = \beta_3 \text{Lean} + \beta_4 \text{GSCM} + \varepsilon_2 \quad (4)$$

$$H4 : \text{environment} = \beta_5 \text{Lean} + \beta_6 \text{GSCM} + \varepsilon_3 \quad (5)$$

The path coefficients $(\beta_1, \beta_3, \beta_5)$ represent the direct effects of lean on economic performance (H2a), operational performance (H3a) and environment (H4a). Similarly, the path coefficients $(\beta_2, \beta_4, \beta_6)$ represent the direct effects of GSCM on economic performance (H2b), operational performance (H3b), and environment (H4b). The error terms $(\varepsilon_1, \varepsilon_2, \varepsilon_3)$ are the unexplained variances. In turn, lean affects the development of GSCM as follows:

$$H1 : \text{GSCM} = \gamma_1 \text{Lean} + \varepsilon_4 \quad (6)$$

where γ_1 is the direct effect of Lean on GSCM (H1), and ε_4 is the corresponding error term. It is also possible to calculate the indirect effect of lean on economic performance, operational performance and environment through GSCM, since lean affects GSCM, which in turn affects these latent performance constructs. The indirect effects (7)-(9) are calculated by substituting Eq. (6) into Eq. (3)-(5), as shown below:

$$\text{Indirect effect}_{\text{Lean} \rightarrow \text{perfecon}} = \beta_2 \cdot \gamma_1 \quad (7)$$

$$\text{Indirect effect}_{\text{Lean} \rightarrow \text{perfoper}} = \beta_4 \cdot \gamma_1 \quad (8)$$

$$\text{Indirect effect}_{\text{Lean} \rightarrow \text{environment}} = \beta_6 \cdot \gamma_1 \quad (9)$$

The indirect effect of lean on economic performance throughout GSCM as a mediating variable is calculated by the product of the direct path coefficient from lean to GSCM (H1 and γ_1) and the direct path coefficient from GSCM to economic performance (H2b and β_2). Hence, the indirect effect is $\beta_2 \cdot \gamma_1$. Similarly, the indirect influence of lean on operational performance via the mediation of GSCM is calculated by multiplying the direct path coefficient from lean to GSCM (H1 and γ_1) and the direct path coefficient from GSCM to operational performance (H3b and β_4). Hence, the indirect effect would be $\beta_4 \cdot \gamma_1$. Finally, the mediating effect of GSCM between lean and the environment factor is calculated by multiplying the direct path coefficient from lean to GSCM (H1 and γ_1) and the direct path coefficient from GSCM to the environment factor (H4b and β_6). Therefore, the indirect effect would be $\beta_6 \cdot \gamma_1$.

Total effects are calculated as the sum of the direct and indirect effects as follows:

$$\text{Total effect}_{\text{Lean} \rightarrow \text{perfecon}} = \beta_2 \cdot \gamma_1 + \beta_1 \quad (10)$$

$$\text{Total effect}_{\text{Lean} \rightarrow \text{perfoper}} = \beta_4 \cdot \gamma_1 + \beta_3 \quad (11)$$

$$\text{Total effect}_{\text{Lean} \rightarrow \text{environment}} = \beta_6 \cdot \gamma_1 + \beta_5 \quad (12)$$

2.3 Survey and questionnaire development

The survey was created by integrating questions on various lean management, sustainability and supply chain management topics, developed by several renowned researchers

and based on validated scales taken from the international literature. The questionnaire consisted of the following sections:

- The first section measures lean manufacturing practices in relation to suppliers, customers, employees, processes and equipment. This section was based on Shah and Ward's [3, 22] classic lean management model, especially along the "lean bundle" concept.
- The measurement of cooperation with suppliers and customers measures the dimensions of close contact, feedback and joint development through several questions, which can also be found in the research of Inman and Green [69].
- The section on employees, for example, cross-functional training and participation in development, stemmed from research on lean people management practices [22, 69].
- Process and equipment management issues rely heavily on the measurement tools of Total Productive Maintenance (TPM), Statistical Process Control (SPC), and JIT-based systems, as described by Shah and Ward [3].
- The second section examined the implementation levels of green supply chain management, following the models of Zhu, Sarkis and Lai [70] and Matos and Silvestre [72] to a significant extent, especially with regard to eco-design, green procurement, ISO 14001 and CSR components. These were discussed by Martinez-Conesa et al. [73] and Wu [74], among others, in the context of enterprise innovation and environmental developments. The section on return on investment links economic rationality and sustainability and was based on the concepts of Abdul-Rashid et al. [75] and Adebajo et al. [76], who examined the cost-saving and profitability effects of green management.
- Sect. 3 (performance measurement) assessed impact across three key areas: environmental, economic and operational. It was based largely on the scales of Zhu, Sarkis and Lai [70] and Inman and Green [71], which defined the output indicators of lean and sustainable operations. The formal design of the scales, which range from -2 to $+2$, evaluated the change in performance indicators and enabled dynamic analysis. This was often employed in longitudinal research to measure implementation results.
- The detailed query of the background variables collected demographic data on companies in a structured way. This was also the basis for the segmented interpretation of the results in the research of Shah and Ward [3, 22] and Baumgartner [77].

2.4 Sample and data gathering

Most respondents to the survey were managers of companies that belong to the Hungarian Logistics, Purchasing and Inventory Management Association (HLPIMA) or are partners of the Lean Enterprise Institute Hungary (LEI Hungary). Another significant group of respondents were company managers and senior and middle managers linked to companies they had previously encountered through training or professional collaboration. For enquiries made with the assistance of HLPIMA and LEI Hungary, the research team did not have the email addresses of companies or managers, as enquiries

were made via the institutes' mail systems. The aim of the questionnaire survey was to invite around 300 companies and their representatives to complete it. The 15-min questionnaire was distributed online in February 2024. A total of 125 responses were received. After reviewing and validating the responses, they were all included in the analysed database, as they met the pre-defined research criteria. It is important to note that completion of the questionnaire was entirely voluntary and anonymous. No personal data was collected during completion of the questionnaire and no information was requested that would have allowed the identity or precise company affiliation of the respondents to be identified. Only questions on the sector of activity of the firms were included in the questionnaire, no other firm-specific or personal data were requested. As a result, the authors could not determine exactly how many respondents from a given company completed the questionnaire or to which companies the respondents are linked. The responses are only available in aggregated, anonymous form, thus ensuring the ethical adequacy of the survey and full respect of data protection. The authors applied the minimum R-squared method [78] to determine the minimum sample size required for the study. According to this method, with 0.1 set as the minimum R-squared value and 2 as the maximum number of arrows pointing at an LV, the minimum number is found to be 110. The study sample contains 125 participants, satisfying the minimum requirement. The research presented in this paper has obtained the necessary ethics approval from the Research Ethics Committee of the Faculty of Business and Economics at the University of Debrecen, bearing the registration number GTK-KB 003/2025, granted on 4 January 2025. Assuming that no more than two respondents completed the questionnaire, the true response rate of the current study was estimated to be between 21 and 42%. Based on this, it can be concluded that the response rate was similar to that of previous typical studies, where it was approximately 25–32% [3, 27, 67, 79].

As for the respondents of the sample, most of them work for large companies with more than 3000 employees (Large Company Category III), which means 32.8% (41 people) of the respondents. The second largest group is represented by large enterprises with 250–999 employees (Large Company Category I) with a ratio of 28.8% (36 employees), while large enterprises between 1000 and 2999 employees (Large Company Category II) follow them with a very similar proportion, 28.0% (35 employees). The lowest proportion of medium-sized enterprises (50–249 employees) (10.4% to 13 employees) are listed as places of work.

Most of the respondents work in production, which makes up 36.0% (45 people) of the respondents. This is followed by logistics – procurement with 14.4% (18 people), innovation/research and development with 12.8% (16 people) and logistics – warehousing with 12.0% (15 people). The other areas are present in a smaller proportion (Operational excellence: 7.20%, 9 people, Quality: 6.40%, 8 people; Marketing: 5.60%, 7 people; Sales: 5.60%, 7 people). 61.6% of the respondents (77 people) stated that the annual net sales of the company they represent were over €50 million in the last closed year (large companies), while 38.4% (48 people) stated that the annual net sales of the company were between €10 million and €50 million (medium-sized companies). The largest proportion of the sample is represented by the food industry, which accounts for 22.4% (28 companies) of the respondents. This is closely followed by other industries, which represent a share of 21.6% (27 companies). The electronics industry is in third place with 15.2% (19 companies), while pharmaceutical manufacturing is in 4th place with a share of 12.8%

(16 companies). Smaller shares are represented by the manufacture of vehicles (10.4%, 13 companies) and the rubber and plastics industry (5.6%, 7 companies).

The manufacture of basic metals and fabricated metal products, as well as the chemical industry, water supply and waste management are all represented by 4.0% (5–5 companies), while the independent chemical industry accounts for only 2.4% (3 respondents). The wood and paper industry appeared in the smallest proportion, with a share of only 1.6% (2 companies).

The largest proportion of respondents to the questionnaire are top managers, who make up 37.6% (47 people) of the respondents. They are closely followed by middle managers, who are included in the sample in a proportion of 36.8% (46 people). Both low level managers and subordinates are present in a smaller proportion, both groups represent 12.8% (16 people).

3 Results and discussion

Prior to model construction, an Explanatory Factor Analysis was applied on each studied block of the original variables by creating a single component. In the first stage of the model building, the insignificant items were screened out based on the Kaiser–Meyer–Olkin measure of sampling adequacy value (less than 0.4). Model building then continued with the most important stage: excluding items with a high Variance Inflation Factor (VIF) that violated multicollinearity in the model or had a correlation with their own block lower than 0.6 (Table 1). In the final stage of this preliminary process, only those items were eliminated that helped to improve the interpretability and reliability of the model. The original model contained 70 items, which were reduced by almost half. Only 34 items remained in the final model (Tables 1 and 2).

The GSCM blocks (green procurement, eco-design and cooperation clients) remained relatively stable compared to the lean management practices block, where only the workers construct remained stable throughout the modelling process. The supplier and equipment constructs had to be reduced the most, losing more than half of their items. The second stage, where the final structure was established, was the most important step.

Regarding the endogenous blocks, stage 3 played a crucial role in determining the final structure of the blocks. The market position was the most stable block, while the environment performance block should be reduced to improve the reliability and interpretability of the model.

Structural model quality (R^2) and regression path coefficients (β) were obtained via a regression model using partial least squares (PLS). Bootstrap sampling was also applied to test the model and estimate parameters, with 500 samples generated from the original data as suggested by Chin [38]. The standard errors and the confidence intervals (CIs) were calculated using the bootstrapping procedure. Figure 3 provides a graphical representation of the parameter estimates and the statistically significant path coefficients in the final bootstrapped model. Negative relationships are depicted by dashed lines. Only the direct influence of GSCM on the environment factor is not significant; all other path coefficients are significant at a significance level of 5%.

R^2 measures were calculated as part of In the course of the structural model quality assessment. R^2 values of 0.02, 0.15 and 0.35 are considered to represent small, medium and large effects, respectively [80]. As can be seen in Fig. 3, the primary outcome

Table 1 Model building strategy and descriptives of the Lean and GSCM superblocks

Construct	Description	mean	Standard Deviation	Items screened out		
				Stage 1 /low KMO/	Stage 2 /VIF > 3.0 or loading < 0.6/	Stage 3 /Reliability, interpretability/
<i>Lean</i>	LV1, LV2, LV3, LV4 (32 items)					
Supplier (LV1)	12 items					
Supplier2	We visit our suppliers plants	3.40	0.98	Supplier 1,3,4,6,7,9	Supplier 8, Supplier10	
Supplier5	Suppliers are directly involved in the new product development process	3.04	1.15			
Supplier11	Our suppliers are contractually committed to annual costs reduction	2.80	1.39			
Supplier12	Our key suppliers are located in close proximity to our plants	2.53	1.10			
Clients (LV2)	6 items					
Client2	Our customers visit our plants	3.64	1.10	-	Clients1, Clients3	
Client4	Our customers are actively and directly involved in current and future product offerings	3.56	1.10			
Client5	Our customers share current and future demand information with marketing department	3.76	1.04			
Workers (LV3)	4 items					
Worker2	Production employees are key to problem solving teams	4.16	0.93	-	-	Worker1
Worker3	Production employees participate actively in product/process improvement efforts	3.40	1.14			
Worker4	Production employees undergo cross functional training	3.60	1.10			
Equipment (LV4)	10 items					
Equipment7	We use fishbone type diagrams to identify causes of quality problems	3.68	1.23	-	Equipment2-Equipment6, Equipment10	Equipment 1
Equipment8	We conduct production process capability studies before product launch in the market	3.48	1.40			
Equipment9	The machines in our plant have low setup times	3.52	0.90			
<i>GSCM</i>	LV6, LV7, LV8 (11 items)					
Green procurement (LV5)	5 items					

Table 1 (continued)

Construct	Description	mean	Standard Deviation	Items screened out		
				Stage 1 /low KMO/	Stage 2 /VIF > 3.0 or loading < 0.6/	Stage 3 /Reliability, interpretability/
Greenproc2	Collaborate with suppliers for environmental goals	3.55	0.98	Greenproc 1	-	-
Greenproc3	Environmental audit for the internal management of suppliers	3.52	1.37			
Greenproc4	Supplier ISO14000 Certification	4.01	0.99			
Greenproc5	Evaluation of environmentally friendly practices of second-tier suppliers	2.72	1.32			
Eco-design (LV6)	3 items					
Ecodesign1	Design of products with reduced material and energy consumption	2.92	1.06	-	-	-
Ecodesign2	Design of products for recycling and recycling of materials	2.92	1.17			
Ecodesign3	Designing products to avoid the use and production process of hazardous products	2.88	1.15			
Cooperation clients (LV7)	3 items					
Cooperclient2	Collaborate with customers for cleaner production	2.48	0.85	-	Cooperclient1	-
Cooperclient3	Cooperation with customers on green packaging	2.64	0.89			

variable, economic performance, had a substantial R^2 value of 0.220 ($F = 17.21$; $p < 0.001$). Economic performance is more strongly related to cost reduction, particularly waste disposal and production costs. Market position is mostly determined by capacity usage and sales volume. Operational performance also had a large R^2 value of 0.343 ($F = 31.85$; $p < 0.001$), and it is strongly related to inventory management, especially investment in surplus stocks and waste disposal. The environmental factor had a medium R^2 value of 0.096 ($F = 6.48$; $p = 0.002$) and was determined by the volume of solid waste and the company's environment pollution activity.

According to both Table 3 and Fig. 3, there was a strong positive relationship between lean management and GSCM ($\gamma_1 = 0.622$; $t = 18.743$; $p < 0.001$), which supports H1. GSCM also mediated the influence of lean on both economic performance ($\beta_2 = 0.264$; $t = 1.940$; $p = 0.027$) and operational performance ($\beta_4 = 0.355$; $t = 3.261$; $p < 0.001$), which proves H2b and H3b. However, GSCM did not have a direct relationship with the environmental factor ($\beta_6 = -0.081$; $t = -0.772$; $p = 0.221$), so H4b was not. Lean management practices directly influence the economic factor ($\beta_1 = 0.257$; $t = 1.986$; $p = 0.025$), the operational performance ($\beta_3 = 0.294$; $t = 3.804$; $p < 0.001$) and the environmental factor

Table 2 Model building strategy and descriptives of the endogeneous blocks

Construct	Description	mean	Standard Deviation	Items screened out		
				Stage 1 /low KMO/	Stage 2 /VIF > 3.0 or loading < 0.6/	Stage 3 /Reliability, interpretability/
<i>Economic performance</i> LV8 and LV9 (12 items)						
Costs (LV8) 6 items (1–6)						
Perfecon4	Waste Drop-off Fee	3.70	1.01	Perfecon 5	Perfecon 2,3	Perfecon 1
Perfecon6	Production costs	4.07	0.69			
Market position (LV9) 6 items (7–12)						
Perfecon8	Market share	3.00	0.70	Perfecon 12		Perfecon 7
Perfecon9	Sales volume	3.08	1.14			
Perfecon10	Product quality	3.60	0.57			
Perfecon11	Capacity utilization	3.48	0.90			
<i>Operational performance</i> LV10 and LV11 (9 items)						
Stock & waste (LV10) 5 items (1–5)						
Prefoper2	Inventory levels	3.00	0.94	-	Perfoper 1,4,5	
Prefoper3	Scrap rate	2.60	0.85			
Inventory management (LV11) 4 items (6–9)						
Prefoper7	Capitalizing on investment in surplus stocks/ materials	3.14	1.16	-	Perfoper 6	Perfoper 9
Prefoper8	Sale of scrap and used materials	3.17	1.25			
<i>Environment (LV12)</i> 6 items						
Prefenviron3	Amount of solid waste	2.70	0.80	-	Perfenvi- ron 4,5	Perfenvi- ron 1,2
Prefenviron6	Environmental pollution activity of the company	2.35	0.89			

Economic performance operational performance are superblocks (SBs), environment is just a latent construct (LV)

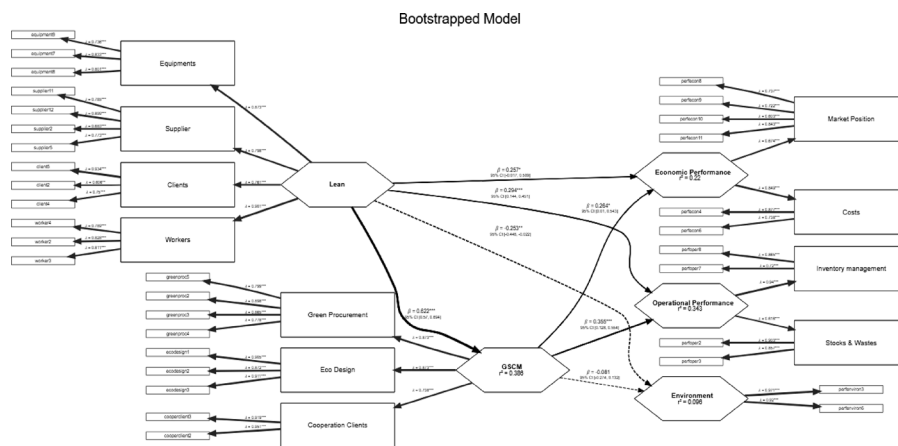


Fig. 3 Bootstrapped estimation of loadings and path coefficients of the PLS-PM model. Note negative relationships are denoted by dashed lines; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; path coefficients were all standardized and all constructs were reflective

Table 3 Total, direct and indirect relationships in the PLS-PM model

Relationship (path)	Coefficient (direct effect)	T-statistics	Hypothesis Test	Indirect effect	Total effect
Lean → GSCM	0.622 (γ_1)	18.743	H1 is True	-	0.622
Lean → Economic performance	0.257 (β_1)	1.986	H2a is True	0.164 ($\beta_2\gamma_1$)	0.421
Lean → Operational performance	0.294 (β_3)	3.804	H3a is True	0.221 ($\beta_4\gamma_1$)	0.515
Lean → Environment	-0.253 (β_5)	-2.396	H4a is True	-0.050 ($\beta_6\gamma_1$)	-0.303
GSCM → Economic performance	0.264 (β_2)	1.940	H2b is True	-	0.264
GSCM → Operational performance	0.355 (β_4)	3.261	H3b is True	-	0.355
GSCM → Environment	-0.081 (β_6)	-0.772	H4b is not True	-	-0.081

$$\beta_2\gamma_1 = 0.264 * 0.622 = 0.164; \beta_4\gamma_1 = 0.355 * 0.622 = 0.221; \beta_6\gamma_1 = -0.081 * 0.622 = -0.050$$

Total effect = direct effect + indirect effect; t-statistics are computed by dividing the bootstrap mean with the standard error. Those path coefficients were considered statistically significant which had larger t-values than 1.96

($\beta_5 = -0.253$; $t = -2.396$; $p = 0.009$) (H2a, H3a, and H4a are all true). The negative coefficient in the case of the environmental factor indicates the benefits of lean management practices, as these reduce the amount of solid waste and the company's general environmental pollution. Table 4 shows that lean management practices had the largest impact on operational performance (0.515), with 43% of the total influence coming indirectly through GSCM (0.221). Lean management practices also had a substantial total impact on the economic performance (0.421), 39% of which came indirectly through GSCM. GSCM had a relatively greater impact on operational performance (0.355) than on economic performance (0.264).

Table 4 provides various statistical measures relating to the LVs and the estimated model (Fig. 3). The reliability of the studied LVs must be validated, and the characterised model must be assessed further. Multicollinearity may be a relevant issue in PLS-PM modelling [49], which can result in unreliable and unstable regression path coefficients. This issue was investigated by calculating the Variance Inflation Factors (VIFs). VIFs measure the extent to which the variance of an estimated coefficient increases due to high correlations between two or more predictor variables. A VIF value above 3 suggests that the correlation between the model's predictor variables is high enough to inflate the standard errors of the regression path coefficients. VIF values were also used to measure common method bias (CMB) for a single LV using its items as predictor variables. CMB is the influence of the source on the data collected. In this study, since the data came from self-reported surveys, potential for CMB may exist. A VIF value should be lower than 3.0 for no significant common method bias and multicollinearity issues.

Higher t-statistic values indicate a more significant relationship, the one-tailed threshold is approximately 1.65 for the significance level of 5% and a sample size of 125. According to the t-statistics, the most influential blocks are equipment and workers in lean management practices, green procurement and eco-design in the GSCM block. Clients had a significant, but relatively less importance in both lean and GSCM blocks. In PLS-PM modelling, composite reliability and convergent (divergent) validity both assess the measurement model's quality, but they are different in concept. Convergent validity refers to the extent to which different items correlate with other items within the same underlying construct (LV). The convergent validity of the blocks was tested by the average variance explained (AVE) and the factor loadings. AVE values greater than 50% suggest good convergent validity, as the intended items measure accurately the same concept. The so-called factor loadings represent the strength of the relationship between each observed item and its corresponding LV. Loadings should also be higher than 0.6.

Table 4 Construct validity and reliability of the PLS-PM model

Construct	Loading ≥ 0.6	VIF < 3.0	t-statistics > 1.65	AVE ≥ 0.5	Composite reliability ≥ 0.7
Supplier (LV1)	0.798	1.960	12.677	62.2%	0.867
Supplier2	0.683	1.464	8.668		
Supplier5	0.773	1.576	10.065		
Supplier11	0.785	1.722	21.977		
Supplier12	0.899	2.425	71.977		
Clients (LV2)	0.761	1.935	3.670	60.1%	0.814
Client2	0.606	1.303	2.606		
Client4	0.750	1.621	4.009		
Client5	0.934	1.441	3.477		
Workers (LV3)	0.901	2.496	44.543	65.5%	0.851
Worker2	0.828	1.591	19.773		
Worker3	0.811	1.334	28.035		
Worker4	0.789	1.619	11.296		
Equipment (LV4)	0.873	2.174	54.953	62.6%	0.834
Equipment7	0.833	1.562	25.614		
Equipment8	0.801	1.303	19.288		
Equipment9	0.736	1.386	17.029		
<i>Lean superbloc</i>		1.630		69.7%	0.902
Green procurement (LV5)	0.873	1.504	33.099	69.9%	0.903
Greenproc2	0.898	2.751	43.966		
Greenproc3	0.865	2.493	38.929		
Greenproc4	0.778	1.580	18.710		
Greenproc5	0.799	1.929	23.808		
Eco-design (LV6)	0.873	2.380	24.708	80.3%	0.924
Ecodesign1	0.905	2.564	43.175		
Ecodesign2	0.872	2.312	28.122		
Ecodesign3	0.911	2.383	53.875		
Cooperation clients (LV7)	0.738	1.889	8.894	87.4%	0.933
Cooperclient2	0.951	2.302	78.264		
Cooperclient3	0.919	2.302	31.140		
<i>GSCM superbloc</i>		1.630		68.9%	0.869
Market position (LV8)	0.674	1.035	4.365	53.5%	0.819
Prefecon8	0.737	1.469	4.555		
Prefecon9	0.722	2.208	4.080		
Prefecon10	0.603	1.884	4.057		
Prefecon11	0.843	1.292	4.286		
Costs (LV9)	0.849	1.035	11.809	65.7%	0.792
Prefecon4	0.844	1.116	34.895		
Prefecon6	0.780	1.116	11.544		
<i>Economic performance superbloc</i>		-		58.8%	0.738
Inventory management (LV10)	0.940	1.107	43.035	63.3%	0.774
Prefoper7	0.720	1.081	6.793		
Prefoper8	0.865	1.081	20.904		
Stock & waste (LV11)	0.616	1.107	6.417	77.5%	0.873
Prefoper2	0.903	1.440	51.883		
Prefoper3	0.857	1.440	29.906		
<i>Operational performance superbloc</i>		-		63.2%	0.767
Environment (LV12)		-		89.5%	0.944
Prefenviron3	0.971	2.775	69.486		
Prefenviron6	0.920	2.775	23.798		

Composite reliability measures how well the set of items together measure consistently the same LV. Composite reliability was measured by calculating the so called Jöreskog's rho [81] which is a better measurement of reliability than Cronbach's alpha since it is based on the factor loadings of the measurement model rather than the item correlations in the raw data. Values greater than 0.7 indicate appropriate internal consistency. Table 5 shows that all LVs meet the criteria for AVE, composite reliability indicating good convergent validity and internal consistency. The model did not have CMB as VIF values were under 3.0. Divergent validity, also known as discriminant validity, measures the uniqueness of LVs by showing the extent to which an LV explains the variance of its related items (measured by AVE) compared to items related to other LVs. The more distinct an LV is, the greater its correlation with its items as compared to its correlation with other LVs in the model. To assess the discriminant validity of the model, the Fornell-Larcker criterion [82] was applied.

Table 5 shows the FL criteria table, which reports the AVE on the diagonal and the squared LV correlations in the lower triangle. A squared correlation between two different LVs indicates how much variance each LV shares with each other. The Fornell-Larcker criterion [82] provided evidence of discriminant validity, as all AVE values for the LVs were higher than the squared intervariable correlations. Based on the above mentioned, the measurement model was found to be reliable and valid.

In the final stage of the investigation the authors created the scores for each SBs (Lean, GSCM, financial and operational performance) and the environment LV in the PLS-PM model and analysed the differences with respect to the respondent's department and industry (Figs. 4 and 5).

Figure 4 shows that combining lean and GSCM improved financial and operational performance, with the greatest improvement seen in innovation/R&D (lean: 1.20; GSCM: 0.96; financial performance: 0.91; operational performance: 0.85), and operational excellence (lean: 0.27; GSCM: 0.49; financial performance: 0.69; operational performance: 0.83). Marketing and Sales were the departments less likely to adopt lean and GSCM (-0.71 and -0.12), while also having the lowest financial (-1.19 and -1.17) and operational performance scores (-0.60 and -0.30). To properly interpret Fig. 5, the authors should note that a positive case occurs when the environment factor is negative and all the other values are positive.

Figure 5 shows that the "wood and paper", and "water supply, wastewater and waste management" sectors are less likely to use Lean (-0.69 and -0.49) and GSCM (-1.07 and -0.42) together and less environmentally efficient (0.94 and 1.34). This was particularly evident in the "wood and paper" sector, where it was reflected in the operational (-0.38) and economic performance (-0.43). Lean was applied at a higher level in the pure chemical (1.62) and "metal and metalworking" industries (1.38) and has succeeded in reducing environment pollution and solid waste generation (0.08 and -0.21). However, the situation was very different in two sectors. In the chemical industry, lean has been combined with GSCM (0.62), positively impacting economic (0.62) and operational performance (0.51). This contrasted with the "metal and metalworking" industries. Here, GSCM (-0.12) was not applied on such a high level, and economic (-1.09) and operational (-0.22) performance is lower than in the chemical industry. The automotive and pharmaceutical industries are also interesting. In the automotive industry, GSCM (0.15) was present, but lean (-0.15) was less prevalent, resulting in a negative impact on

Table 5 AVE values and Fornell–Larcker (FL) test of discriminant validity for the LVs

	LV1	LV2	LV3	LV4	LV5	LV6	LV7	LV8	LV9	LV10	LV11	LV12
LV1	0.622											
LV2	0.401	0.601										
LV3	0.371	0.353	0.655									
LV4	0.288	0.301	0.511	0.626								
LV5	0.366	0.092	0.591	0.530	0.699							
LV6	0.041	0.022	0.244	0.056	0.335	0.803						
LV7	0.006	0.002	0.121	0.067	0.162	0.471	0.874					
LV8	0.092	0.141	0.047	0.042	0.035	0.083	0.007	0.535				
LV9	0.069	0.063	0.134	0.068	0.040	0.243	0.158	0.033	0.657			
LV10	0.085	0.026	0.285	0.269	0.252	0.317	0.098	0.031	0.331	0.633		
LV11	0.005	0.022	0.021	0.266	0.131	0.001	<0.001	<0.001	0.001	0.097	0.775	
LV12	0.087	<0.001	0.048	0.143	0.190	0.004	0.007	0.011	0.006	0.021	0.340	0.895

LV1:Supplier; LV2: Clients; LV3: Workers; LV4: Equipments; LV5: Green procurement; LV6: Eco-design; LV7: Cooperation clients; LV8: Market position; LV9: Costs; LV10: Inventory management; LV11: Stock & waste; LV12: Environment

operational performance (−0.96) and a positive impact on economic performance (0.26). In the pharmaceutical industry, lean (0.34) is used, but GSCM (−0.27) is not prevalent. Nevertheless, there was a positive impact in all areas, lower level of environmental burden (−0.42) and positive economic (0.34) and operational performance (0.19).

4 Conclusions

This study examined the impact of lean management and green supply chain management (GSCM) practices on manufacturing company performance. The results clearly showed that lean methods alone significantly improve the economic and operational efficiency of companies and can positively impact environmental performance both directly and indirectly.

4.1 Sectoral findings

Regarding sectors, the following conclusions were reached:

1. The wood and paper, chemical, water, wastewater and waste management sectors use lean (and GSCM as well) at a lower level and they are associated with higher levels of environmental burden.
2. Lean is very widespread in the clean chemical, metal and paper industries, as well as in metalworking. It has managed to reduce environmental pollution and solid waste.
3. In the chemical industry, the combination of lean and GSCM has had a positive impact on economic and operational performance, unlike in the metalworking. GSCM is not widespread in this industry, and operational and economic performance is lower.
4. The automotive and pharmaceutical industries are also interesting. In the automotive industry, GSCM is present, but lean is less prevalent. This has a negative impact on operational performance, but a positive impact on economic performance.
5. Lean management practices are mostly commonly used in the pharmaceutical industry at a higher level, but GSCM is not widespread. However, the positive effects remain in all areas: environmental pollution has decreased, and positive operational and economic performance has improved.

4.2 Implications

The following conclusions can be drawn regarding the hypotheses:

1. The first hypothesis was confirmed, showing that lean manufacturing has a positive impact on green supply chain management (GSCM). This is because lean practices facilitate the implementation of GSCM; waste reduction and process optimisation are in line with environmental sustainability goals.
2. The second hypothesis was that lean manufacturing and GSCM stimulate a company's economic performance. The research confirmed this, as using lean methods improves operational efficiency and financial performance.
3. The third hypothesis was that lean manufacturing and GSCM positively impact a company's operational performance by facilitating inventory management and optimising inventory and waste levels. The research has confirmed this.
4. According to the fourth hypothesis, both Lean (a) and Green Supply Chain Management (GSCM) practices (b) were expected to have a direct positive effect on the company's environmental performance by reducing environmental pollution

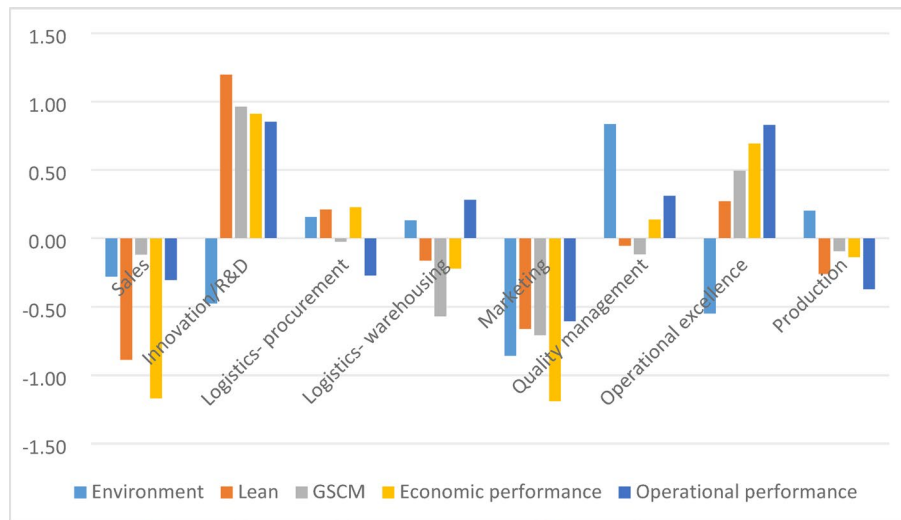


Fig. 4 Analysis of the major latent variable blocks by department

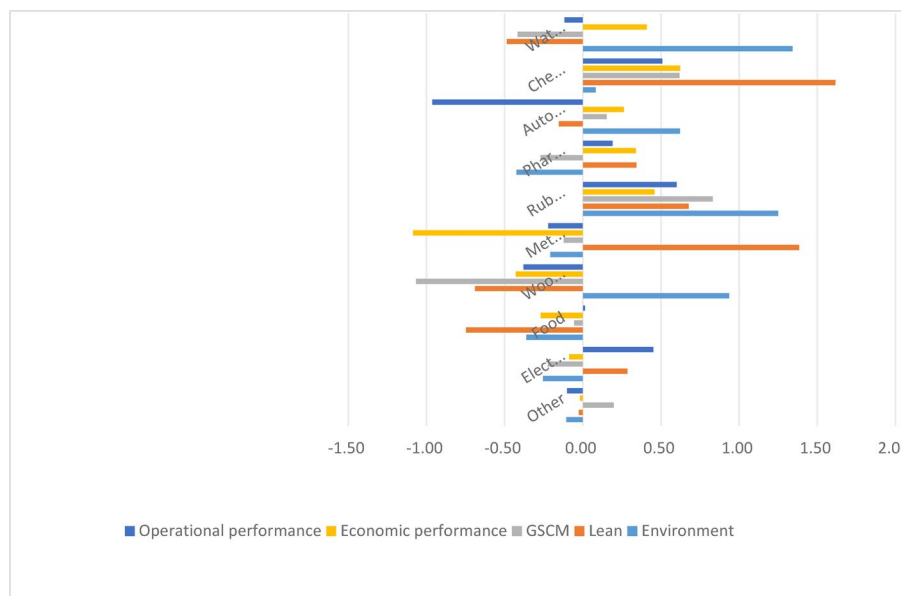


Fig. 5 Analysis of the major latent variable blocks by industry

and its adverse impacts. However, the hypothesis could not be fully confirmed. In the case of environmental indicators, a negative coefficient was observed, which—counterintuitively—reflects the beneficial impact of Lean practices, as they contribute to the reduction of solid waste and environmental emissions. This suggests that while Lean management exerts a measurable positive effect on environmental performance, a similar effect could not be clearly identified for GSCM in this analysis.

Implementing lean can be effective, as it can lead to significant cost reductions and improvements in operational efficiency, particularly through reducing scrap, shortening lead times, and improving capacity utilisation. Even introducing lean principles (e.g. 5S, continuous improvement and Kaizen) can improve competitiveness in the short term.

Companies should integrate lean and green practices, as combining them can increase operational efficiency and environmental sustainability. For instance, waste reduction initiatives can be combined with energy efficiency projects to deliver cost savings and environmental benefits simultaneously. Therefore, GSCM is effective when built on lean management foundations. According to the results, green supply chain methods (e.g. green procurement and eco-design) are most effective when combined with a lean approach. For this reason, companies should strive to integrate GSCM elements into their lean management practices.

Based on the results, particular focus should be placed on closer cooperation with suppliers and the procurement of environmentally friendly materials to reduce vulnerability to external disturbances.

It is important to continuously measure and analyse the impact of lean and green practices on company performance. There are existing indicators for this purpose, and more indicators can be developed to monitor the achievement of sustainability and efficiency goals, enabling continuous improvement. Environmental protection cannot be treated as a campaign; it requires a design of internal processes to improve material and energy efficiency, for example.

Tools aimed at sustainability and efficiency (e.g. ISO 14001, CSR reports) are effective when supported at a strategic level. Management commitment and employee involvement are key to a successful implementation. For example, lean ambassadors could be appointed or an incentive system could be created to encourage proposal submissions.

Training employees in lean and green practices can increase acceptance of, and improve the effectiveness of, new methods. This can be achieved by organising regular workshops and training sessions where best practices and case studies are presented.

According to the current research, lean and GSCM integration benefits the pharmaceutical and chemical industries the most from, while the wood and paper industry and marketing departments do not apply them. Adapt the company's lean and GSCM strategy to the specific needs of the industry and department—for example, these methods can be implemented more quickly in the areas of operations, logistics and R&D.

Overall, the combination of lean and green supply chain management is a set of tools and methods, but also a strategic approach that provides companies with a measurable competitive advantage at the economic, operational and environmental levels – especially when applied systematically and consistently.

4.3 Limitations

The research had some limitations. Although the sample size of 125 met the minimum requirements but did not necessarily represent all industries or company size categories. Furthermore, it did not allow for an examination of the long-term effects of lean and green practices. Future research should seek to address this issue.

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Author contributions

T.G., E. B.Ny. and S.K. wrote the main manuscript. T.G. and E.B.Ny. conceptualized the article and established the methodology and set up the theoretical model. E.B.Ny., M.Cs. and V.F. collected the data. S.K. was responsible for the formal analysis, visualization and software. L.T. validated the repeatability of the research. V.F supervised the project and responsible for the funding of the article. M.C. and L.T. reviewed and edited the final manuscript. **Third Party Material:** All the materials are owned by the authors and no permissions are required. **Dual Publication:** The results/data/figures in this manuscript have not been published elsewhere, nor are they under consideration (from any of the Contributing

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Data availability

Data will be made available on request from the corresponding author.

Declarations

Ethics approval and consent to participate

The protocol was reviewed and approved by the Institutional Review Board at the University of Debrecen. The Committee has approved the study by decision GTK-KB 003/2025.

Competing interests

The authors declare no competing interests.

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