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**Bányai Attila
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**HUNGARIAN UNIVERSITY OF
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SCIENCES
DOCTORAL SCHOOL OF ECONOMIC
AND REGIONAL SCIENCES**

**DEVELOPMENT OF A LEAN
PERFORMANCE EVALUATION
MODEL BASED ON FINANCIAL
AND ACCOUNTING DATA**

**Bányai Attila
GÖDÖLLŐ
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Doctoral school

Name: Doctoral School of Economic and Regional Sciences

Discipline: Management and Business Administration Studies

Head: **Dr. Szente Viktória PhD**
Professor/PhD
Hungarian University of Agriculture and Life Sciences
Institute of Sustainable Development and Farming

Supervisor(s): **Dr. Tóth Márk PhD**
Professor/PhD
Hungarian University of Agriculture and Life Sciences
Department of Investment, Finance and Accounting

Dr. Thalmeiner Gergő PhD
Assistant Professor/PhD
Hungarian University of Agriculture and Life Sciences
Department of Investment, Finance and Accounting

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Approval of Head of Department

.....

Approval of Supervisor

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1. ANTECEDENTS AND OBJECTIVES OF THE WORK

1.1. Introduction

In today's globalized and continuously changing economic environment, efficiency, flexibility, and sustainable competitiveness have become increasingly important for companies. As a result of technological advancement, digitalization, and market uncertainty, organizational processes have become significantly more complex, increasing the importance of management approaches that are capable of minimizing waste and optimizing resource utilization. Among these approaches, lean management has become one of the most widely applied and recognized organizational development philosophies. The core objective of the lean approach is the maximization of customer value and the elimination of all activities that do not directly contribute to value creation. Accordingly, lean operations seek to reduce different forms of waste, such as overproduction, waiting time, excess inventory, unnecessary movement, and administrative bottlenecks, while emphasizing the efficient management of the entire value stream.

The implementation of lean management can generate significant operational and economic benefits for organizations. The optimization of production and administrative processes may contribute to shorter lead times, increased productivity, reduced defect rates, and improved resource utilization. Lean should not only be interpreted as an operational methodology, but also as a strategic management approach that influences organizational culture, decision-making processes, and the entire value creation system. Despite these advantages, the objective measurement and comparable evaluation of the organizational impacts of lean implementation remain major challenges. In practice, lean performance evaluation is typically based on company-specific indicators, internal development systems, and non-public data, which limits comparability and reduces the possibility of broader industry benchmarking. Consequently, the level of lean maturity and its economic implications are often difficult to quantify using objective and standardized methodologies.

Parallel with the development of digitalization, the amount of financial and controlling data available about organizational operations has increased significantly. Financial statements, controlling reports, and management information systems contain large volumes of structured data that may not only support the analysis of financial performance, but may also indirectly reflect operational efficiency and organizational performance. The primary role of the controlling function is to organize data into structures that effectively support managerial decision-making and the achievement of strategic objectives. Although controlling is traditionally not considered a directly value-creating activity, its role in structuring information, evaluating

performance, and identifying organizational problems makes it highly relevant in the assessment of lean operations.

One of the most important research questions in lean management is how operational efficiency improvements can be transformed into objective financial and accounting-based indicators. As a result, increasing attention has been devoted to approaches that attempt to quantify lean performance through publicly available and audited data sources. Such models may provide an opportunity to evaluate organizational performance not exclusively through internal and subjective assessment systems, but through objective, comparable, and broadly applicable methodological frameworks as well.

1.2.Objectives

The core problem areas of this research field have already appeared in the lean management literature since the 1990s. Numerous studies have examined the methods applied for evaluating lean operations, as well as the relationships between operational and financial performance. Nevertheless, most existing studies are based on isolated approaches, and no unified and standardized performance evaluation model has been developed that would be capable of objectively assessing corporate lean operations based on publicly available financial and accounting data. The relevance of the research area is further strengthened by the continuously changing economic and technological environment, while increasing operating costs and competitive pressure are forcing more companies to reassess and optimize their internal processes. Consequently, the application of lean management today is no longer interpreted solely as an operational issue, but has become closely connected to strategic decision-making, data-driven corporate management, and the development of controlling systems.

The objective of my research is to explore the controlling, financial, and accounting evaluation methods related to lean management, as well as to examine their relationships with corporate operational performance. Furthermore, my objective is to identify financial and accounting indicators that may be suitable for the objective evaluation of lean operations. During my research, I aimed to demonstrate through individual cases the operation of controlling systems applied by companies implementing lean methods, as well as the practices used for measuring lean performance. Another objective of my research is to develop a structured and standardized evaluation model capable of supporting the objective measurement and comparability of lean performance based on publicly available financial and accounting data. The foundation of the model is based on the analysis of methodological elements identified in the literature, the practical experiences revealed through case

studies, and the synergistic integration of mathematical-statistical modeling methods.

During my research, the following objectives were defined, which served as the fundamental basis of the study:

- To explore lean methods and tools, with particular emphasis on lean controlling and accounting analysis methods.
- To identify, through statistical and machine learning methods, those financial and accounting KPIs that show significant co-movement with corporate lean performance.
- To examine, through individual case studies, the controlling, financial, and accounting evaluation practices of companies, as well as the KPI-based measurability of areas affected by lean implementation.
- To synthesize literature findings, quantitative modeling approaches, and case study results in order to establish the KPI set serving as the foundation of the model.
- To develop a general and structured mathematical model based on publicly available financial statement data.
- As a result of the model development, to provide company managers with the opportunity to evaluate lean performance regardless of whether the organization applies internally defined lean performance indicators.

2.MATERIAL AND METHODS

During my research, I aimed to integrate both qualitative and quantitative research methodologies in order to examine the relationships between lean management and corporate performance in a complex and multidimensional manner. The application of quantitative research enables the objective and statistically based analysis of phenomena, the identification of causal relationships, and the formulation of generalizable conclusions (CRESWELL 2014). From the perspective of investigating the relationship between lean management and controlling systems, it was particularly important to establish a structured and quantifiable evaluation framework capable of integrating financial and accounting indicators into the measurement of corporate efficiency. Although the literature related to lean management can be considered relatively rich in quantitative studies, most of these studies focus primarily on isolated areas or specific industrial contexts, while comprehensive system-level approaches remain limited (SHAH – WARD 2007).

As the first step of the research, I conducted a systematic literature review in order to identify those financial and accounting KPIs that may show relationships with lean operations. During the analysis, particular attention was devoted to examining how the indicators applied in the literature could be connected to the sources of waste defined by OHNO (1982). The systematization of the literature findings provided the foundation for the subsequent mathematical and statistical modeling process and contributed to the development of a structured KPI set.

During the quantitative modeling process, I analyzed the financial statements of publicly listed automotive companies. The automotive industry focus was justified both by the historical significance of lean methodologies and by the dominant industrial focus of empirical research available in the literature. Publicly available and audited financial data covering the period between 1994 and 2024 were utilized for the modeling process. During the analysis, lean benchmark companies and a control group were established in order to enable the comparison of different operational models and performance characteristics.

Several quantitative methods were applied to evaluate lean performance. The statistical analyses included logistic regression models, machine learning algorithms, and Data Envelopment Analysis (DEA) in order to identify which financial and accounting indicators show significant relationships with lean operations. One of the main advantages of quantitative methodology is that it ensures the reliability and validity of results through standardized and reproducible procedures (BABBIE 2020), while also providing opportunities for predictive model development and the examination of relationships between variables (HAIR et al. 2010). The quantitative modeling process was complemented with a fuzzy logic model, which is particularly suitable in cases where the relationships between variables cannot be sharply separated but instead reflect gradual transitions and uncertainty. The theoretical framework of fuzzy logic based on fuzzy sets was originally introduced by ZADEH (1965), while its applicability in corporate performance evaluation has been confirmed by several later studies (BASAR 2020). The parallel application of different quantitative methods contributed to the triangulation and scientific robustness of the research findings (JICK 1979).

In addition to the quantitative methodology, I also applied a qualitative case study approach, which is well suited for research aiming to achieve a deeper understanding of organizational processes. Case study methodology is one of the most frequently applied approaches in qualitative organizational research (BRYMAN 1992). EISENHARDT (1989) and YIN (1994) emphasize theory building as one of the most important functions of case studies, while STAKE (1994) argues that the primary objective of qualitative case studies is the in-depth understanding of the examined case. In my research, the cases were not interpreted as individual companies themselves, but rather as controlling and performance evaluation systems related to lean operations.

Qualitative data collection was conducted through semi-structured in-depth interviews. Semi-structured interviews provided the opportunity for interviewees' individual experiences and interpretations to emerge alongside the predefined thematic areas. In qualitative research, data collection is typically conducted iteratively until the point of theoretical saturation is reached (GLASER – STRAUSS 1967). During the sampling process,

particularly in interpretive research, the researcher may rely on personal intuition, experiential knowledge, and professional judgment (KVALE 1996).

During the research, four automotive companies served as case studies, where interviews were conducted with controlling managers, controllers, financial managers, and analysts. The semi-structured interviews covered the following main topics: controlling processes, management reporting systems, the application of lean methods, and the role of financial and accounting KPIs in lean performance measurement. The qualitative and quantitative findings complemented each other throughout the research process and contributed to the development of a structured lean performance evaluation model capable of supporting the objective and comparable assessment of corporate operational efficiency based on publicly available financial and accounting data.

3.RESULTS AND DISCUSSION

During the literature review forming the basis of the quantitative statistical analyses, a total of 56 financial and accounting indicators were identified that could be associated with the organizational effects of lean management. During the systematization of these indicators, it quickly became evident that substantial conceptual overlaps and definitional inconsistencies existed among several KPIs, particularly regarding the use of different profit categories. To address this issue, the indicators were classified into two major groups: absolute and composite indicators. During model development, absolute indicators were excluded because they are highly dependent on firm size and operational volume, thus failing to provide objective comparability. Consequently, the research primarily focused on composite, relative indicators, while capital market-related measures were also excluded in order to ensure that the model relied exclusively on publicly available financial and accounting statement data. In the final selection phase, only those KPIs were retained that had been applied in at least three independent empirical studies.

In the first stage of the research, the financial and accounting indicators expected to exhibit a strong relationship with lean operations were identified through a meta-analytical approach combined with qualitative corporate observations. Based on the literature review, approximately half a dozen key KPIs were identified and subsequently expanded using insights derived from qualitative interviews. The analyses primarily focused on inventory management, asset efficiency, and profitability indicators, particularly ROA, ROI, ROS, NPM, ITO, and ATO, as well as IAR, ISR, DIO, and COGS, which frequently emerged during the interviews. The results indicated that ROA was the most commonly applied indicator, followed by ROI, ROS, NPM, ITO, and ATO. One of the most important findings of the research was that these indicators could be directly linked to the lean waste categories defined by OHNO (1982). ROA, ROS, ROI, and NPM were associated with virtually all categories of waste, whereas ATO and especially ITO were primarily connected to overproduction and excess inventory.

Preliminary descriptive analyses clearly demonstrated that companies applying lean principles generally achieved more favorable performance across most examined indicators than firms classified within the control group. Particularly significant differences were observed in inventory

management indicators, which is fully consistent with one of the core objectives of lean management: minimizing inventory-related waste and improving resource utilization efficiency. At the same time, the analyses also revealed that no unified financial and accounting framework currently exists that systematically connects lean waste categories with corporate performance measurement. Consequently, the developed KPI framework not only integrates findings from the literature and qualitative observations but also provides a methodological foundation for constructing an objective lean performance evaluation model based on financial data.

The results of the logistic regression models showed that the selected financial indicators exhibited statistically significant relationships with lean operations. Particularly strong relationships were identified for ITO, ISR, IAR, and ROS. These findings suggest that one of the most important characteristics of lean companies is faster inventory turnover, lower inventory intensity, and more stable operational profitability. This represents a particularly important result, as it confirms that lean management is not merely an operational philosophy but also generates measurable effects within the financial structures of firms. It is important to emphasize that an iterative modeling approach was applied during the logistic regression analyses. The effects and sensitivity of the currently included indicators were continuously examined, and subsequent models were estimated to further refine the variable set. This approach ensured that the regression framework was not based solely on a single indicator set derived from the literature review but also accounted for collinearity issues and the effects of less frequently emphasized indicators that were nevertheless strongly supported by the qualitative expert interviews.

The logistic regression analyses also revealed that performance patterns associated with lean operations are only partially linear in nature, while more complex nonlinear relationships emerged for several indicators. This was particularly evident in the case of ISR and IAR, where the effects of changes were not uniformly reflected in the probability of lean group membership across different value ranges. Even at this stage, the results indicated that more advanced nonlinear methodologies would be necessary for the more accurate modeling of lean performance.

A total of four sequential logistic regression models were developed and tested throughout the analysis process. During the gradual refinement of the models,

the statistical significance, sensitivity, and collinearity relationships of the variables were continuously evaluated in order to establish the most stable and informative final variable set possible. In the final, fourth model, those indicators were selected that later served as input variables for the fuzzy logic-based lean performance evaluation model. These indicators were ROS, ITO, ISR, IAR, and COGS, collectively representing different dimensions of profitability, inventory management, and operational efficiency. One of the most important outcomes of the iterative modeling process was that several indicators receiving less emphasis in the literature, yet frequently appearing in the qualitative corporate interviews, demonstrated significant explanatory power in identifying lean operations.

Accordingly, in the next phase of the research, Random Forest models were applied in order to examine the predictive performance of the selected financial indicators and their complex interrelationships within a more advanced nonlinear methodological framework. One of the most important findings of the Random Forest analyses was the exceptionally high predictive performance of the model: the explained variance reached 93.91%, while prediction accuracy achieved 98.33%. These results indicate that the selected indicators possess substantial informational value regarding the identification of lean operations. Variable importance analyses repeatedly identified ITO, ISR, IAR, COGS, and ROS as the most influential factors, with COGS and IAR particularly standing out both in terms of mean squared error increase and node purity increase. The findings confirmed that the financial manifestations of lean operations primarily emerge in the dimensions of inventory management, cost control, and operational efficiency.

Another important contribution of the Random Forest models was their ability to capture complex nonlinear relationships that classical linear models could only represent to a limited extent. The analyses demonstrated that the effects of certain indicators were not uniformly reflected in the probability of lean operations. For example, ITO exhibited an extremely strong positive relationship with lean operations within certain ranges, while this relationship became more moderate at other levels. Similar nonlinear patterns also appeared in the case of ISR and COGS, suggesting that lean performance cannot be adequately described through simple linear relationships. At the same time, the results of the logistic regression and Random Forest models showed substantial consistency, as both approaches identified highly similar

variable importance structures. This provided particularly strong methodological support for the subsequently developed fuzzy logic-based lean performance evaluation model.

In the next stage of the research, Support Vector Machine (SVM) classification models were applied to investigate the extent to which financial performance patterns associated with lean operations could be described using linear versus more complex nonlinear decision boundaries. During the analysis, models employing linear, second-order polynomial, and radial basis function (RBF) kernels were compared. The linear and polynomial kernel models produced relatively weak results. Although both models achieved high precision values, with the linear model exceeding 90% precision, the recall and F1 scores fell considerably below the expected level. This suggests that the models frequently failed to correctly identify positive observations associated with lean operations. The linear model proved particularly limited in capturing more complex patterns, while the polynomial kernel demonstrated excessive sensitivity to local variations, resulting in less stable predictive performance.

In contrast, the RBF kernel SVM model produced outstanding results. The model achieved 88.89% accuracy, 93.44% precision, and an F1 score of 85.07%, while recall substantially exceeded the performance of the other two models. These findings clearly indicate that the financial and accounting patterns associated with lean operations are fundamentally nonlinear in nature, requiring more flexible machine learning algorithms for accurate modeling. The RBF kernel was capable of constructing complex decision boundaries that much more precisely represented the differences between lean and non-lean firms. The SVM results were also consistent with the conclusions of the earlier Random Forest analyses, which similarly highlighted the dominant role of nonlinear relationships. Altogether, these findings further reinforced the assumption that the financial impacts of lean performance cannot be adequately modeled using simple linear structures but instead require the consideration of complex, multidimensional relationships.

Based on the overall results of the different machine learning models, it can be concluded that the selected financial and accounting KPIs possess strong predictive capabilities in identifying lean operations. Logistic regression, Random Forest, and SVM models frequently achieved accuracy levels around

or above 90%, indicating that lean operations manifest not only at the operational level but also clearly within the financial and accounting structures of firms. The results particularly emphasized the importance of inventory management, cost-control, and resource-efficiency indicators, especially ITO, ISR, IAR, and COGS. The consistency of the different models further strengthened the reliability and relevance of the selected KPI framework.

At the same time, the analyses also demonstrated that the financial patterns associated with lean operations cannot be fully explained through simple linear relationships. Particularly the Random Forest and RBF kernel SVM models revealed the existence of complex nonlinear relationships for several indicators. This represents an important methodological conclusion, as it supported the necessity of developing a more flexible fuzzy logic-based performance evaluation model capable of handling the complex and gradual transitions inherent in lean operations and corporate performance.

In the next stage of the research, Data Envelopment Analysis (DEA) was applied in order to translate the findings of the previous machine learning models into a scalable firm-level efficiency evaluation framework. The DEA models aimed to assess the relative technical efficiency of firms while considering the complex relationships between inputs and outputs. The input variables consisted primarily of the key KPIs and their components identified during the earlier analyses, particularly ITO, IAR, and COGS, while operating income and revenue served as output variables. The application of DEA proved particularly justified because lean operations inherently exert their effects through complex input-output relationships, while the method itself is capable of handling multivariate performance evaluation problems without requiring prior functional assumptions.

The results clearly demonstrated that lean companies achieved significantly higher technical efficiency scores than firms belonging to the control group. Particularly strong relationships emerged with inventory management indicators: firms characterized by higher ITO and lower ISR values generally achieved higher technical efficiency levels. This closely aligns with the core principles of lean management, which emphasize inventory minimization, reduced lead times, and more efficient resource utilization. During the aggregated analyses, a statistically significant Pearson correlation of approximately 0.7 was identified between DEA efficiency and the binary lean

variable, further strengthening the assumption that a close relationship exists between lean operations and technical efficiency. The DEA models also validated the results of the earlier logistic regression, Random Forest, and SVM models, confirming that the selected financial and accounting KPIs are indeed capable of capturing the structural differences arising from lean operations.

However, the DEA results also indicated that the differences between lean and non-lean firms are not always sharply distinguishable. Certain control-group firms, particularly those operating in premium market segments or characterized by high technological sophistication, achieved relatively high technical efficiency scores that, in some cases, approached those of lean firms. This suggests that operational logics and resource efficiencies similar to those associated with lean management may also emerge through alternative management systems. Consequently, one of the most important findings of the DEA models was not merely the confirmation of higher average efficiency among lean firms, but also the demonstration that complex and partially converging operational structures underlie financial and operational efficiency.

One of the most important methodological contributions of the research was the development of the fuzzy logic-based Lean Score model. The application of the fuzzy approach was justified by the fact that corporate performance and lean operations cannot be adequately described through rigid, discrete categories, as gradual transitions typically exist among firms. The model built upon the findings of the earlier logistic regression, Random Forest, SVM, and DEA analyses while simultaneously applying a more flexible and differentiated evaluation logic. During the development of the fuzzy system, four different membership function types – triangular, trapezoidal, Gaussian, and sigmoid – were tested in order to determine the most suitable structure for modeling lean performance. Comparative analyses demonstrated that the Gaussian fuzzy system was the most appropriate, as it exhibited the strongest relationship with DEA efficiency scores while also providing high discriminatory capability and stability.

The input variables of the fuzzy model consisted of the key KPIs identified during the previous analyses: ROS, ITO, ISR, IAR, and COGS. Model parameterization was performed using the Particle Swarm Optimization

(PSO) algorithm, which optimized the membership function structures by evaluating several million possible parameter combinations. The objective of the optimization process was to maximize the correlation between the Lean Score and the DEA-based technical efficiency measure while simultaneously incorporating the theoretically desirable directional effects implied by lean management principles. Accordingly, ROS and ITO were treated as positive factors, whereas ISR, IAR, and COGS were incorporated as negative effects within the system. This normative approach ensured that the fuzzy model did not merely follow statistical patterns but also reflected the underlying operational logic of lean management.

The results demonstrated that the Gaussian fuzzy model exhibited the strongest relationship with DEA efficiency scores ($r = 0.7285$; $p < 0.001$), while entropy and variance measures also indicated that this model provided the most balanced and informative performance evaluation framework. At the level of aggregated firm averages, the correlation between Lean Score and DEA efficiency approached 0.9, suggesting that the fuzzy system was capable of capturing the structural patterns underlying technical efficiency. At the same time, considerable variation was observed across individual firm-level time series correlations, indicating that the Lean Score is not simply a direct representation of DEA but rather interprets KPI combinations according to its own complex rule-based logic. This represents a particularly important finding, as it confirms that the model is capable of handling firm-specific operational characteristics in a differentiated manner.

The fuzzy model was also validated using an expanded sample consisting of thirty companies. The results remained consistent within this larger sample: Toyota, Suzuki, Honda, and Hyundai achieved exceptionally high Lean Score values, while several newer electric vehicle manufacturers, such as NIO, XPeng, and VinFast, displayed lower or medium performance levels. This suggests that the model is not limited exclusively to traditional automotive structures but is also capable of evaluating new technological and operational business models. Based on the model results, more than three-quarters of the examined firms were classified into high or very high lean categories, indicating that financial and operational patterns associated with lean operations are detectable across a substantial portion of the automotive industry.

One of the most important advantages of the fuzzy system was that it proved suitable not only for static benchmarking but also for time-series performance evaluation. Through the example of Subaru, it became clearly observable that the Lean Score responded sensitively to changes in the company's operational and financial condition. During the COVID-19 pandemic, for example, the negative shift in ROS, the dramatic decline in ITO, and the substantial increase in ISR were all reflected in the sudden deterioration of the Lean Score. At the same time, the model also accurately captured the subsequent normalization period, suggesting that the Lean Score functions not merely as a static indicator but also as a dynamic performance evaluation tool. This is particularly important in the context of lean operations, as corporate efficiency and operational stability are continuously evolving phenomena that remain highly sensitive to external shocks.

4. CONCLUSIONS AND SUGGESTIONS

Evaluating lean performance based on publicly available financial and accounting data

Numerous studies have demonstrated that the effects of lean management practices extend far beyond the immediate operational outcomes observed at the production level and are also directly reflected in companies' financial statements and accounting reports. Both the international and Hungarian literature indicate that companies consistently and systematically applying the principles of lean management, including the targeted reduction of waste, the optimisation of inventory management, the minimisation of lead times and the implementation of continuous improvement (kaizen), achieve demonstrably better performance not only in terms of operational efficiency but also in terms of financial performance.

My research has demonstrated that these effects can be monitored through changes in corporate financial and accounting performance indicators calculated from publicly available financial statement data, particularly indicators related to profitability and asset and operational efficiency. Based on the underlying mechanisms of lean principles and the lean methods applied, I identified the financial and accounting indicators that are directly or indirectly affected by these practices. The resulting relational framework establishes a structured link between lean practices and the measurable components of financial performance and provided the foundation for developing the performance evaluation model. The purpose of my research was not to incorporate previously developed indicators, typically intended for internal use and based on subjective assessments or questionnaires, into a mixed system for evaluating lean management. Company-specific, non-public qualitative data are difficult to compare methodologically and offer only limited transparency; consequently, they do not support an objective and reliable comparative analysis. The results of the research demonstrate that excluding such data does not reduce the validity of the analysis. On the contrary, an approach based on publicly available financial data can consistently reflect the effects of lean principles on corporate operations.

In my view, to ensure objectivity and comparability, the evaluation approach should primarily rely on publicly available data rather than subjective assessment criteria or internal information. At the same time, when evaluating lean performance, it is particularly important to recognise that industry- and company-specific characteristics may significantly influence the interpretation of financial and accounting indicators. Therefore, although an approach based on publicly available financial statement data increases

objectivity and comparability, the factors limiting its general validity must be considered both when developing the evaluation methodology and when interpreting the results.

The relationship between lean principles and financial indicators in performance evaluation

In four qualitative case studies, I examined the management control systems of automotive companies, with particular attention to the relationship between financial and accounting KPIs and lean management methods. Based on the results of the qualitative in-depth interviews, I concluded that the integration of a lean perspective into management control practices not only contributes to operational efficiency but is also directly related to the indicators used to assess financial performance. Nevertheless, these indicators are measured through systems that differ substantially across companies in terms of both methodology and effectiveness. Accordingly, my research has demonstrated that measuring and evaluating the application of lean methods requires the development of a unified model based on financial and accounting data, as no generally accepted methodological framework has emerged either in the literature or in corporate practice. In the absence of such a framework, although companies widely apply financial and accounting key performance indicators to evaluate lean processes, the comparability of their results remains limited. This further reinforces the need to develop a standardised evaluation system.

Several similarities can be identified among the management control practices of the companies examined in terms of the financial and accounting indicators used to evaluate lean methods. Although the selection and interpretation of indicators vary across companies, identical or highly similar indicators are used in several cases, particularly in the areas of inventory management, asset efficiency and profitability. The case studies demonstrate that KPI-based evaluation makes it possible not only to measure lean processes but also to compare their performance at the organisational level. However, the definition and weighting of indicators are closely aligned with the organisational structure and data architecture of each company, highlighting the importance of adapting the evaluation to the specific corporate environment. The corporate practices examined clearly indicate that lean management remains a relevant and influential corporate philosophy. Consistent with the findings of the literature, lean management affects corporate operations not only at the operational level but also from a strategic perspective, and its effects can be detected in financial statements. Corporate practice corroborated many of the relationships identified through the theoretical and statistical analyses while also enriching the interpretative framework with additional experience. This

made it possible to develop a more flexible evaluation model that takes account of the diversity of corporate environments. Consequently, although the assessment criteria associated with lean management are often heterogeneous and subjective, they can be structured and quantified within an appropriate methodological framework.

Nevertheless, the unified quantitative evaluation of the effects of lean management remains a complex task, primarily because of the diversity of corporate interpretations, industry differences and measurement systems. Substantial differences in methods, indicators and data architectures make it difficult to develop a general model that can be applied equally in every corporate context. My findings nevertheless demonstrate that, drawing on the literature and empirical experience, it is possible to establish a measurement logic that can address this heterogeneity through appropriate methodological foundations and sufficient flexibility, thereby advancing the practice of lean performance evaluation. The practical applicability of the approach is significantly enhanced by the fact that, in the case of listed companies, the financial and accounting data underlying the model are publicly available as part of mandatory financial reporting. Applying the model therefore does not require access to company-specific internal data, questionnaire-based data collection or direct cooperation with the company concerned. Consequently, the evaluation can be performed in a reproducible manner not only by corporate management or management control departments but also by external stakeholders such as analysts, investors and auditors. An approach based on public databases therefore improves not only the objectivity and comparability of the evaluation but also the practical accessibility and broader applicability of the model.

The developed lean performance evaluation model

The first and most important step in constructing the lean performance evaluation model is to identify the corporate sector under examination and, where necessary, the relevant subsector. Lean philosophy and the associated methodology are primarily linked to the secondary sector, particularly to the various subsectors of manufacturing, where improving operational efficiency is of particular importance. Although lean management originated and remains most prominently applied in the automotive industry, the model is not limited exclusively to this sector. With appropriate adaptation, it may also provide relevant evaluations in other areas of the secondary sector and, under certain conditions, in selected service processes within the tertiary sector. The selection of the KPIs underlying the model must be based both on recommendations in the literature and on the financial and accounting characteristics of companies operating in the sector concerned. The selected

indicators must also be consistent with the objectives of lean principles. Accordingly, an important consideration in developing the model was that the components of the evaluation system should be closely related to the main sources of waste identified by lean management. The indicators were therefore selected to reflect directly the objectives of reducing overproduction, inventory, unnecessary movement and transportation, waiting, overprocessing, scrap and defective products. As a result, the evaluation system captures not only financial and operational performance but also establishes a direct relationship with the practical implementation of lean principles.

The extent to which a company can transform lean methods aimed at improving operational efficiency into financial performance cannot be described using simple linear relationships. For this reason, I decided to apply fuzzy logic in developing the model. This makes it possible to evaluate performance through classification categories characterised by continuous transitions rather than discrete boundaries, thereby flexibly accommodating small variations in performance differences (ZADEH 1965). Using the selected indicators, the model calculates technical efficiency scores through data envelopment analysis (DEA), which provide the basis for parameterising the fuzzy system. Based on the principles of lean management and the requirements of operational efficiency, I specified in advance the desired directions of change in the individual KPIs, such as an increase in profitability or a decrease in inventory relative to revenue. The objective function accordingly optimises the parameters of the fuzzy membership functions of the selected KPIs using the particle swarm optimisation (PSO) algorithm. The optimisation seeks to maximise the correlation between the fuzzy lean score and the DEA-based technical efficiency scores while simultaneously satisfying the prescribed directional constraints.

The novelty of the model lies in the fact that it is not based merely on a simple combination of the selected indicators. Instead, it uses an adaptive, data-driven objective function to perform a complex, nonlinear logical evaluation while consistently incorporating lean principles. The innovation of the model therefore primarily derives from treating the individual financial and operational indicators not as separate, isolated measures but as elements of an aggregated fuzzy-logic-based evaluation system linked to technical efficiency. This approach enables the relationships among different dimensions of performance to be represented jointly in the evaluation of lean performance while ensuring that the predefined lean principles and directional requirements are incorporated into the model's logic. This complex approach has proved not only methodologically effective but also necessary from the perspective of lean management, as the evaluation of the indicators often involves

nonlinear relationships and certain components of the model also depend on conceptual assumptions.

In addition to its contribution to economics, the developed model can also be applied in corporate management practice. As a supplementary decision-support tool, it enables the standardised evaluation of a company's lean performance based on financial and accounting data. Corporate management and management control departments can use the model to monitor changes in lean performance over time, compare the company's performance with that of other companies operating in the same sector, and identify the performance areas that adversely affect its aggregated Lean Score. The results may therefore support the determination of development priorities, the ex post evaluation of previously implemented lean measures, and corporate and industry benchmarking. The model is not intended to replace company-specific operational indicators or managerial decision-making. Rather, it provides objective, quantifiable supplementary information that can significantly improve the evidential basis of management decisions.

Recommendations for the further development of the lean performance evaluation model

The model developed in this research evaluates lean performance using corporate financial and accounting data, that is, on the basis of the company's income and financial position. This approach primarily captures the direct relationships between operational efficiency and financial performance. However, the model does not incorporate company valuation measures, such as discounted cash flow (DCF) or economic value added (EVA), or capital-market valuation indicators, such as the price-to-earnings ratio or Tobin's Q, which reflect the company's long-term value-creation capacity and investor perception. Addressing this limitation represents a potential direction for future model development. An integrated evaluation system could be constructed that considers not only financial performance indicators but also dynamic changes in corporate value. Such an enhanced approach would make it possible to measure the effects of lean management not only at the level of operational efficiency but also in terms of longer-term economic value creation.

The technical operation of the model also offers relevant directions for future research. One possible area for development is the refinement of the parameterisation of the fuzzy logic system. In addition to the membership functions already tested, alternative functions, such as sigmoid or adaptive functions, could increase the sensitivity and robustness of the performance evaluation. Optimising the objective function may also represent an important

area for the model's future development. The particle swarm optimisation (PSO) algorithm was used to fit the parameters in the current model and proved to be an appropriate choice because of its efficiency and ease of implementation. However, incorporating additional optimisation algorithms, such as genetic algorithms and differential evolution, as well as machine-learning methods or neural networks could facilitate an even more effective estimation of the model parameters.

Refining the calculation of DEA-based efficiency scores, for example by combining input- and output-oriented models, could also improve the accuracy of the evaluation system. The current fuzzy logic system is based on a simplified but readily interpretable aggregation method that effectively captures the combined effects of the individual KPIs. A further direction for development could involve the application of a multidimensional fuzzy evaluation system, such as a Mamdani- or Sugeno-type system. Such a more advanced fuzzy system could model more complex logical relationships and account for nonlinear and interactive effects among the indicators. This could not only improve the accuracy of the performance evaluation but also enable the model to adapt more flexibly to different corporate environments and sectoral characteristics, thereby further strengthening its general validity and practical relevance.

Another promising direction for the technical development of the model would be to integrate a more detailed analysis of time-series financial and accounting data. Although the model in its current form can process time-series financial and accounting data and evaluate them according to lean principles, future developments could integrate trend analysis and predictive time-series methods. Identifying trends and volatility and filtering out seasonal effects would provide a deeper understanding of the temporal stability and developmental dynamics of lean performance. Such an extended approach would support not only the evaluation of past performance but also the forecasting of future performance, further increasing the model's practical applicability.

The lean performance evaluation model developed in this research can also be adapted to numerous other fields of application and evaluation purposes, provided that the environment under examination meets the following fundamental criteria:

- Quality of financial and accounting data: the organisations examined must be able to provide audited and publicly available financial and accounting data or, where these are unavailable, reliable internal data

prepared with an appropriate level of accounting discipline and suitable for objective performance evaluation.

- Availability of time-series data: financial and accounting data must be available for several consecutive periods, allowing for a more accurate evaluation of aggregated performance and an analysis of the underlying performance over time. The longer the available time series, the more accurate and reliable the model's evaluation of the long-term effects of lean practices can be.
- Central role of operational efficiency: improving operational efficiency must represent a major strategic objective in the organisations examined, irrespective of whether they formally apply lean methods or follow other management approaches with similar objectives.
- Benchmarking: it is particularly important to select a sample comprising a sufficiently large number of companies operating in the same sector, thereby ensuring the statistical reliability and validity of the comparative analysis.
- Treatment of evaluation thresholds: although the model is data-driven, the selection and interpretation of performance indicators are partly context-dependent. Particularly in sectors outside manufacturing, this may require recalibrating the parameters to reflect environmental and company-specific characteristics.

Based on these criteria, the model developed in the research can be widely applied in areas where the evaluation of operational efficiency and financial and accounting performance is particularly important. The model can be integrated into benchmarking analyses and, as a complement to traditional technical analysis methods, into the efficiency-based evaluation of the financial performance of listed companies. It can also support investment decisions, particularly in sectors characterised by intense competitive and innovation pressures. Furthermore, the model can be applied to evaluate the effects of investments and developments related to production systems and supply chains, as well as to analyse operational efficiency initiatives in service-sector organisations.

The internal logic and methodological framework of the model can also be adapted to and further developed for other efficiency- and profitability-oriented evaluation systems. As the model relies exclusively on publicly available financial and accounting data, it may also enable external analysts, auditors and other market participants to compare the lean performance of companies. It can thereby contribute to a more transparent evaluation of corporate operations and enhance the information content of financial analyses.

Limitations of the research

The objective of this research was to develop a lean performance evaluation model based on publicly available financial and accounting data. Several deliberate methodological decisions were made during its development. The analysis focused exclusively on the automotive industry because lean management is historically associated with this sector and because the automotive industry represents its most extensively documented field of application in the literature. Although this focus strengthens the model's internal validity, it also limits the direct generalisability of the results to other industries. The relatively small sample size represents an additional limitation, particularly in the case of the machine-learning models. To mitigate this issue, I assessed the robustness and generalisation capacity of the models not only through conventional performance measures but also by applying supplementary validation procedures and multiple independent modelling approaches.

A further limitation of the model is its fundamentally retrospective nature. It does not evaluate lean performance in real time, simultaneously with the execution of corporate processes, but instead relies on the representation of previously realised operational outcomes in financial and accounting data. Consequently, in its current form, the model is primarily suitable for ex post performance evaluation and comparison and cannot be regarded as a dynamic or predictive decision-support system. The validity and comparability of the data used represent an additional limiting factor. Although publicly available financial and accounting data enhance the objectivity and reproducibility of the evaluation, differences in accounting practices, reporting characteristics and corporate structures may affect the direct comparability of individual indicators across companies. The cross-sectional nature of the analysis also limits the interpretation of the results, as comparing the performance of individual companies during a particular period does not in itself allow causal relationships to be identified unambiguously. In addition to lean operations, the observed performance differences may reflect other corporate and environmental factors, including company size, market position, technological characteristics, the macroeconomic environment and business cycles. Accordingly, the model's results should primarily be interpreted for comparative and performance evaluation purposes and cannot, in themselves, be regarded as evidence of the causal effects of lean management.

It is also important to emphasise that the binary classification of companies into lean and non-lean groups represents a methodological simplification because, in practice, lean maturity is better understood as a continuous spectrum. This classification primarily facilitated the objective identification

of the KPIs underlying the model and the establishment of the benchmark model. The fuzzy model presented in the dissertation partially addresses this limitation by evaluating companies on a continuous lean performance scale. The companies assigned to the control group should not necessarily be regarded as non-lean organisations. Rather, they are companies for which the literature does not provide clear empirical evidence of a documented lean benchmark status extending over several decades. Finally, the model relies exclusively on publicly available financial and accounting data. Although these data permit comparative evaluation, they cannot directly capture certain operational characteristics of lean management. The limitations described primarily affect the generalisability of the results; at the same time, they also identify potential directions for the further development of the model and its adaptation to other industries.

5. NEW SCIENTIFIC RESULTS

1. A statistically significant relationship can be identified between the application of lean methods and publicly available financial and accounting indicators

Based on my research findings, it can be concluded that the application of lean management and related methods is significantly associated with several financial and accounting performance indicators. The identified patterns of co-movement can be interpreted in relation to lean principles and sources of waste, while their potential underlying mechanisms can also be identified in corporate financial statements. This supports the conclusion that the effects of lean management are not confined to internal operational processes and indicators but are also systematically reflected in companies' publicly available financial and accounting data. The quantitative analyses and the expert opinions obtained through the qualitative interviews allowed the identification of a set of KPIs whose components, when applied jointly and synergistically, can be used with a high degree of reliability to evaluate lean performance.

2. Lean organisations can be regarded not only as more successful in terms of profitability but also as more efficient in technical terms

The empirical findings indicate that the technical efficiency of lean-oriented companies, measured through Data Envelopment Analysis (DEA) using financial and accounting indicators, is generally higher than that of companies assigned to the control group. This suggests that the relationship presented in the first thesis is not the result of a random or isolated observation but represents a performance difference that is also supported by a non-parametric efficiency evaluation method and reflects the systemic effects of a lean orientation. It also indicates that the waste-reduction and resource-optimisation objectives of lean management may generate operational advantages that can be transformed into additional technical efficiency. It should nevertheless be emphasised that improvements in technical efficiency are not always immediately reflected in financial results. Their realisation also depends on the quality with which lean practices are implemented and their alignment with corporate strategy.

3. A data-driven, fuzzy-logic-based model has been developed for evaluating lean performance by integrating technical efficiency and lean principles within a unified evaluation framework

The model developed in this research combines various statistical, mathematical and optimisation methods that jointly contribute to a complex,

multidimensional evaluation of organisational lean performance. Lean performance is measured by aggregating and combining individual indicators on a weighted basis. Their alignment with the technical efficiency of the organisations examined is achieved through fuzzy logic and a normative, sign-based rule system. The model can interpret the theoretical expectations associated with different indicators within a unified logical framework, thereby reducing subjectivity in performance evaluation, interpretative bias and uncertainty arising from different evaluation principles. Its data-driven operation enables the evaluation of lean performance to be closely aligned with technical efficiency while flexibly incorporating the evaluation criteria derived from financial performance and lean principles.

4. The research resulted in the development of an aggregated Lean Score that expresses organisational lean performance consistently and comparably by integrating financial and accounting performance indicators

The developed Lean Score aggregates selected financial and accounting indicators into a single composite measure of organisational lean performance. The indicator is not based merely on the mathematical aggregation of financial and accounting variables. Instead, it transforms the interpretative framework associated with lean principles, sources of waste, and the findings of the literature review and qualitative research into a unified performance measure. Based on the literature examined, no Lean Score could be identified that uses publicly available financial and accounting data to represent the functional manifestation of lean principles in a similarly integrated manner. The Lean Score therefore enables an integrated and comparable evaluation of organisational lean performance while reducing the interpretative uncertainty arising from the isolated application of individual financial indicators.

5. The joint evaluation of the Lean Score and technical efficiency can be used for the ex post assessment of the quality of lean implementation

My research findings indicate that the Lean Score calculated from publicly available financial statements can be used not only to compare the lean performance of organisations but also, when evaluated jointly with DEA-based technical efficiency, to provide information about the quality of lean implementation. As the model is based on historical financial statement data, its purpose is not to forecast future performance but to reconstruct the lean pattern of operations that have already been realised. The Lean Score summarises how lean principles are manifested in financial and accounting indicators, whereas DEA measures technical efficiency using the same underlying data. A divergence between the two rankings has an informative

value of its own. A high Lean Score accompanied by lower technical efficiency may indicate that a lean pattern is already visible in the financial statements, although its effects have not yet been fully realised in technical efficiency. The reverse situation may indicate efficient operations whose results have not yet formed a consistent lean performance pattern in the financial and accounting indicators. The qualitative interviews suggest that these differences can be explained, among other factors, by the quality of lean implementation and its alignment with corporate strategy. Based on the literature examined, no approach could be identified that jointly applies a Lean Score calculated from publicly available financial statements and DEA-based technical efficiency for ex post evaluation purposes.

6. SCIENTIFIC PUBLICATIONS RELATED TO THE TOPIC OF THE

Journal articles published

1. **BÁNYAI, A.** – **BÁRCZI, J.** – **THALMEINER, G.** (2026): Normative Lean Performance Score Model Based on Financial and Accounting Metrics. *INTERNATIONAL JOURNAL OF FINANCIAL STUDIES* 14 : 6 142. p.
2. **BÁNYAI, A.** (2024): Evaluating Lean Performance by Using Financial Accounting Metrics. *ECONOMICS & WORKING CAPITAL* 2024 : 1-2 pp. 35-41. p.
3. **BÁNYAI, A.** - **TATAY, T.** - **THALMEINER, G.** - **PATAKI, L.** (2025): Consumer Expenditure-Based Portfolio Optimization. *INTERNATIONAL JOURNAL OF FINANCIAL STUDIES* 13 : 2 Paper: 99, 18 p.
4. **BÁNYAI, A.** - **TATAY, T.** - **THALMEINER, G.** - **PATAKI, L.** (2025): Evaluating the Risk-Return Profile of a Portfolio of ESG and Traditional Assets Using a Hybrid Optimisation Model. *Virtual Economics* 8 : 1 pp. 16-39. p.
5. **THALMEINER, G.** - **GÁSPÁR, B.** - **BÁNYAI, A.** - **TÓTH, M.** - **GÁSPÁR, S.** (2023): Lean controlling modellezés fuzzy logika alkalmazásával: szintetizált megközelítés tejelő tehenészetek iparági specifikus környezetében. *CONTROLLER INFO* 11 : 3 pp. 12-18. p.
6. **THALMEINER, G.** - **GÁSPÁR, B.** - **BÁNYAI, A.** - **TÓTH, M.** - **SEMJÉN, B.** (2023): Matematikai modell fejlesztés a vállalati folyamatok teljesítményértékelésének szubjektivitására: egy tejtermelő tehenészet vállalkozás esettanulmánya. *CONTROLLER INFO* 11 : 4 pp. 12-17. p.

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