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Sectoral Technical Efficiency and Its Determinants in Turkish Manufacturing: Evidence from a Stochastic Frontier Model

Master's Thesis

Hamidreza Savehdarbandsari

Department of Economics
Master of Science in Economics

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Acknowledgement

I would first like to express my deepest gratitude to my supervisor, Assoc. Prof. Seyid Fahri Mahmud, for his insightful guidance, encouragement, and invaluable academic support throughout each stage of this research. His thoughtful comments and expert knowledge helped me in developing and shaping the study.

I would like to acknowledge the faculty members of the Economics Department, whose dedication to academic excellence and constructive feedback contributed meaningfully to my development through their courses, discussions, and guidance.

I would particularly like to thank my friend Fatih Furkan Akosman, the Research Assistant of the Economics Department, for sharing academic experiences and valuable conversations.

Last but not least, I would like to express my special thanks of gratitude to my parents Jalil Savehdarbandsari and Maryam Shemshaki, for their unwavering support, constant encouragement, and unconditional belief in my abilities. I am equally grateful to my brother, Hooman Savehdarbandsari for always standing by me and believing in my goals. Reaching this point would not have been possible without their enduring patience and sacrifices.

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Abstract

This thesis investigates the determinants of profitability-based efficiency among Turkish two-digit manufacturing industries using a Stochastic Frontier Model (SFM) with inefficiency effects for the period 2019–2023. Motivated by the limitations of traditional production-based efficiency studies and the structural heterogeneity of Turkish manufacturing, the study employs Return on Assets (ROA) as the frontier output to capture financial performance across sectors with diverse technologies, cost structures, and product mixes. A stochastic profit frontier is estimated using liquidity, leverage, and inventory turnover as core determinants of profitability, while inefficiency is modeled as a function of fixed-asset structure, interest-coverage capacity, R&D intensity, operating expenses, and the COVID-19 pandemic period. The empirical results show that liquidity and inventory turnover significantly enhance profitability, whereas high leverage reduces sectors' ability to reach the profit frontier. Inefficiency effects indicate that stronger equity-backed capital structures, higher debt-servicing capacity, and greater R&D investment reduce inefficiency, while high operating expenses increases it. The pandemic dummy confirms substantial efficiency losses during COVID-19. Variance parameters reveal that approximately 39 percent of profitability variation stems from structural inefficiency rather than random shocks, validating the use of a stochastic frontier framework. Technical efficiency scores demonstrate a clear hierarchy: high-technology industries, including electronics, motor vehicles, and pharmaceuticals, operate near the frontier, while traditional industries such as textiles, wood products, and apparel exhibit persistent inefficiency. Pandemic-period comparisons reveal intensified disparities between advanced and low-technology sectors. Overall, the thesis provides one of the first profitability-based frontier assessments of Turkish manufacturing and highlights the critical roles of financial resilience, innovation capacity, and cost-structure modernization in strengthening sectoral efficiency and competitiveness.

Keywords: Stochastic Frontier Analysis (SFA); Technical Inefficiency; Turkish Manufacturing Industry; Profitability Frontier (ROA)

Özet

Bu tez, 2019–2023 döneminde Türkiye'nin iki haneli imalat sanayi kollarında kârlılığa dayalı etkinliğin belirleyicilerini, teknik etkinsizlik etkilerini içeren Stokastik Sınır Modeli (SFM) aracılığıyla incelemektedir. Geleneksel üretim temelli etkinlik çalışmalarının sınırlılıkları ve Türk imalat sektöründeki yapısal heterojenlikten hareketle, farklı teknoloji, maliyet yapısı ve ürün çeşitliliğine sahip alt sektörlerin karşılaştırılabilir bir performans göstergesine ihtiyaç duyulduğundan, sınır çıktısı olarak Varlık Karlılığı (ROA) kullanılmıştır. Kâr sınırı likidite, kaldıraç ve stok devir hızı değişkenleriyle tahmin edilirken; etkinsizlik, sabit sermaye yapısı, faiz karşılama oranı, Ar-Ge yoğunluğu, faaliyet giderleri ve COVID-19 dönemi gibi faktörlerle modellenmiştir. Ampirik bulgular, likidite ve stok devir hızının kârlılığı artırdığını; yüksek kaldıraç oranının ise sektörlerin kâr sınırına ulaşma kapasitesini zayıflattığını göstermektedir. Etkinsizlik sonuçları, daha güçlü özkaynak destekli sermaye yapılarının, yüksek faiz karşılama gücünün ve artan Ar-Ge yatırımlarının etkinsizliği azalttığını; yüksek faaliyet giderlerinin ise etkinsizliği artırdığını ortaya koymaktadır. Pandemi kukla değişkeni, COVID-19 döneminde etkinlik kayıplarının belirgin şekilde arttığını doğrulamaktadır. Varyans parametreleri, kârlılık varyasyonunun yaklaşık yüzde 39'unun rassal etkilerden ziyade yapısal etkinsizliklerden kaynaklandığını göstermekte ve stokastik sınır yaklaşımının uygunluğunu desteklemektedir. Teknik etkinlik skorları, sektörler arasında belirgin bir hiyerarşi sunmaktadır: elektronik, motorlu taşıtlar ve ilaç gibi yüksek teknoloji sektörleri sınırın yakınında faaliyet gösterirken; tekstil, ağaç ürünleri ve giyim gibi geleneksel sektörler kalıcı etkinsizlik sergilemektedir. Pandemi dönemine ilişkin karşılaştırmalar, ileri teknoloji ile düşük teknoloji sektörleri arasındaki farkların daha da belirginleştiğini ortaya koymaktadır. Bu tez, Türk imalat sanayinde kârlılık temelli ilk sınır analizlerinden birini sunmakta ve finansal dayanıklılık, yenilik kapasitesi ve maliyet yapısının modernizasyonunun sektörün etkinlik ve rekabet gücünü artırmadaki kritik önemini vurgulamaktadır.

Anahtar Kelimeler: Stokastik Sınır Analizi (SFA); Teknik Etkinsizlik; Türk İmalat Sanayi; Kârlılık Sınırı (ROA).

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1. Introduction

Manufacturing sector plays critical a critical role in shaping the economic development of a country. It helps in creating high-quality jobs, technological advancement and last but not least in contributing to productivity and technological innovations, which directly supports GDP growth. Although in recent decades most economics have gradually shifted towards service sectors, manufacturing is still plays a crucial due to structural change. This matter is particularly important for those countries that seek to improve their production, increasing export competitiveness, and creating a stronger economic framework. The capacity of manufacturing sectors to stay competitive, cope with financial constraints and faster innovation have become more crucial than ever due to shifting in global trade patterns and rapid technological advancements. Thus, it is essential to take into consideration how effectively sectors manage financial resources, adjust to technological progress, and remain profitable under dynamic economic fluctuations rather than just focusing on output.

In the context of Türkiye, the dynamics of different phases of the development of the sector provides an interesting case to study. The Turkish manufacturing sectors have undergone through an export-oriented transformation and a gradual process of differentiation, due to economic liberalization, integration of its economy at the European level, and involvement in global value chains over the last four decades. The Turkish manufacturing sector is characterized by a variety of activities, including both labor-intensive and middle and high-technology activities, which are linked to international manufacturing networks. However, the industry is currently experiencing some challenges such as macroeconomics instability, exchange rate fluctuations, financial constraints, and more recently COVID-19 pandemic which has caused supply chain disruptions. These conditions have increased the significance of employing model(s) that help quantify the technical efficiency scores, such as those outside the production to management decisions, innovation capacity and financial strength.

In order to understand how sectors perform below their potential and to identify financial constraints that prevent optimal performance, technical efficiency analysis is one of the effective approaches.

Several empirical studies of Türkiye have examined mostly production-based technical efficiency differentials, at the firm level by employing stochastic frontier approaches and also non-parametric methods to measure them.

However, limited number of studies have examined sector-level profit efficiency and the effect of financial and innovation factors on inefficiency across different two-digit manufacturing industries. Addressing these gap is important as financial conditions increasingly affect competitiveness, particularly those sectors that in are financially vulnerable and heavily dependent on imported intermediate inputs. Moreover, during the pandemic period, industries were impacted differently by COVID-19 shocks, showing differences in resilience and adaptability.

To fill these gaps, this thesis analyzes profitability-based technical efficiency across Turkish two-digit manufacturing industries, for the 2019–2023 period. By employing a stochastic frontier model in which return on assets serves as the performance indicator, this thesis provides a comprehensive efficiency analysis that goes beyond traditional production-based measures.

This framework captures inefficiency as a function of financial structural and innovation-related factors by evaluating how variables such as liquidity, leverage, cost structure, capital structure, and R&D activity affect profitability. In addition, a Pandemic dummy is also included to measure crisis-related shocks impacting profitability. The findings are expected to shed light on the competitiveness and resilience of Türkiye's manufacturing sector and to support policy efforts to enhance industrial performance.

1.1. Manufacturing, structural transformation, and economic development

The manufacturing sector is commonly regarded as a key engine of economic growth and structural transformation. Its role in promoting productivity growth, generating quality employment, and supporting economy-wide upgrading is strongly highlighted in classical, and modern growth theories (Kaldor, 1966, Chenery, 1979, Lewis, 1954). From these perspectives, manufacturing is distinguished from agriculture and many other service industries by its unique characteristics, particularly its strong capacity in learning, innovation, and technological advancement.

One of the main reasons manufacturing holds a central position in economic development is its capacity to drive productivity growth. The sector benefits from increasing scale economies, learning-by-doing, and rapid technological advancement, which together contribute to declining average costs as production expands (Arrow, 1962). Cross-country findings consistently highlight that manufacturing productivity growth often outperforms overall economic productivity, especially in the early and middle stages of development.

Manufacturing industries function as key centers of technological advancement. According to (Chenery, 1979), sectors such as machinery, transportation equipment, electronics, and chemicals generate innovations that influence the wider economy by supplying capital goods, intermediate inputs, and production expertise. As a result, efficiency improvements in manufacturing frequently contribute to economy-wide productivity growth.

The tradability of manufactured goods also enhances the importance of developing the manufacturing sector. Moreover, they could be produced in standardized forms, stored efficiently, allowing for international trade at a relatively low cost. Such an approach allows countries to overcome constraints in domestic demand and integrate more successfully into global value chains. Evidence from export-oriented industrialization in East Asia demonstrated that how manufacturing, supported by effective economic policies, could generate faster structural changes, promote learning, and improved competiveness (Amsden, 1989, Rodrik, 2008).

With respect to formal employment generation, the manufacturing sector is a key driver as compared to other sectors, such as agriculture and low productivity services. This is reflected in the historical role of manufacturing in providing stable jobs and higher wages. While, the shifting in technology has change the structure of industrial employment, manufacturing still serves as key sources of employment generation and skills development, particularly in emerging economics (UNIDO, 2013).

Although manufacturing remains critical, it is increasingly challenged by global pressures. They encompasses global competition, faster technological progress, and weakening cost advantages in labor-intensive sectors. This phenomenon is known as premature deindustrialization and is observed in many developing countries. It happens when manufacturing output begins to decline at relatively low income levels (Rodrik, 2016). These challenges show the importance of examining both the growth of manufacturing and its operational efficacy within a changing economic and technological environment.

1.2. Türkiye's manufacturing sector, evolution, structure, and contemporary dynamics

Turkish manufacturing sector has become developed increasingly since the early 1980s. During the import substitution period, strong protective measures, limited market competitions, and active state participation contributed in industrial development. However, such an approach commonly lead to inefficiency and a lag in technological advancement.. In 1980s, liberalization reforms brought a major change. The reforms included revising exchange rate policies and promoting exported-oriented production (Onis & Senses, 2009). As a result of these reforms, manufacturing firms were able to accesses to international markets and enhanced their operational capabilities.

Türkiye's participation in the Customs Union with the European Union in 1996 was one of the most crucial development in this regard. The elimination of tariffs on industrial products and aligning with European standards, competitions increased and technological upgrading improved rapidly including automotive, machinery, and electrical equipment industries (Togan, 1997). By becoming integrated into European production networks, investment increased, the quality of product improved and expanded industrial capabilities. Currently, the industry includes a wide range of activates. Industries, such as textiles, apparel, leather, and food production, which are low-technology industries, continue to employ a large workforce and play an important role in export.

Industries with medium technological intensity, including plastics, rubber, basic metals, fabricated metal products, and machinery, represent the foundation of TürkiyeTürkiye's industrial output. In contrast, high-technology industries such as automotive, electronics, and pharmaceuticals have grown gradually and play a key role in export performance.

These contrasting approaches leads to market differences in terms of productivity and efficiency. High-technology based industries are supported by advanced production technologies, higher (R&D) spending and closer linked to global value chains. By contrast, labor-intensive sectors often face higher costs, limited innovation incentives and competition from countries with lower labor costs. Manufacturing performance is strongly influenced by macroeconomic factors. Rising inflation, exchange rate instability, and financial constraints significantly influenced firms' investment behavior and cost structures. Turkish manufacturing depends heavily on imported intermediate goods and capital machinery. This makes it vulnerable to exchange rate movements. While, a weaker currency can enhance export competitiveness, it can also increase higher input costs and reduce profitability.

During the COVID-19 pandemic, industries were effected in different ways. Boosting demand in essential sectors like food manufacturing, pharmaceuticals, and packaging, while, causing significant disruptions and demand declines in export-oriented industries such as automotive, electronics, and textiles (Yücel & Durak, 2021). These trends show the importance of conducting industry-level efficiency and resilience analyses.

1.3. Technical efficiency and its relevance in contemporary manufacturing analysis

Technical efficiency measures how effectively a production unit transforms available inputs into output, relative to the maximum achievable performance, given the existing resources and technology. Any shortfall, gap or distance from this potential level of performance is interpreted as inefficiency. In manufacturing, the scope of technical efficiency goes beyond the efficient use of physical productivity but also includes to financial decision-making, innovation potential, supply chain efficiency and organizational structure.

Traditional efficiency studies primarily focused on physical input–output relationships. By contrast, modern manufacturing operates in an environment that is influenced by financial constraints, technological advances and competitive pressures, which are critical determinants of performance. As a result, modern efficiency analysis integrates financial and structural aspects together with production-related factors. Technological capability plays an important role in determining efficiency. Firms' ability to achieve performance levels close to their potential is strongly shaped by investment in machinery, automation, digitalization and innovations in production processes. In contract, technological lag may give rise to sustained inefficiencies, while digitalization and data-driven production systems are reshaping efficiency patterns worldwide (Brynjolfsson & McAfee, 2014).

Financial structure is another key factor which directly shapes how firms finance investment and manage risk. Incensing leverage constrain investment, heighten vulnerability to shocks, and weaken operational flexibility. By contrast, firms with stronger equity bases or stable financing structure are able to respond more effectively to market fluctuations. Higher liquidity allows firms to manage inventories, acquire inputs and avoid costly disruptions to production.

Higher level of innovation and (R&D) intensity are key drivers of efficiency improvement. Through investments in research and development, firms can implement advanced technologies improve process efficiency, and reduce production costs. Evidence from international research indicates a strong relationship between innovation activities, productivity growth and competitive strength (OECD, 2019).

Overall firm performance is strongly influenced by Operational efficiency, including supply chain operations and inventory management. Effective control of these processes reduces production delays, enhances quality, and increases adaptability to market fluctuations. The COVID-19 pandemic showed how supply chain disruptions can temporarily push firms away from the efficiency frontier, even in firms with strong internal capabilities. Consequently, efficiency analysis should incorporate profitability-based indicators that capture both operational and financial factors.

1.4. Analytical framework and rationale for the stochastic frontier approach

To estimate efficiency and profitability across Turkish manufacturing industries, a stochastic frontier model (SFA) is being employed in this study, which is well suited for evaluating performance under an uncertain environments with external shocks and measurement error. Unlike deterministic approaches, SFA is able to separate statistical noise and inefficiency (Aigner et al., 1977, Meeusen & van den Broeck, 1977), this increase its ability to adapt to the dynamic and volatile challenges within Türkiye's manufacturing industry.

The return on assets (ROA) is selected as the dependent variable due to its ability to measure how efficiently industries generate profits from their assets. As a comprehensive performance indicator, ROA combines efficiency in operations, cost management, and financial decision-making within one performance metric. In addition, it also enables cross-industry comparisons with different asset size and production technology.

Variables measuring financial structure, liquidity, operating costs, capital composition, and innovation activity are included in the inefficiency effect model. The pandemic dummy variable is used, which allows for the assessment of how crisis periods influenced profitability performance across different industries. The empirical analysis is conducted using panel data from the Central Bank of the Republic of Türkiye's Company Accounts Statistics and covers the period from 2019 to 2023. This data source offers comparable financial data across two-digit manufacturing sectors, which enables a robust assessment of efficiency trends over time.

By emphasizing efficiency in terms of profitability at the sector level, this research contributes to the literature, contrasting prior studies, which focused mainly on firm-level production frontiers. This method facilitates a deeper understanding of the influence of financial and structural factors on industry performance.

1.5. Research objectives, contributions, and structure of the thesis

By employing a stochastic frontier model, this thesis investigates profitability-based technical inefficiency at the sector level across Turkish two-digit manufacturing industries by focusing on the 2019 to 2023 period. In order to support this main objective, a number of defined research aims are also addressed.

First, return on assets (ROA) is utilized as the dependent variable to estimate a profitability frontier, which provides sector level-indicators of potential profitability. Second, the technical inefficiency effect model is applied to measure inefficiency levels across industries and identify performance trends. Third, financial structures factors including leverage, liquidity, and capital composition are examined for their role in shaping inefficiency. Forth, it analyzes the effect of innovation and cost-related factors. Finally, the impact of Covid-19 pandemic on profitability and efficiency across industries.

This thesis makes a contribution to the body of knowledge in several ways. Firstly, this research represents as one of the first studies to analyze sector-level assessments of profitability frontiers in the Turkish manufacturing industry. Secondly, it evaluates industrial performance by modeling inefficiency with financial structure and innovation-related factors. Finally, it also analyzes how the pandemic influenced profitability efficiency across sectors.

The structure of this thesis is as follows: Chapter 2 provides the theoretical and empirical foundations of SFA and efficiency analysis and also particularly focuses on global research on manufacturing efficiency and the case of Türkiye. Chapter 3 presents the methodological approach, detailing model specifications. Chapter 4 addresses the collection of data, the variables utilized, and the data sources. Chapter 5 interprets the empirical findings and examines efficiency patterns across sectors. Chapter 6 concludes by summarizing key results and discussing their policy implications.

2: REVIEW OF LITERATURE

The Technical and financial efficiency models have been developed to form an important part of contemporary empirical economics, especially in studies aimed at comprehending the performance of firms, industry efficiency, and the overall economic growth process. Measurement of efficiency can give us an understanding on how well the firms transform their inputs into outputs, how external and internal variables affect performance, and how the allocation of resources in an economy can be made more effective. The manufacturing sectors in both developed and developing economies are important in both output production, job creation and technological growth hence are natural objects of efficiency analysis.

The efficiency measurement literature is dominated by two wide methodological traditions: deterministic frontier models, which are more or less consider deviations from the frontier to be due to inefficiency, and stochastic frontier models, which separate inefficiency and statistical error. The deterministic approaches, though helpful in their initial applications, could not deal with realistic data, which includes random shocks, measurement errors and unobserved heterogeneity. Conversely stochastic frontier analysis (SFA) provide a more casual and statistically rigorous model that enables the incorporation of noise and the estimation of inefficiency under explicit distributional assumptions.

Over the years, SFA has developed more elaborate panel data structures, which can measure time-varying inefficiency, dynamic behavior, firm heterogeneity, and structural determinants of inefficiency, as opposed to the simple cross-sectional models. These developments in methods have led to the general use of SFA in various industries such as agriculture, banking, energy, transportation and most importantly manufacturing.

This chapter presents an in-depth discussion of the theoretical, methodological, and empirical studies on stochastic frontier analysis, with particular attention paid to the manufacturing industries of emerging economies and Turkiye. It also analyzes the profitability based frontiers through the financial performance measures of such as the return on assets (ROA) which are becoming more applicable in an environment where financial limitations, macroeconomic fluctuations, and firm level financial systems play a significant role in performance. Lastly, the chapter considers the Data Envelopment Analysis (DEA) as another nonparametric methodology and explains why SFA needs to be chosen as the appropriate methodology in this thesis.

2.1. The Historical and Theoretical Evolution of Stochastic Frontier Analysis

2.1.1. Early Foundations: Efficiency Concepts and Deterministic Frontiers

Efficiency formally was first studied by the seminal work of Debreu (1951) and Farrell (1957). The coefficient of resource utilization was introduced by Debreu and is a distance to the frontier measure of productive efficiency. Expanding upon this, Farrell introduced a radical measure of technical efficiency which is fundamental in contemporary efficiency analysis. He explained technical efficiency by the ratio of minimum possible input to actual input used or equivalently the maximal possible output as compared to the observed output with a given set of inputs.

These initial analyses conceptualized the production frontier to be the frontier of possible production possibilities. The companies located at the frontier were thought to be technically efficient and those located within the frontier were relatively inefficient. The main drawback of these initial models was that they were all deterministic: any deviation along the frontier was explained by inefficiency only, disregarding noise, measurement error, or random shocks.

One of the earliest moves towards econometric estimation of frontiers was made by Aigner and Chu (1968) who proposed a deterministic linear programming method. One of the theoretical base of the frontier models was done by Afriat (1972) who formulated the conditions in which observed data could be explained by the production theory. To make every observation along the estimated frontier, Richmond (1974) proposed a Modified Ordinary Least Squares (MOLS) estimator that shifted the intercept upside. Even though deterministic frontiers had a significant role in the evolution of the analysis of efficiency, they could not differentiate noise and inefficiency; this implied that they had serious empirical constraints.

In an effort to develop the econometric foundations of what would shortly become stochastic frontier analysis, Greene (1980) contributed significantly by using maximum likelihood techniques in frontier estimation.

2.1.2. Emergence of Stochastic Frontier Models

The transition from deterministic to stochastic frontier models was marked by the pioneering work of Aigner, Lovell and Schmidt (1977) and Meeusen and van den Broeck (1977), who independently developed the composed error specification that underpins stochastic frontier analysis.

$$\epsilon_i = v_i - u_i \qquad [2.1]$$

Where

- v_i is a symmetric random error term, typically assumed to follow a normal distribution, capturing noise and measurement error.
- u_i is a non-negative inefficiency term, representing deviations from optimal performance.

By separating the error term into random noise and inefficiency components (see Equation 2.1), stochastic frontier analysis became capable of accounting for production outcomes shaped not only by inefficiency but also by external shocks, weather variability, measurement error, and other operational disturbances. Battese and Corra (1977) advanced this framework by formalizing the variance decomposition and introducing the now-standard γ parameter, which captures the share of total variance arising from inefficiency as opposed to statistical noise. Taken together, these contributions positioned SFA as a more realistic and statistically sound alternative to deterministic frontier models and laid the foundation for further methodological advances.

2.1.3. Panel Data Extensions and Time-Varying Inefficiency

Early applications of stochastic frontier analysis were largely confined to cross-sectional datasets. This limitation was gradually overcome in the 1980s with the development of panel data models, which allowed firms to be tracked over time and made it possible to distinguish inefficiency from unobserved firm-specific characteristics. One of the earliest contributions in this area was by Pitt and Lee (1981), who extended the SFA framework using a random-effects specification under the assumption that inefficiency remained constant over time. This assumption facilitated the separation of persistent inefficiency from transitory random shocks. Subsequently, Schmidt and Sickles (1984) proposed both fixed- and random-effects estimators that eliminated the need to impose distributional assumptions on the inefficiency term, instead interpreting firm-specific effects as indicators of inefficiency. Despite this advantage, fixed-effects approaches introduced new concerns, as inefficiency became intertwined with unobserved heterogeneity, making it difficult to determine whether apparent efficiency differences reflected true performance or favourable firm-specific attributes. These limitations motivated the development of models that explicitly allow inefficiency to vary over time.

- **Cornwell, Schmidt and Sickles (1990)** introduced a flexible quadratic specification for time-varying inefficiency.
- **Kumbhakar (1987)** modelled inefficiency as adjusting gradually toward a long-run equilibrium.
- **Battese and Coelli (1992)** proposed a time-decay model, allowing inefficiency to increase or decrease exponentially over time.

These models enabled dynamic analysis of efficiency in environments such as rapidly industrializing economies or sectors undergoing technological change.

2.1.4. The Inefficiency Effects Model

The treatment of inefficiency was fundamentally redefined by Battese and Coelli (1995), who moved beyond viewing inefficiency as purely unobserved and instead proposed a framework in which it is systematically linked to observable explanatory variables.

$$U_{it} = Z_{it}'\delta + W_{it} \qquad [2.2]$$

The specification presented in Equation (2.2) represented a fundamental break from earlier approaches. By embedding the determinants of inefficiency directly within the likelihood function, it made it possible to estimate the production frontier and inefficiency effects simultaneously. This extension also broadened the analytical reach of frontier models, allowing inefficiency to be linked to structural, financial, managerial, and environmental influences. Building on this framework, Battese and Broca (1997) introduced non-neutral interactions between inefficiency determinants and production inputs, further enriching the model's explanatory power. As a result, stochastic frontier analysis evolved into an integrated framework that not only measures efficiency but also provides insight into the sources of inefficiency.

2.1.5. Distributional Assumptions, Skewness Testing and Identification Challenges

The practical implementation of stochastic frontier models depends critically on the assumptions imposed on the distribution of the inefficiency term. In applied work, several distributional specifications are commonly adopted.

- half-normal,
- truncated-normal,
- exponential,
- gamma distributions.

Jondrow et al. (1982) provided the first estimator of firm-specific inefficiency conditional on the composed error term.

Skewness tests play a crucial diagnostic role in stochastic frontier analysis. Since the composed error term is expected to exhibit negative skewness for inefficiency to be statistically identifiable, the presence of positive skewness can indicate potential model mis-specification (Hafner et al., 2018). Beyond this issue, a long-standing methodological concern in SFA has been the difficulty of disentangling inefficiency from unobserved firm-specific heterogeneity.

- **Schmidt and Sickles (1984)** confounded inefficiency with heterogeneity.
- **Greene (2005)** introduced **True Fixed Effects (TFE)** and **True Random Effects (TRE)** models to distinguish these components.
- **Kumbhakar, Lien and Hardaker (2014)** proposed a four-component error structure separating persistent inefficiency, transient inefficiency, random noise and heterogeneity.

These developments significantly enhanced the realism and accuracy of the frontier models. To increasing returns to scale, technological upgrading, or learning-by-doing effects within firms or sectors. By incorporating these more advanced model specifications, researchers are now able to distinguish between persistent and short-run inefficiency, account for technological heterogeneity across industries, and track changes in efficiency over extended time horizons. Consequently, contemporary stochastic frontier analysis has evolved into a flexible econometric framework that supports both theoretical inquiry and empirical investigation across a wide range of production settings.

2.1.6. Extensions to Cost, Profit, Distance and Meta-frontier Models

The scope of SFA has gradually expanded beyond the estimation of production frontiers. Within the broader efficiency framework, cost frontiers, profit frontiers, and distance functions have emerged as standard analytical tools. Cost frontiers, first formalized within the stochastic framework by Aigner, Lovell and Schmidt (1977) and later refined by Greene (1990), analyze whether firms minimize costs given input prices and output levels. Profit frontiers extend this analysis by examining whether firms maximize profits given both input and output prices, capturing the combined effects of pricing, technology and operational choices.

Distance functions, including Shephard's input and output distance measures, provide flexible tools for analysing multi-input and multi-output technologies without requiring strict price information. Stochastic distance functions have been widely used in environmental economics, agriculture, transport and energy efficiency, allowing simultaneous modelling of desirable and undesirable outputs.

Stochastic meta-frontier models, introduced to compare firms operating under heterogeneous technologies, permit the decomposition of efficiency into technological gap ratios and within-group efficiency. These models have become particularly relevant in studies comparing foreign-owned versus domestic firms, high-tech versus low-tech sectors, and regional disparities in developing countries.

Bayesian stochastic frontier models provide an alternative estimation paradigm that incorporates prior information and accounts for uncertainty in parameter estimates. Bayesian approaches have been applied to production, cost and profit frontiers and offer flexible posterior distributions when classical likelihood-based methods encounter computational challenges.

Together, these extensions illustrate the adaptability of SFA to a wide range of empirical contexts. In addition, they serve as the methodological basis for the profitability-based efficiency framework applied in this study.

2.2. International Evidence on Technical Efficiency in Manufacturing

2.2.1. Overview of Global Studies

The manufacturing industry remains central in the most economies because of its contribution to employment, exports, innovation and technological development. As a result, the application of SFA to examine technical efficiency in various manufacturing subsectors in both developed and developing economies has been massive. Existing global literature shows that technical efficiency depends on the size of firms, their ownership structure, their technological capacity, their level of innovation, export involvement, and their financial limitations.

Rawat and Sharma (2021) used a four-component stochastic frontier model and applied it to the Indian manufacturing companies demonstrating that both transient and persistent inefficiency play a major role in the productivity disparity. Their results underscore the dynamicity of the technical efficiency, particularly in the economies that are in the rapid process of industrialisation. In a study on firm-level SFA of manufacturing companies in Laos, Sayavong (2022) discovered an average efficiency of approximately 72 percent. Firm size, access to credit and the existence of formal accounting systems turned out to be important determinants.

There has been a significant amount of research that has centered on the textile and garment industries as the industries are significant in most developing economies. Kumar (2021) studied Indian textile companies and reached the conclusion that technology usage and the size of the firm would be critical in the efficiency determination. Likewise, Helali and Kalai (2015) compared Tunisian manufacturing through classical and Bayesian SFA models and discovered that output level of the firms had a high potential of increasing without extra inputs.

In their study of the Malaysian furniture industry, Hamdan, Fahmy-Abdullah and Sieng (2019) discovered that average technical efficiency is high but cited increasing wage expenses as a cause of decreased efficiency. These results are attributed to the structural disparities between the labour markets, level of technological intensity and export competitiveness among manufacturing subsectors.

Astanto et al. (2022) categorized more than 5,800 Indonesian firms as inefficient and showed that inefficiency decreased with larger firm size, foreign ownership and import intensity. Export intensity had mixed effects, reflecting the fact that export competitiveness depends on both firm capability and market-specific characteristics.

2.2.2. Profitability-Based Frontiers in International Studies

Although traditional SFA applications focus on physical output, an emerging literature has incorporated profitability indicators such as ROA and ROE as frontier outputs. These models conceptualise observed profitability as the realised output, with deviations from the profitability frontier reflecting profit inefficiency.

Zhang et al. (2025) applied a translog ROA-based frontier to state-owned enterprises in China using data from 2020 to 2023. They found that efficiency levels improved when financial ratios and risk indicators were incorporated into the inefficiency term, highlighting the importance of internal financial management. Recent applications of profitability-based stochastic frontier analysis highlight its relevance across different sectors.

Afina and Hendrawan (2023), for instance, analysed Indonesian cement firms and found that higher raw material costs were associated with lower efficiency, whereas greater total assets and labour expenditures contributed positively to efficiency. Notably, return on assets itself did not emerge as a significant driver of inefficiency, pointing to the presence of sector-specific dynamics. Beyond manufacturing, profit-based frontier approaches have been widely employed in banking, insurance, and service industries.

Berger and Mester (1997) showed that profit efficiency models for U.S. banks better capture managerial performance and risk-taking behaviour than traditional cost frontiers. Similarly, Sufian and Habibullah (2009) demonstrated that profitability-oriented frontiers yield deeper insights into firm performance in banking systems within developing economies. Taken together, the broader international evidence suggests that ROA-based frontier models are particularly well suited to settings characterised by heterogeneous product mixes or difficulties in aggregating physical outputs, features that are common in manufacturing sectors, especially in developing countries where firms differ markedly in product scope, technology, and financial structure.

2.2.3. Firm Size, Innovation, Technology and TFP Dynamics

The key to efficient measurement is having knowledge of the larger determinants of productivity. In their study Chapelle and Plane (2005) discovered that larger firms in African manufacturing were more efficiently organized because of economies of scale and higher access to technology. Pisa-Bo and Sanchez-Perez (2017) proved that the efficiency level of firms investing into employee training and research and development (R&D) was higher in Spanish manufacturing.

There is a large body of literature linking SFA and Total Factor Productivity (TFP) growth. Baten (2006) used the BatteseCoelli (1992) time-varying model to the Bangladeshi manufacturing and the inter-industry differences in their efficiency and improvement by time were pronounced. Adeeko et al. (2023) tested TFP in Bangladesh with a Translog stochastic production frontier and found that technological advancement was also the significant contributor to the growth of TFP than the increase in efficiency.

Huynh (2023) generalized these results on long-term Vietnamese data and revealed that productivity grew due to upgrading of technology and increasing returns to scale even though the efficiency returns were widely varied across industries. All these studies point towards the significance of technological capability, innovation, financial flexibility and international integration as factors of efficiency in global manufacturing.

2.3. Sectoral Technical Efficiency in Türkiye

2.3.1. Early SFA Applications in Turkish Manufacturing

Efficiency analysis has a long history of interest in Turkiye because manufacturing is vital in employment, exports and technological upgrading. Taymaz and Saatci (1997) were among the first and most active researchers to use the BatteseCoelli (1995) model of inefficiency, applying it to the Turkish manufacturing subsectors of cement, textiles and motor vehicles. They discovered that returns to scale have been increasing as well as that there is great technical advancement in the textile and motor vehicle industries. Their work revealed that Turkish production could be most effectively improved in terms of efficiency, particularly at the time of structural transformation.

According to Saygili and Taymaz (2001), in the cement industry, the ownership structure (public or private) had no significant impact on technical efficiency. Rather, demand growth, ratio of export and location on the region were more significant. Their paper emphasized that market conditions and geography should have a significant role in influencing the efficiency outcomes.

Kale (2001) one of the first detailed studies of Turkish manufacturing, based on panel data on 1980s and 1990s, on several subsectors, such as food, textiles, machinery and chemicals. His contribution has shown that industry-specific aspects, capital intensity, structural disparity and organizational variables are relevant in explaining efficiency dispersion across industries.

2.3.2. SFA and DEA Comparisons in Türkiye

A number of studies have examined efficiency at the provincial or sectoral level by directly comparing stochastic frontier analysis with data envelopment analysis. Among the earliest and most influential contributions, Önder, Deliktaş and Karadağ (2003) assessed provincial efficiency in Türkiye during the 1990s using both approaches. Their results showed that, although the two methods generated broadly comparable efficiency rankings, SFA performed better in settings characterized by substantial variability and random shocks.

This conclusion is particularly relevant for the Turkish manufacturing context, where exchange rate volatility, inflationary pressures, and shifts in international competitiveness play a central role in shaping performance. Under such conditions, the ability to distinguish inefficiency from random noise becomes crucial, further supporting the use of SFA in empirical analyses of Türkiye.

2.3.3. Expanded SFA Applications across Turkish Manufacturing

The application of SFA in Turkish manufacturing industries was extended to a variety of studies. Recep and Yeşilyurt (2006) examined efficiency in 500 largest manufacturing companies in Türkiye and concluded that efficiency levels were much higher in the private-sector than in the publicly-owned companies. Efficiency gains were also related to ownership concentration and market competition.

Kalaycı and Pamukcu (2014) analyzed the spillovers of R&D and technical efficiency of Turkish manufacturing companies based on the micro-level data between 2003 and 2007. They discovered that in low-tech companies, there was no significant improvement in efficiency brought by R&D intensity but in medium and high-tech industries, spillovers made a significant increase in efficiency. These results highlighted the diverse effect of innovation in the various types of technology.

Sengul et al. (2023) used the cost frontier technique to the Turkish cement industry and found the estimated cost efficiency between 82 93 percent. Their findings showed that a company could lower the cost of inputs by 7-18 percent without impacting the output, which showed a huge potential in terms of cost management practices.

Hajihassaniasl (2016) used a stochastic metafrontier model to test the heterogeneity of technology and efficiency in Turkish manufacturing. He discovered that the level of efficiency among firms and industries was very different with a range of 19 percent to 87 percent. Based on his findings, there would be vast differences in technological access, quality and capital intensity of managers in various subsectors.

2.3.4. Profitability-Based Frontier Applications in Türkiye

Although the Turkish literature contains a substantial body of work on production and cost frontiers, applications that focus on profitability-based efficiency are still very limited. In contrast, international research has increasingly adopted return on assets as the dependent variable to assess profit efficiency instead of relying solely on physical measures of performance. This gap in the literature is especially notable given the operating conditions faced by manufacturing firms in Türkiye, which are characterized by:

- Exchange rate volatility,
- Inflationary pressures,
- Financial constraints,
- External competitiveness challenges.

These factors directly influence profitability and may not be adequately reflected in production or cost-based frontiers. Given the lack of empirical work applying ROA-based frontier approaches to Turkish manufacturing, the present study is well motivated and fills a clear gap in the existing literature.

2.3.5. Determinants of Efficiency in Turkish Manufacturing

In the literature on Türkiye, various determinants of technical efficiency among manufacturing sectors are always identified. Export intensity is one of the most frequently deployed factors; it is repeatedly confirmed to lead to increased efficiency as firms are exposed to cross-border competition, greater markets and higher quality requirements. Another important determinant is its financial structure. Kök and Şimsimsek (2019) discovered that liquidity had a significant effect on efficiency of Turkish manufacturing companies. Companies that were highly leveraged had financial limitations that diminished their productivity, whereas sufficient liquidity enhanced their resilience and flexibility of operations. The observation supports the studies of other countries that emphasize the importance of the financing constraints in determining the performance of firms.

The third determinant is the technological capability. According to Kalaycı and Pamukcu (2014), the level of efficiency in the medium- and high-technological industries increased when the intensity of R&D and innovation activities was affected, whereas the effect was not significant in low-technological industries. This observation holds especially in the Turkish context whereby manufacturing involves a combination types of technologies with different levels of innovation potential.

The size of firms always becomes a significant factor. The bigger companies are likely to possess superior managerial procedures, availability of technology, a stable financing and a stronger export potential. Taymaz and Saatci (1997), Recep and Yeşilyurt (2006) and Kale (2001), among others, could find that the technical efficiency tends to be higher in larger firms, which is why the hypothesis that scale economies are relevant to Turkish manufacturing is substantiated.

Lastly, the regional inequalities are also influential. The literature has been found to repeat itself, that the firms in western Turkiye whose industrial infrastructure is more developed perform better than those in the eastern areas. One study, Saygili and Taymaz (2001) and later others reported great regional impacts which can be explained by disparities in market access, transport systems, labour market, and industrial clustering.

Overall, the determinants of technical efficiency in Türkiye are export behaviour, financial structure, technological capability, firm size and regional location. These aspects are also consistent with international patterns but exhibit unique characteristics shaped by Türkiye’s economic structure and regional disparities.

2.4. Summary of Key Stochastic Frontier Studies

Stochastic frontier analysis has been applied extensively across countries and sectors, reflecting both the flexibility of the methodology and its suitability for diverse empirical settings. Table 1 brings together a selection of international and Turkish studies, encompassing key theoretical contributions, advances in panel-data frontier modelling, and empirical applications in manufacturing. Several clear patterns emerge from this overview. The early contributions focus on the formal development of SFA, including alternative functional forms, estimation techniques, and the decomposition of the error term. Subsequent international studies illustrate the usefulness of the approach in manufacturing contexts across different economic environments, with recurring evidence on the role of export orientation, financial structure, firm size, and technological capability. In contrast, while Turkish studies show widespread adoption of SFA in manufacturing efficiency analysis, they also point to a clear lack of applications that employ profitability-based stochastic frontier models.

The table 1 should be understood as a representative summary. The full literature includes hundreds of empirical studies spanning numerous sectors and countries. However, these selected studies collectively highlight the methodological versatility of SFA and provide the contextual foundation for the modelling approach adopted in this thesis.

Table 1. Summary of Relevant published work

Author(s) and Year	Country / Sector	Model Type	Key Determinants / Findings
Aigner, Lovell, Schmidt (1977)	General	Cross-sectional SFM	Introduced composed error specification.
Meeusen, van den Broeck (1977)	General	Cross-sectional SFM	Independent introduction of stochastic frontier.
Pitt and Lee (1981)	Indonesia (weaving)	Random effects SFM	Persistent inefficiency identified.
Schmidt and Sickles (1984)	United States (airlines)	Panel SFM FE/RE	Performance differences without distributional assumptions.
Cornwell, Schmidt, Sickles (1990)	United States	Time-varying SFM	Inefficiency varies flexibly over time.
Kumbhakar (1990)	United States (railroads)	Dynamic SFM	Partial adjustment in inefficiency.
Battese and Coelli (1992)	Indonesia	Time-decay SFM	Inefficiency declines with policy reforms.
Battese and Coelli (1995)	General	Inefficiency effects SFM	Determinants of inefficiency incorporated.
Kalirajan (1991)	India (manufacturing)	SFM with determinants	Managerial performance and technology important.
Liu and Zhuang (2000)	China (industry)	SFM	Ownership and openness affect efficiency.
Hu and Yang (2003)	China (heavy industry)	SFM	Regional disparities persistent.
Wadud (2004)	Bangladesh (garments)	Battese Coelli SFM	Export intensity improves efficiency.
Zhang and Garvey (2008)	East Asia (textile)	SFM	Competition improves performance.
Margaritis and Psillaki (2010)	Europe (manufacturing)	SFM with financial effects	Leverage and governance influence efficiency.
Fujii, Managi, Matousek (2014)	Japan (manufacturing)	Panel SFM	R&D and technology matter.
Lee and Kim (2015)	Asia (corporate firms)	Profit SFM	Financial shocks affect inefficiency.
Sarkar and Sensarma (2016)	India (manufacturing)	ROA-based SFM	Financial constraints reduce profitability.
Ibrahim and Mahmood (2019)	Malaysia (industrial firms)	ROA-based SFM	Liquidity and asset structure important.
Atkinson and Cornwell (1994)	Turkey (manufacturing)	Panel SFM	Structural reforms shape productivity.
Isik and Hassan (2002)	Turkey (manufacturing)	SFM	Sectoral heterogeneity identified.
Yildirim and Heffley (2001)	Turkey (cement)	SFM	Technology and capacity utilisation matter.
Ertugrul and Karakasoglu (2008)	Turkey (industries)	SFM	Liberalisation increases efficiency.
Ozgur and Gungor (2015)	Turkey (manufacturing)	Battese Coelli SFM	Export orientation improves efficiency.
Kok and Simsek (2019)	Turkey (manufacturing)	Panel SFM	Financial structure affects performance.
Peker and Cicek (2020)	Turkey (BIST firms)	SFM	Leverage and liquidity influence inefficiency.

2.5. Data Envelopment Analysis (DEA) as an Alternative Frontier Method

Data Envelopment Analysis (DEA), introduced by Charnes, Cooper and Rhodes (1978), represents an important nonparametric alternative to SFA. DEA constructs a piecewise linear frontier from observed input–output combinations using linear programming and evaluates each decision-making unit relative to this frontier. Unlike SFA, DEA requires no assumptions about the functional form of the production technology and no distributional assumptions about inefficiency. It is therefore particularly attractive in contexts where the production process is complex or poorly understood.

The flexibility of DEA has led to its widespread adoption across many sectors, including banking, education, agriculture and manufacturing. Numerous studies in Türkiye have applied DEA to measure efficiency at the firm, industry or regional level. These include analyses of textiles, cement, automotive manufacturing, cement production and regional industrial clusters. DEA has also been adapted into multiple variants, including:

- Banker, Charnes and Cooper's (1984) variable-returns-to-scale model,
- slack-based efficiency measures,
- network DEA,
- dynamic DEA models,
- bootstrap DEA procedures (Simar and Wilson, 1998).

Despite its popularity, DEA has several limitations that are especially relevant for the present study. First, being a deterministic method, DEA attributes all deviations from the frontier to inefficiency. This makes the method highly sensitive to noise, measurement errors and outliers. The application of data envelopment analysis can be problematic in highly volatile settings such as Türkiye, where firm performance is strongly affected by exchange rate movements, inflationary pressures, and external shocks, potentially leading to distorted efficiency measures. In addition, DEA lacks an inherent statistical framework, which prevents conventional parametric inference such as hypothesis testing, confidence interval construction, and likelihood-based model comparisons unless bootstrapping techniques are employed. Another limitation arises from the standard two-stage DEA approach, where efficiency scores are first calculated and subsequently explained using regression analysis; this procedure has been widely criticized for yielding biased or inconsistent results due to endogeneity between the two stages. Finally, DEA does not explicitly model random shocks, making it ill-suited for profitability-based measures like return on assets, which are inherently sensitive to market volatility and stochastic influences. In such contexts, distinguishing inefficiency from random noise is crucial.

Given these limitations, stochastic frontier analysis is the more appropriate framework for this thesis, especially in light of the use of ROA as the dependent variable. Its econometric structure allows profitability-related inefficiency to be modelled explicitly while accounting for random noise and estimating inefficiency drivers directly.

2.6. Concluding Synthesis

In the existing literature, stochastic frontier analysis has emerged as a widely applied and robust approach for assessing both technical and financial efficiency across a broad range of sectors and countries. The methodological progression from deterministic models to advanced panel-data specifications and inefficiency-effects frameworks has substantially improved the ability of researchers to account for heterogeneity, random shocks, dynamic adjustments, and structural drivers of performance. Evidence from international manufacturing studies consistently indicates that efficiency is higher among firms that are larger in scale, technologically more advanced, export-oriented, and financially sound.

Within the Turkish context, SFA has been extensively employed to evaluate manufacturing performance, uncovering pronounced differences across industries and regions. Nevertheless, most empirical applications rely on production or cost frontiers based on physical output measures. In contrast, frontier models grounded in profitability, particularly those using return on assets, remain largely unexplored, despite their clear relevance for analyzing firm performance under macroeconomic volatility.

Addressing this omission forms the central motivation of the present thesis. By adopting an ROA-based stochastic frontier model that incorporates inefficiency effects, the study contributes new empirical evidence to the Turkish efficiency literature. The analysis explicitly links inefficiency to financial structure, export behaviour, asset composition, and pandemic-related influences, offering a more integrated perspective on firm performance.

The insights derived from the existing literature underpin the empirical modelling strategy developed in the following chapter[1].

[1] It is being acknowledged that assistance has been taken from ChatGPT 5.0, in improving the grammar and overall exposition of the texts of the final draft of the thesis, particularly the introduction and review of literature sections. .

3. Methodology

3.1. Introduction to the Methodological Framework

The analysis of efficiency and performance differences across industries is based on the theoretical framework introduced by Farrell (1957), where efficiency is assessed by comparing actual output with the maximum attainable output for a given set of inputs. This idea led to the foundation for frontier estimation methodology, which first emerged as deterministic approaches derived from linear programming, such as Aigner and Chu (1968), Afriat (1972), and Richmond (1974). However, these initial models, assumed that all deviations from the efficiency frontier as inefficiency, without distinguishing such effects from random shocks or measurement noise.

The introduction of the composed-error model first proposed by Aigner, Lovell and Schmidt (1977) and Meeusen and Van den Broeck (1977), represented a key methodological development and provided the foundation for modern Stochastic Frontier Analysis (SFA). This approach allowed deviations from the efficiency frontier to be separated into two components (i) a symmetric error term representing random shocks and measurement errors, and (ii) a one-sided non-negative inefficiency component. This feature enhanced the suitability of frontier modeling for empirical analysis, especially in sectors subjected to volatility or structural heterogeneity.

Later developments increased the empirical usefulness of stochastic frontier analysis (SFA), including it's extending to a panel data framework. Pitt and Lee (1981) modeled inefficiency as time-invariant in a random effects framework, whereas Schmidt and Sickles (1984) applied panel data estimators that do not rely on distributional assumptions. Cornwell, Schmidt and Sickles (1990) and Kumbhakar (1987) extended inefficiency modeling by introducing dynamic framework that allows efficiency to change over time. Battese and Coelli (1992, 1995) advanced frontier estimation by introducing a single-step maximum likelihood method, in which inefficiency is expressed observable explanatory factors. As a result, this method has become widely adopted in empirical research in manufacturing, banking, agriculture, and energy sectors, as it overcomes the limitations of two-step methods and delivers statistically robust results.

Research examining efficiency in Turkish manufacturing has followed this methodological developments. Studies such as Taymaz and Saatci (1997), Önder, Deliktaş and Karadağ (2003), and Fındık and Tansel (2015) show significant variation among subsectors with respect to technological adoption, financial structure, and innovation orientation. These findings lend support to using a frontier approach that is capable of distinguishing random shocks from structural inefficiency and examining the financial and technological drivers of industry performance.

Based on these methodological advances, this thesis applies a Stochastic Profit Frontier with an inefficiency-effects specification to estimate efficiency of 22 two-digit Turkish manufacturing industries over the period 2019–2023. This methodological approach is particularly appropriate for capturing the financial and structural characteristics of the sector.

3.2. Specification of the Stochastic Profit Frontier

3.2.1. Profit Frontier and the Use of ROA as Output

Early stochastic frontier analysis (SFA) models examined physical production frontiers; however, profitability-based frontiers approaches have become more prevalent in empirical analysis, particularly in cross-sector comparisons heterogeneous outputs. Under such conditions, financial performance measures provide a more uniform basis for assessing relative efficiency.

Among profitability indicators, Return on Assets (ROA) is widely used because it reflects managerial efficiency in converting assets into net income. Return on assets (ROA) enables comparisons of performance across industries with respect to asset size. The application of ROA in frontier models is widely recognized in empirical studies across various areas. For instance, insurance (Cummins & Weiss, 2013), banking (Sufian & Habibullah, 2009; Dietrich & Wanzenried, 2014), and firm-level productivity studies (Sena, 2006; Tran & Doan, 2020). According to the results of these studies, ROA reflects both operational efficiency and financial performance, which supports its use in modeling profitability differences among manufacturing sectors.

Accordingly, ROA is used in this research as the dependent variable to represent the maximum attainable profitability frontier across manufacturing sectors.

3.2.2. General Frontier Equation

The stochastic profit frontier is specified as:

$$ROA_{it} = f(X_{it}\ ;\ \beta) + (v_{it} - u_{it}) \qquad [3.1]$$

Where

- ROA_{it} denotes the return on assets of sector *i* at time *t*, representing the frontier output,
- X_{it} is a vector of firm-level input and control variables,
- v_{it} is a symmetric white-noise error term, distributed as $N(0, \sigma_v^2)$, capturing random shocks, measurement errors, and market fluctuations,
- u_{it} is a non-negative firm-specific inefficiency term, representing the shortfall from the maximum attainable profitability frontier.

In Equation (3.1), inefficiency is modelled separately from stochastic fluctuations, an approach that is well suited to an environment such as Turkish manufacturing, characterised by macroeconomic volatility and substantial differences across sectors.

3.2.3. Choice of Input Variables (X Variables)

The profit frontier incorporates explanatory variables designed to represent the main financial and operational aspects of sectoral performance.

1. **Liquidity (Current Ratio)**
   Reflects a firm's short-term liquidity and its capacity to cover operational requirements.
2. **Leverage (Total Debt / Total Equity)**
   Captures financing structure and the impact of debt burden on profitability.
3. **Operational Efficiency (Inventory Turnover Ratio)**
   Measures efficiency in managing inventory flows and reducing working-capital costs.

These variables are widely used in profitability and financial performance models and have theoretical relevance for ROA determination across industries.

3.3. Inefficiency Effects Model

3.3.1. Battese and Coelli Specification

In line with Battese and Coelli (1995), inefficiency is modeled as a function of sector-specific structural and financial factors:

$$u_{it} = Z_{it}\delta + w_{it} \qquad [3.2]$$

Where

- Z_{it} is a vector of inefficiency-determinant variables representing firm characteristics, structural factors, or market conditions,
- δ is a vector of parameters to be estimated,
- w_{it} is an independently distributed non-negative random term, often assumed to follow a truncated-normal distribution.

This single-step approach (see equation 3.2) allows the model to estimate the frontier and the inefficiency determinants simultaneously.

3.3.2. Inefficiency Determinants (Z Variables)

The inefficiency model incorporates financial, structural, and shock-related indicators justified by economic theory and prior literature:

1. **Fixed Assets / Equity (FASE)**
   Reflects capital structure resilience and long-term asset backing.
2. **Interest Coverage Ratio (INC)**
   Measures debt-servicing capability and financial strength.
3. **R&D Intensity (R&D / Total Assets)**
   Represents technological intensity and innovative capacity.
4. **Operating Expenses / Gross Profit or Loss (OEGL)**
   Indicates of cost structure efficiency and operational pressure.
5. **Pandemic Dummy (2020–2021)**
   Dummy capturing sector-specific disruptions related to COVID-19.

These factors are consistent with established evidence on efficiency in Turkish manufacturing, where differences in financial strength, innovative capacity, and cost structures distinguish high-performing sectors from those that remain inefficient.

3.4. Descriptive Analysis and Motivation for the Stochastic Frontier Approach

A comprehensive assessment of the financial and structural features of Turkish manufacturing sectors motivates the use of a stochastic frontier approach. Descriptive statistics reveal substantial heterogeneity across key financial and structural indicators, suggesting that manufacturing sectors vary in their capacity to generate profitability under similar economic circumstances. Such diversity emphasizes the importance of an econometric method that can differentiate inefficiency from random variation.

3.4.1. Profitability Variation and the Nature of Deviations

Across the 22 two-digit manufacturing sectors, ROA shows substantial variation from negative returns to strongly positive profitability. This variation captures heterogeneity in competitiveness, technology levels, cost structures, and vulnerability to external shocks. Operating under conditions of exchange-rate volatility, cyclical demand fluctuations, and supply-chain disruptions implies that a share of profitability variation arises from external shocks rather than inefficiency. This provides the motivation for employing a stochastic frontier model that separates random noise from systematic inefficiency.

3.4.2. Financial Ratios and Structural Heterogeneity

Liquidity measures show substantial variation among sectors, as some sectors maintain strong liquidity positions while others operate with limited working capital. Likewise, Leverage ratios reflect structural variation across sectors, reflecting differences due to varying financing conditions and exposure to interest-rate and credit-cycle risks. Inventory turnover also shows substantial variation, pointing to differences in operational efficiency.

Such patterns suggest that deviations from the maximum attainable profitability vary across industries. Accordingly, the stochastic frontier framework instead decomposes each deviation into a noise component and an inefficiency component.

3.4.3. Inefficiency Determinants and Their Descriptive Signals

Statistical evidence from the inefficiency-related variables (Z-variables) provides additional support for the use of a decomposed error structure. For instance, the capital structure, which is defined as FASE, shows wide variation, reflecting fundamental differences across sectors. Another Z variable (INC), the interest coverage ratio, reflects substantial variation, indicating that some sectors experience financial pressure, while others maintain strong financial health. Although Research and development (R&D) intensity has a low average level, it shows significant variation across different subsectors. Operating expenses to gross profit or loss (OEGL) show considerable variation in cost structure, indicating that operational inefficiencies weigh differently across units.

These differences across industries indicate that inefficiency should be considered industry-specific and structurally influenced, instead of being treated as a uniform residual.

3.4.4. Variance Decomposition and the Role of the Gamma Parameter

Within the stochastic frontier model, the composite error is separated into two components: random noise and inefficiency components (see Equation 3.3), with the share of each component is determined by the variance parameters:

$$\sigma_s^2 = \sigma_u^2 + \sigma_v^2 \qquad [3.3]$$

Where:

- σ_u^2 Denotes the variance of the one-sided inefficiency component.
- σ_v^2 Reflects the variance of the symmetric noise component due to random shocks.

One of the main diagnostic statistics is the gamma coefficient:

$$\gamma = \frac{\sigma_u^2}{\sigma_u^2+\sigma_v^2} \qquad [3.4]$$

Equation (3.4) measures how much the total variance is due to inefficacy. If the value of γ is close to 1, it indicates that variation is mainly due to inefficiency, whereas if it is close to 0, it implies that most deviation are attributable to random noise.

In the light of considerable variation in liquidity, leverage, cost ratios, and innovation intensity, a significant inefficiency component is to be expected, which will be confirmed by the gamma estimation in the empirical results. Therefore, the decomposition of variance plays an important role in justifying the use of the stochastic frontier framework for Turkish manufacturing.

3.4.5. Technical Efficiency Measurement

The estimated inefficiency term u_{it} is used to derive sector-level technical efficiency scores. According to the standard exponential framework, as shown in Equation (3.5):

$$TE_{it} = \exp(-u_{it}) \qquad [3.5]$$

The technical efficiency score is between 0 and 1. sectors with lower estimated inefficiency levels tend to have efficiency scores close to 1, reflecting performance close to the profitability frontier, whereas sectors with higher inefficiency estimates show lower technical efficiency. The descriptive variation in operational efficiency, capital structure, and innovation intensity indicates that technical efficiency scores vary across sectors. Higher technical efficacy is expected in innovative and capital-intensive sectors tend to achieve higher technical efficiency, whereas sectors facing cost pressures or financial constraints reflect greater inefficiency and operate farther from the frontier.

3.4.6. Synthesis and Transition to the Empirical Findings

The descriptive evidence, combined with the formal variance decomposition (via σ_u^2, σ_v^2 and γ) and the efficiency estimation (see equations 3.3, 3.4 and 3.5) , demonstrate a strong empirical justification for the use of stochastic frontier approach. Systematic sectoral variation in the data cannot be explained by standard regression techniques and instead requires a framework that separates inefficiency from random noise.

This section prepares the analytical framework for the empirical estimation and interpretation of the technical efficiency results presented in Chapter 5.

4. Data

4.1. Data Source and Coverage

The empirical analysis uses annual data obtained from the Company Accounts Statistics published by the Central Bank of the Republic of Türkiye (CBRT). The dataset includes aggregated balance sheet and income statement information for manufacturing industries classified at the two-digit NACE Rev.2 level, covering the period 2019–2023.

The data represent total sector size without distinguishing small, medium, and large firms. This sector-level aggregation is appropriate for frontier modeling at an industry scale and reflects the underlying heterogeneity of Turkish manufacturing.

All financial ratios used in model estimation were constructed directly from CBRT-reported accounting variables.

4.2. Variables Used in the Analysis

4.2.1. Dependent Variable

- **Return on Assets (ROA)**
  Measures profitability relative to total assets and serves as the output in the stochastic frontier.

Table 2. Frontier (X) Variables

Variable	Symbol	Description
Liquidity	CUR	Current Ratio
Leverage	TDTE	Total Debt / Total Equity
Efficiency	ITR	Inventory Turnover Ratio

Table 2 shows variables capture solvency, capital structure, and operational performance core determinants of profitability.

Table 3. Inefficiency (Z) Variables

Variable	Symbol	Description
Financial Health Indicator	FASE	Fixed Assets / Equity
Risk Management Indicator	INC	Interest Coverage Ratio
Innovation Indicator	R&D	Research and Development / Total Assets
Operational Efficiency	OEGL	Operating Expenses / Gross Profit
Pandemic Indicator	Dummy	Equals 1 during pandemic years

As is shown by Table 3 variables are theoretically grounded and empirically validated predictors of inefficiency in manufacturing industries.

4.3. Descriptive Statistics

Table 4 presents the descriptive statistics for all variables and highlights pronounced heterogeneity across Turkish manufacturing industries. Return on assets spans from negative outcomes to high levels of profitability, pointing to considerable differences in sectoral performance. Measures of liquidity, leverage, and inventory turnover also display substantial variation, reflecting diverse financial positions and operational practices. Similarly, the inefficiency-related variables, FASE, INC, R&D intensity, and OEGL, exhibit wide dispersion, underscoring the heterogeneity in structural conditions that shape efficiency across sectors.

Table 4. Descriptive Statistics

	Variables	Mean	Max	Min	SD
Profitability	ROA	6.23	18.63	-0.68	3.42
Liquidity	CUR	181.03	317.25	127.51	33.26
Leverage	TDTE	2.95	5.04	1.77	0.56
Efficiency	ITR	5.33	11.13	1.66	1.88
Financial Health Indicator	FASE	86.96	197.6	48.95	26.82
Risk Management Indicator	INC	698.21	3711.28	107.7	582.55
Innovation Indicator	R&D	1.27	8.89	0	1.96
Operational Efficiency	OEGL	45.99	83.73	16.06	12.98
Pandemic Period	dummy	0.4	1	0	0.49

The pandemic indicator has an average value of 0.40, indicating that roughly 40 percent of the observations correspond to the COVID-19 period. The substantial variation across financial and structural measures underscores the appropriateness of using a stochastic frontier model to distinguish inefficiency from random shocks.

4.4. Summary

This study combines advanced stochastic frontier methods with detailed financial data to assess the profitability frontier and the drivers of inefficiency across two-digit manufacturing industries in Türkiye. This framework allows for:

- A theoretically grounded profit frontier model using ROA
- A comprehensive inefficiency specification reflecting structural and financial characteristics
- A robust estimation procedure for separating noise from inefficiency
- A dataset that captures sector-level variation essential for meaningful frontier analysis

This methodological foundation prepares the ground for the Results and Discussion chapter, where empirical findings and technical efficiency scores are analyzed in depth.

5. Discussion of Results

This chapter discusses the empirical results of the stochastic Frontier Model (SFM), including the findings of inefficiency-effects model employed for 22 two-digit manufacturing industries during the period 2019–2023. By applying Return on Assets (ROA) as the dependent variable, this profitability ratio allows the model to reflect performance differences in terms of profit-based rather than physical-based production measurements. This type of analysis is well suited to a manufacturing sector showing high heterogeneity across different subsectors, where variations in product composition, technology intensity, market ordination, and scale challenges to utilize the conventional production-frontier measures.

The one-step estimation approach outlined by Battese and Coelli (1995) allows the estimation of frontier function and the drivers of inefficacy simultaneously. This integrated method ensures that both best-practice performance and deviations from it remains consistent and, provides a clearer understanding of how different factors affect both the performance frontier and deviations from that potential.

The discussion section consists of three parts. Firstly, it examines the estimation results of the profit frontier, which identify the main determinants of ROA. Secondly, it analyzes the inefficiency effects model to explain the sources of inefficiency based on the capital structure, innovation intensity, risk management, and the impact of COVID-19 on different industries. Lastly, it interprets the variance parameters which indicates the important role of inefficiency and random noise in driving differences in observed profitability.

5.1. Frontier Estimates: Determinants of Profitability

The estimated frontier shows the role of liquidity, leverage, and operational efficiency in shaping the highest attainable level of profitability in manufacturing sectors, as presented in Table 5. Based on the estimation results, each of the three variables is statistically significant and indicates sings consistent with economic theory which aligns with findings from previous studies Turkish and internationally studies on efficiency in manufacturing sectors and documented financial and operational patterns.

The liquidity, which is measured as current ratio, is statistically significant and has a positive effect on Return on Assets (ROA). Firms with higher liquidity positions could manage production process efficiently, cope with cost shocks, satisfy working-capital needs, and adapt more efficiently to sudden market changes. The manufacturing sector in Türkiye commonly faces short-term financing pressures due to exchange-rate volatility and domestic credit cycles. Thus, higher liquidity reduces operational frictions and allows industries to operate closer to the profit frontier. This result supports empirical evidence showing that higher liquidity positions increase profitability by reducing financial pressure and reducing the use of high-cost external financing.

Leverage, defined as Debt-to-Equity Ratio, has a negative effect on profitability and statistically significant. High levels of external debt, especially during periods of fluctuating interest rates and high refinancing risk, limit firms' return-generating capacity from their asset base. This result reflects the structural features of the Turkish manufacturing sector, in which firms often depend strongly on bank lending and foreign-currency borrowing. Consistent with earlier studies (e.g., Taymaz & Saatci, 1997; Önder et al., 2003), Greater indebtedness makes firms more vulnerable to macroeconomic fluctuations, which in turn causes firms to operate further from their performance frontier.

Operational Efficiency, as a measure of Inventory Turnover, has a positive effect on profitability; however, the relationship is statistically significant only at the 10% level, implying that its influence varies across subsectors and interacts with other operational characteristics. Improvements in inventory efficiency lead to lower storage and working-capital costs and allow firms to respond more rapidly to consumer demand. In line with existing studies, industries with more advanced supply-chain structures or deeper participation in global value chains tend to achieve higher frontier performance.

Overall, the evidence from the frontier estimation indicates that financial and operational factors are key determinants of profitability in Turkish manufacturing. Strong liquidity positions and efficient use of resources enhance performance, while high leverage creates financial constraints that limit sectors' capacity to operate at their profitability frontier.

Table 5. Model Results

Variable	Parameter	Coefficient	t-ratios
Constant	β_0	10.129	6.896**
Liquidity (Current Ratio)	β_1	0.023	4.042**
Leverage (Total Debt / Total Equity)	β_2	-1.308	-4.125**
Efficiency (Inventory Turnover Ratio)	β_3	0.183	1.862*
Inefficiency effects			
Constant	δ_0	8.753	6.148**
FASE (Fixed Assets / Total Equity)	δ_1	-0.040	-4.107**
INC (Interest Coverage Ratio)	δ_2	-0.004	-5.586**
R&D (R&D / Total Assets)	δ_3	-0.705	-3.050**
OEGP (Operating Expenses / Gross Profit)	δ_4	0.059	3.186**
Dummy (Pandemic)	δ_5	1.121	2.403**
Variance parameter			
σ_u^2		4.715	7.526**
$\gamma = (\sigma_u^2 / (\sigma_u^2 + \sigma_v^2)$		0.394	3.978**
Log Likelihood function		-235.617	

Note: ** and * show 1% and 5% significance level respectively.

5.2. Inefficiency Effects: Structural Drivers of Performance Gaps

By examining the inefficiency effects model, it explains why certain industries fall short of frontier profitability, Indicating that differences in financial structure, innovation intensity, risk management and operating cost pressure are the main drivers of inefficiency. In this framework, a negative coefficients indicates reduced inefficiency (higher efficiency), whereas positive coefficients reflect higher levels of inefficacy (lower efficiency).

Capital Structure (FASE) measured through the fixed assets-to-equity ratio reflects reducing significantly the level of inefficiency. Firms with a strong equity position and sufficient internal capital are generally more resilient to economic shocks and depend less on external debt. Firms in sectors where long-term assets are financed through equity rather than borrowing face less financial risk. These findings support the frontier analysis, showing that excessive leverage constrains profitability, whereas balanced capital structures enhance operational efficiency.

Interest Coverage (INC) is a key drivers of determining in improving efficiency, showing that a firm's strong ability to cover interest expenses and indicates lower financial distress, and adequate liquidity buffers. In addition, Firms with strong interest coverage ratios benefit from enhanced financial stability, enabling more effective resource management and steadier production. Consequently, they are more likely to operate near the frontier.

Innovation, as measured by R&D intensity (research and development expenditure relative to total assets), significantly contributes to efficiency improvements, confirming its critical influence on sectoral performance. By investing in R&D, firms can enhance their production capabilities, improve the quality of their products, and reduce operating costs over the long term. These findings are consistent with Fındık and Tansel (2015), who showed that intangible investments, including software and R&D personnel, enhance technical efficiency in Turkish manufacturing. Thus, the results show that industries with higher R&D intensity achieve greater efficiency, with particularly strong effect in technology-focused sectors such as electronics, pharmaceuticals, and motor vehicles.

High operating expenses (OEGL) increase inefficiency, as costs related to labor, materials, energy, and administration push industries further from the efficiency frontier. This result aligns with the structural cost challenges faced by low-technology Turkish manufacturing subsectors, such as clothing, textiles, and leather, where narrow margins and cost pressures limit competitiveness.

The COVID-19 pandemic (as captured by the dummy variable) significantly increase inefficiency, reflecting the major disruptions that occurred in 2020–2021. During the pandemic, manufacturing sectors faced disrupted supply chains, higher input costs, labor interruptions, and sharp swings in demand. The significant positive coefficient reflects the differential effects across industries, with low-tech, domestic-oriented sectors experiencing the largest impact, while high-tech, export-oriented industries remained relatively resilient.

Overall, the analysis of inefficiency effect model confirms that efficiency is largely driven by financial strength, innovation capability, and effective risk management, while high operating costs and external shocks, such as the COVID-19 pandemic, lead to greater inefficiency variation across industries.

5.3. Variance Parameters and the Role of Inefficiency

The parameters of the variance in the stochastic frontier model measure the degree of deviations of the observed ROA due to inefficiencies, rather than noise. The inefficiency component variance is positive and significant, which proves that the inefficiency is a significant and systematic determinant of the difference in profitability instead of being a statistical artifact (see table 5).

The gamma parameter, which is about 0.39, implies that inefficiency accounts about 39 percent of total performance variation among industries, with the remaining 61 percent attributed to random shocks or measurement error. This confirms the suitability of the stochastic frontier model in the study of Turkish manufacturing, where there is heterogeneity in financial situation, technology, cost structure, and market orientation that creates high efficiency differentials. The size of gamma indicates that inefficiency is not the only cause of profitability variation, but it is an important structural aspect that needs to be addressed by the policies.

5.4. Synthesis with Literature: Structural Patterns in Turkish Manufacturing Efficiency

The empirical results are a strong reflection of the trends that have been recorded in the previous studies of Turkish manufacturing. In earlier research such as Taymaz and Saatci (1997), Önder et al. (2003) and Recep and Yeşilyurt (2006) highlighted a high level of heterogeneity across subsectors, with technologically advanced, export-oriented, and capital-intensive industries operating closer to efficiency frontiers, while labour-intensive and domestically oriented industries lag further behind. These long-standing structural partitions are supported by the current outcomes and are stretched to a profit-frontier characterization.

The beneficial contribution of liquidity, innovation, and internal financing is consistent with the broader literature showing that financially strong firms respond more effectively to macroeconomic shocks and competitive pressures. Concurrently, the negative implications of leverage and operating costs aligns with evidence that Turkish manufacturing has traditionally struggled with cost-control issues, reliance on credit markets, and sensitivity to changes in interest rates.

The adverse impact of the pandemic on efficiency is consistent with the global findings, with traditional and low-technology industries being more vulnerable, whereas highly-innovative, including electronics and pharmaceuticals, appear to have been relatively resilient.

5.5. Overall Interpretation

The overall picture of the Turkish manufacturing performance during the 2019-2023 period emerges from the combined evidence of both the frontier and inefficiency effects models. Potential profitability is determined by the liquidity, leverage, and operational efficiency and it fully realized only when firms maintain the financial structure, innovation capability, and operating cost. The structural inefficiencies remain persistent, significant, and unevenly distributed across industries.

These results show that, although technological advancement and innovation are vital for long term competitiveness, the financial structure of firms is also critical in determining that a firm is close to profit frontier. Policies that enhance equity financing, reduce debt burdens, strengthen interest-coverage capacity, and incentivize R&D investment would therefore support higher technical and financial efficiency across Turkish manufacturing.

I conducted robustness checking hypothesis tests for the stochastic production frontier estimates, based on the Battese and Coelli (1995). And the findings are reported below.

$$\lambda = -2\ln(Likelihood\ H_0 - Likelihood\ H_1)$$

Table 6: the test of null Hypothesis

Null Hypothesis	LR Statistics	Critical Value at 1%	Decision
$H_0: \gamma = \delta_0 = \cdots = \delta_5 = 0 *$	91.17	18.48	Reject H_0
$H_0: \delta_1 = \cdots = \delta_5 = 0$	91.17	15.09	Reject H_0

Note; * The statistics test has a mixed chi-square distribution (given by Kodde and Palm, 1986).

In Table 6 the first null hypothesis specifies that the model does not include inefficiency effects. Which is strongly reject and second null hypothesis shows the effects of the technical inefficiency are not a linearly dependent function of the selected variables is rejected at the 1% level. This suggests that the selected Z-variables together significantly explain variations in technical inefficiency.

5.6. Discussion of Technical Efficiency scores.

In addition to the results of our model, presented in Table 5, and their interpretation and discussion, we now turn to the estimates of TE scores of each 2-digit manufacturing sectors.

5.6.1. Identify sectors with progressive and consistent performance (Heat Map)

To complement the estimation results of the stochastic frontier model, this section examines the broader patterns of technical efficiency across Turkish manufacturing industries using a heat-map of sectoral TE scores from 2019 to 2023. The purpose of this analysis is twofold. First, it provides an intuitive visual summary of how efficiency levels differ across sectors and how these levels evolve over time. Second, second, it helps us to determine sets of industries that show comparable performance trends, including sustained high efficiency, slow convergence, or poor performance. These patterns can be used to draw conclusions regarding the structural characteristics of the manufacturing industry and their connections to technology intensity, market orientation, and sectoral characteristics recorded in previous literature studies.

The heat-map demonstrates a number of specific trends in the Turkish manufacturing structure of efficiency. High technical efficiency is observed to be present throughout the period in a small number of sectors, including motor vehicles, electronics, and pharmaceuticals, as indicated in Figure 1. Their TE values are also near the high range in all years, which creates a definite cluster of good-performing industries. These are normally technology-based industries that are deeply rooted and embedded in export value chains, and this facilitates efficiency even in changing conditions. Their stability at high efficiency levels is a similar experience to that in the literature, which suggests that higher manufacturing segments will be nearer to the frontier because of greater capacity for innovation, higher barriers to entry, and more stable organizational frameworks.

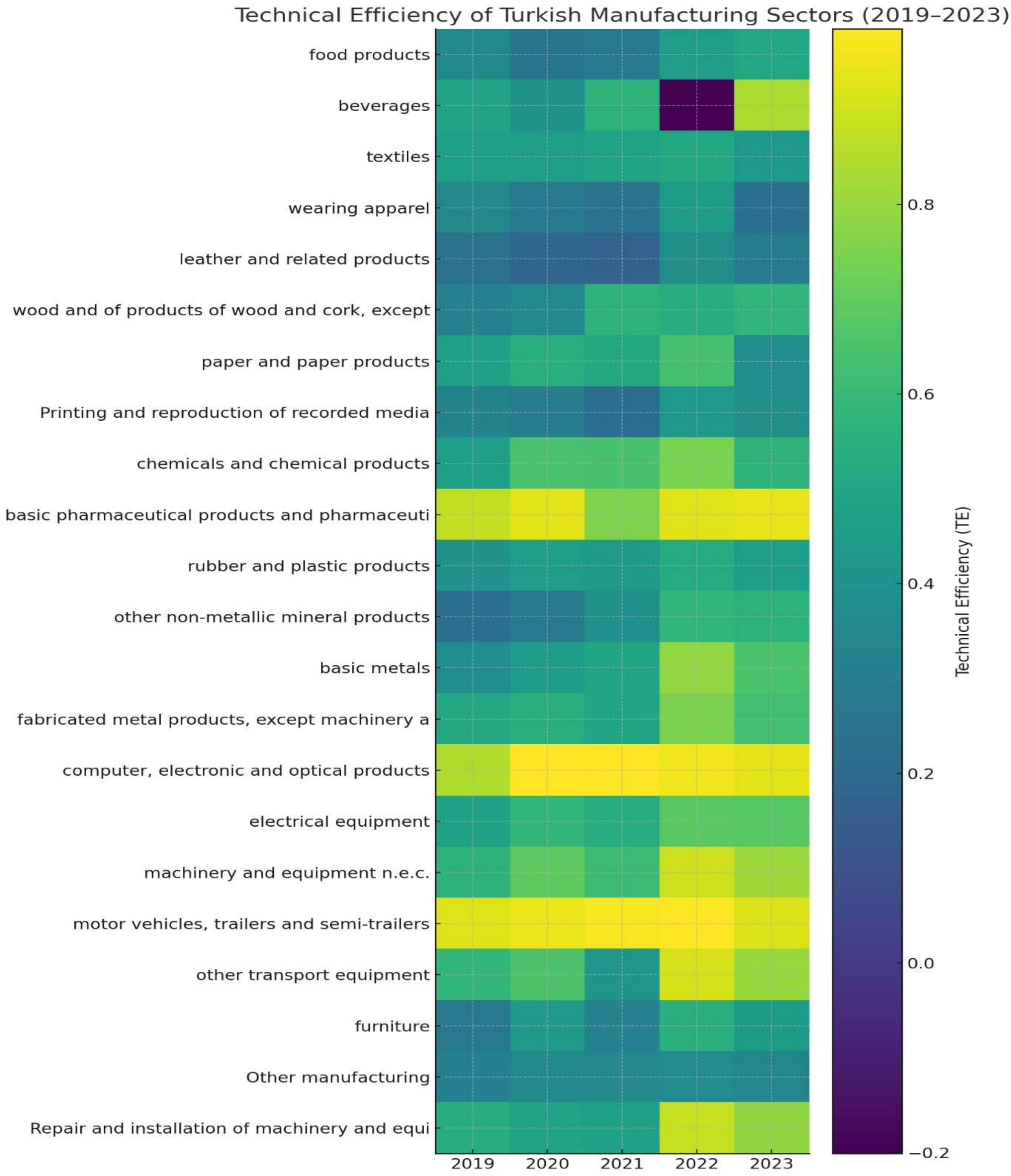
There is a second group of industries that are moderately but slowly becoming efficient. This group includes machinery, chemicals, electrical equipment, basic metals, and fabricated metals. Their TE levels occupy the middle of the heat-map, with noticeable brightening in later years. This implies that it will progressively converge to greater efficiency, perhaps due to the updating of production technologies, the experience of learning and adjusting to competition pressures. Previous research on Turkish manufacturing has also documented these trends of disproportionate yet continuing catch-up in medium-technology sectors, largely those involved in supplying intermediate goods or those involved in export-oriented production networks.

These dynamics are confirmed by the heatmap and the heterogeneity of this broad group is revealed.

Industries that have maintained low efficiency such as textiles, apparel, leather, wood products, furniture and printing dominate the lower end of the heat-map. These industries are found in the darker shade meaning that they are in a much farther location of the efficiency frontier. A large number of these industries are low technology intensive, highly competitive in terms of prices, have low margins, and rely more on domestic demand. Their reduced efficiency improvement over time is consistent with the structural problems that are widely observed in the literature, such as a reduced investment in intangible capital, labour-intensive and reduced access to scale economies. Their efficiency paths indicate a less dramatic productivity potential than high-technology industries even though they constitute a meaningful portion of the manufacturing workforce.

In these trends, the heat-map indicates clearly that Turkish manufacturing is not standardized. Instead, it has a stratified structure, where there is an efficiency core with a high level of performance, a number of middle-performing industries which have slow growth, and a set of structurally weak industries that display minimal efficiency mobility. This visual observation reinforces the frontier estimation findings by demonstrating how latent characteristic features of the sectors affect the capability of industries to exist near to efficient levels of production.

Figure 1. Heat Map of TE Scores (2019-2023)



5.6.2. Sectoral Efficiency Responses to the COVID-19 Shock.

The COVID-19 outbreak caused a sudden and massive shock to the economy, affecting different manufacturing sectors differently. The response of technical efficiency to this shock gives valuable information about the stability and flexibility of the Turkish industries in the face of uncertainty. While the preceding sections analysed long-term patterns and structural drivers of efficiency, the purpose of this subsection is to examine short-run deviations attributable specifically to the pandemic years. To achieve this, a simple comparative indicator is constructed to measure whether technical efficiency declined, stabilized or improved relative to pre-pandemic levels. This allows us to classify sectors according to the severity of the shock they experienced and to interpret these outcomes in the context of sectoral characteristics and international findings on firm performance during COVID-19.

We measure the impact of COVID-19 on technical efficiency by comparing each sector's pre-pandemic efficiency with its performance during the first two years of the pandemic (see Equation 4.1). The year 2019 is taken as the benchmark representing normal operating conditions. The average of TE in 2020 and 2021 is used to represent efficiency during the pandemic period. A COVID-19 impact index is then computed for each sector as:

$$COVID_{Impact_i} = TE_{2019,i} - \frac{TE_{2020,i} + TE_{2021,i}}{2} \qquad [4.1]$$

A positive value of the index indicates that average efficiency fell during the pandemic, a value close to zero suggests little change, and a negative value implies an improvement relative to 2019 (see figure 2). Sectors are classified into four groups according to the size of the observed change: those experiencing a strong negative effect (index values greater than 0.05), those facing a mild negative effect (values ranging from 0 to 0.05), sectors that remained largely resilient or unchanged (values between −0.05 and 0), and sectors that improved during the pandemic period (values below −0.05). For ease of interpretation, the results are presented using a ranked bar chart.

The analysis shows large heterogeneity in the effect of the COVID-19 shock on Turkish manufacturing sectors (see Figure 2). A subset of industries registered certain declines in technical efficiency. Food products, wearing apparel, leather goods, printing and reproduction, and repair and installation activities fall into this classification. These sectors have several characteristics that are observed in international analyses of the economic impact of the pandemic: they are highly reliant on face-to-face transactions, vulnerable to disruptions in retail demand, and rely on labour-intensive production structures. Studies examining the outcomes of the pandemic in different countries continue to observe that labour-intensive and domestically oriented industries were among the worst hit, experiencing lower utilisation rates, supply bottlenecks, and reduced demand. These features contribute to the high efficiency losses observed in these sectors.

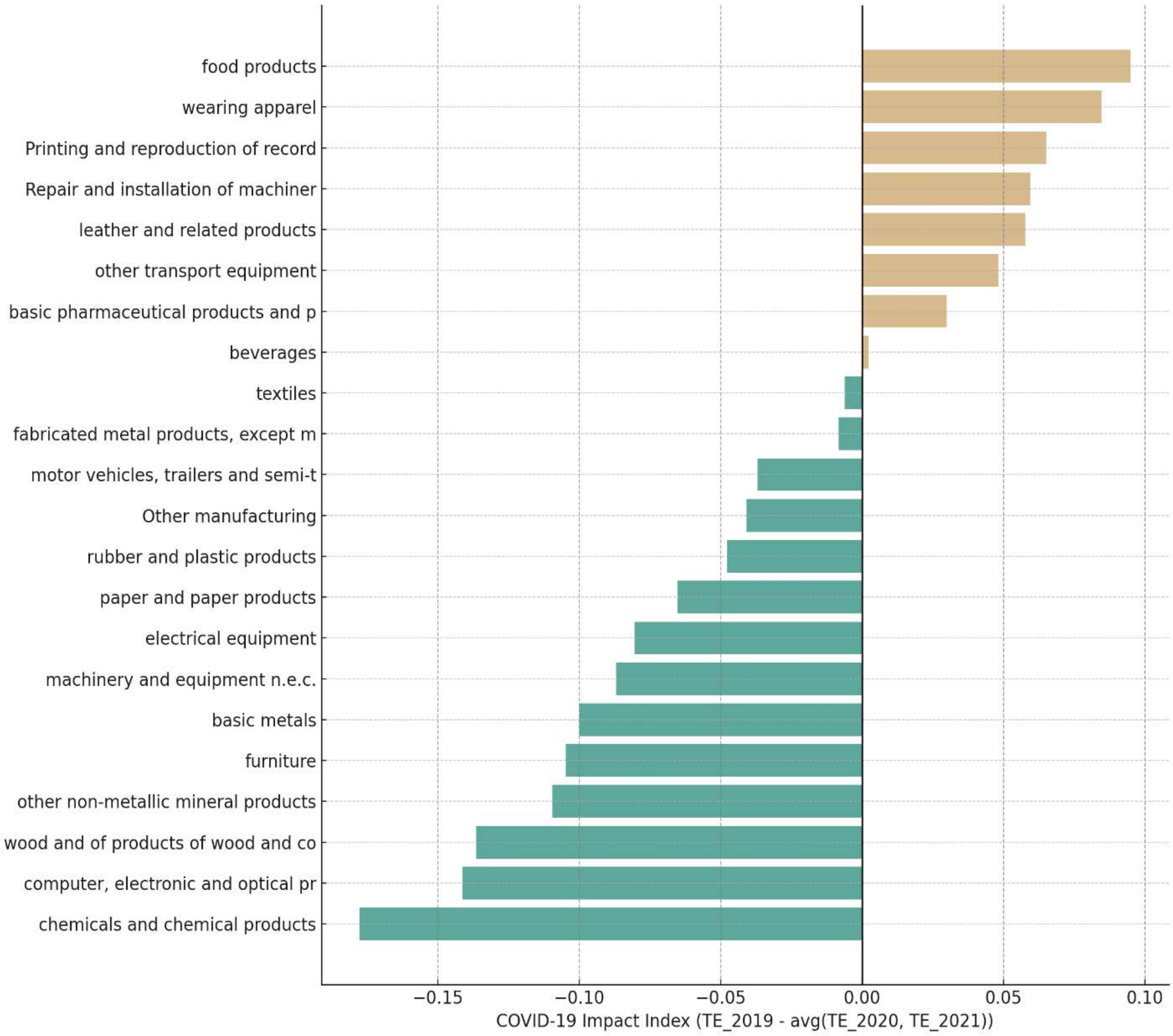
A second group has slight decreases. Other transport equipment, beverages, and pharmaceuticals fall into this category. These industries experienced both steady and disrupted patterns of demand. For example, while pharmaceuticals experienced strong demand, rapid changes in product mix, global supply-chain delays, and capacity constraints may have resulted in temporary inefficiencies. Similarly, limitations imposed on mobility and shifting consumption patterns affected bottles and transport equipment, but efficiency levels in these categories were reduced only to a limited extent. The constrained effects observed in these industries are in line with empirical findings from both country-level productivity analyses and industry-specific studies, which find that output shocks were less severe in demand-affected industries during the pandemic, particularly where firms were able to adjust capacity or shift production.

Several sectors also show little change relative to 2019, according to the efficiency data examined in this study. These include textiles, fabricated metal products, rubber and plastic products, motor vehicles, and others. In these industries, efficiency was generally stable in the face of disruptions. This outcome may be due to features such as diversified product lines, integration into export supply chains, or production processes that are less dependent on face-to-face interactions. International studies on manufacturing performance during the pandemic highlight that sectors embedded in global production networks were able to recover more quickly or reduce volatility in operational efficiency due to continuity in foreign demand and the ability to adjust sourcing and production timing.

The most striking finding is that a comparatively large set of industries saw improvements in efficiency in the pandemic. Chemicals, paper and paper products, electrical equipment, machinery, basic metals, furniture, non-metallic minerals, wood products and electronics all exhibit higher average efficiency in 2020–2021 than in 2019. This pattern is consistent with several mechanisms documented in the literature. First, crises often generate composition effects, whereby less efficient firms contract or exit, raising the average efficiency of the surviving firms. Research by Foster, Haltiwanger and Syverson (2008), among others, highlights how downturns can accelerate reallocation towards more productive producers. Second, demand for certain goods increased during the pandemic, particularly chemicals, packaging materials, electronics and intermediate industrial inputs linked to remote work, hygiene and household consumption. Third, firms with stronger innovation capacity or digital readiness were better able to reorganise production, mitigate disruptions and maintain profitability. Recent analyses of manufacturing performance during COVID-19 emphasise the role of digital adoption and organisational flexibility in sustaining or improving efficiency under adverse conditions. Finally, because efficiency is measured relative to assets rather than output, firms that streamlined their operations, optimised inventories or improved balance-sheet discipline could record higher TE even when production volumes fluctuated.

Overall, the COVID-19 impact assessment shows that Turkish manufacturing includes both highly exposed and relatively resilient sectors. Although a number of labour-intensive and demand-dependent industries experienced declines in efficiency, many medium- and high-technology sectors were able to sustain or even enhance their performance during the pandemic period. These differences point to variations in technological capacity, market orientation, shifting demand conditions, and firm-level adaptability, and are consistent with evidence from international studies documenting the uneven economic consequences of COVID-19.

Figure 2. COVID-19 Impact Index



5.6.3. Technical Efficiency Levels and Stability across Sectors

To supplement this analysis of long-term efficiency trends and the effects of COVID-19 on the sector, this section also assesses the total performance and stability of Turkish manufacturing industries by analyzing their five-year mean technical efficiency and the variation in efficiency over the last three years, 2019–2023, as shown in Table 6. It aims to determine which areas are highly efficient and consistent in their performance, which ones perform strongly with more variability, and those that are weak, unstable, and persistent. Through a combination of analyzing average efficiency and its change over the years of operation in the form of a scatter plot and a heatmap of volatility, the section offers better insight into the strengths and weaknesses of structures in the manufacturing sectors.

The aggregate performance shows a definite ranking of efficiency among Turkish manufacturing industries, as shown in Figure 3. The motor vehicles, electronics, and pharmaceuticals industries continually record the highest five-year average TE scores and also exhibit relatively low volatility. This implies that these industries not only perform near the efficiency frontier, but are also stable in doing so. These outcomes are consistent with established findings showing that technology-intensive and export-driven industries are usually highly productive and financially strong due to economies of scale, investment in intangible resources, and integration into global value chains.

A second group of sectors, such as machinery, electrical equipment, chemicals, and basic metals, which show above-average efficiency but with relatively greater variation. These industries have strong underlying capabilities but are more subject to demand fluctuations, input price changes, or supply-chain dynamics. Their position signals competitiveness and potential for further upgrading, but it is also sensitive to short-term disruptions. This pattern aligns with empirical research showing that medium-technology industries tend to exhibit cyclical changes in utilization and profitability, even though productivity improves in the long term.

At the bottom of the distribution, industries such as apparel, leather goods, printing, and food products have the lowest average performance, which validates structural issues related to labour-intensive production, intense price competition, and limited innovation activity. There are also industries among them with high volatility (see Figure 4), indicating exposure to changing domestic demand conditions or supply shocks. Other industries, such as textiles and rubber and plastics, exhibit relatively stable performance, although their average efficiency remains lower. This implies enduring yet predictable limitations, rather than severe instability, and reflects the low productivity potential of conventional manufacturing segments reported in previous studies.

The combination of the analyses indicates that Turkish manufacturing consists of a core of relatively steady, high-performing industries; a group of competitive but more variable sectors; and a set of structurally weaker industries that remain far from the efficiency frontier. The integration of mean efficiency and volatility measures thus provides a more complete picture of sectoral competitiveness and highlights where long-term strengths exist and where deeper structural reforms may be needed.

Figure 3. Five-Year Averages of TE Scores

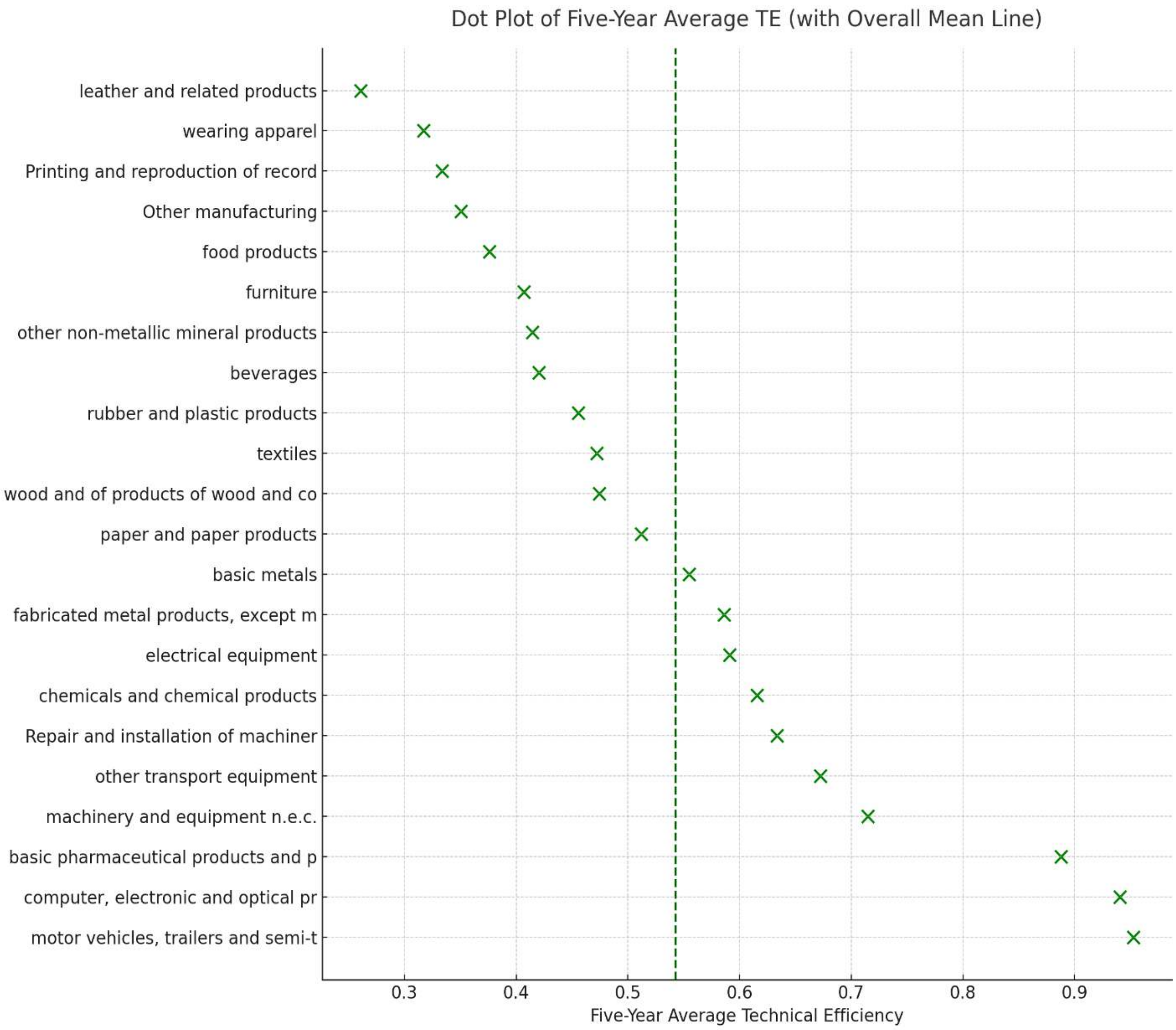
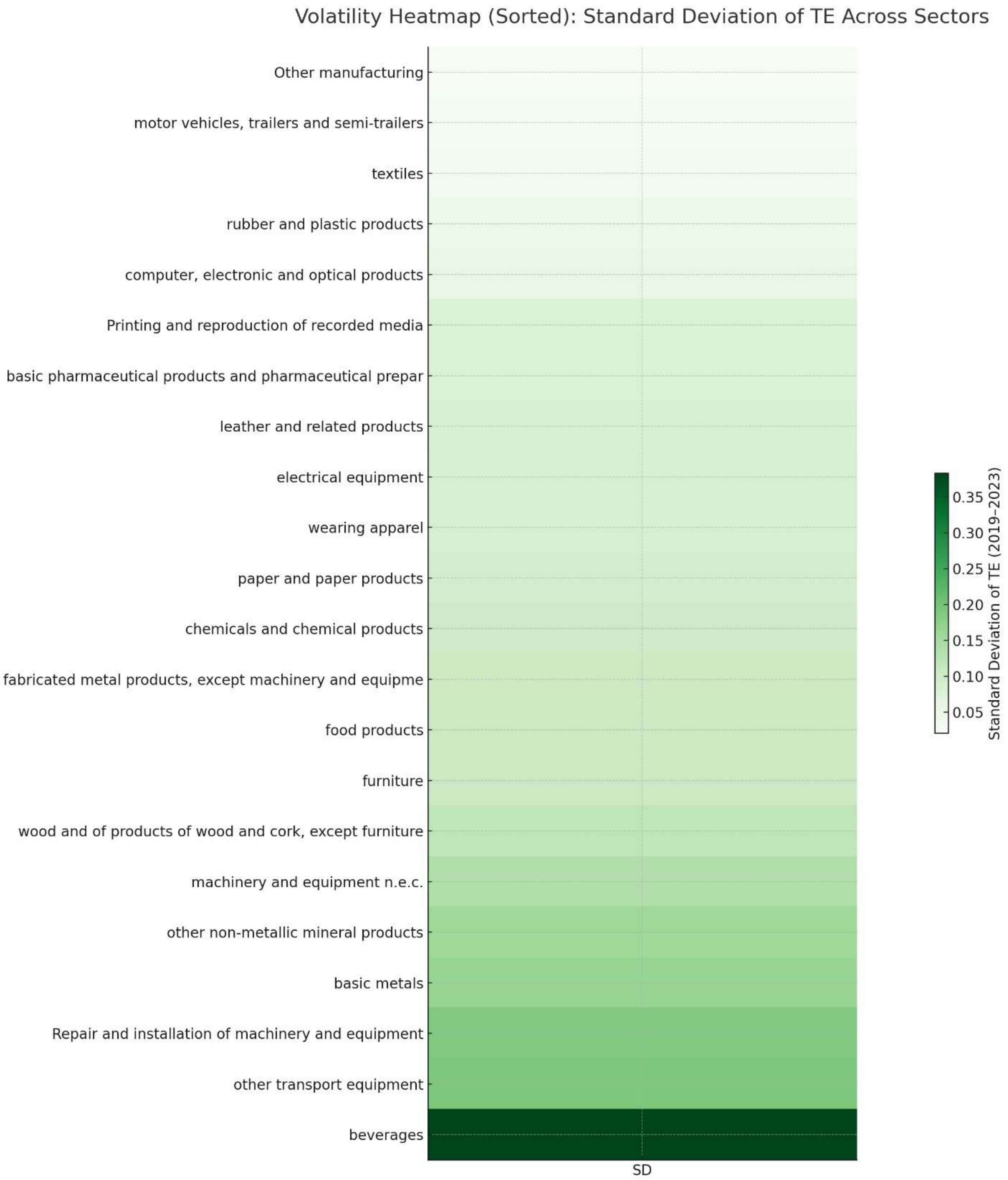


Figure 4. Volatility of Standard deviation of TE (2019-2023)



Limitations of the study:

The first major limitation of this study's methodology is the lack of ability to estimate the stochastic frontier using standard functional forms, such as Cobb–Douglas and Translog production techniques. These functional forms are commonly used in efficiency literature due to their theoretical foundations and flexibility. However, they could not be employed in the present analysis. Estimates of these functional forms revealed that many of the variables became statistically insignificant, making the models difficult to interpret meaningfully. Second, the study explored a wide range of financial ratios frequently referenced in the literature, for including as a Z variable to identify firm- or sector-specific drivers of inefficiency. However, most of these ratios were statistically insignificant across different model specifications.

6: CONCLUSIONS

This thesis aimed at investigating the determinants of profitability-based efficiency in Turkish manufacturing in the context of a Stochastic Frontier Model (SFM) that is not built on classical production-frontier models which uses Return on Assets (ROA) as the frontier output. The manufacturing industry in Turkiye, which constitutes one of the largest pillars of the national economy regarding contribution to the GDP, exports and formal employment, shows a high level of heterogeneity within the two-digit subsectors of the industry. These are differences that have been influenced by variations in financial structure, capital intensity, innovation capacities, cost management and exposure to domestic and external shocks. The shifts brought about by the COVID-19 pandemic also increased these changes, making it more appropriate to use an analytical method that would be capable of capturing both monetary and structural performance determinants. The study is motivated by gap in the literature on the efficiency research that has been done in Turkiye excluding the fact that most of its research is based on physical output which does not best reflect sectors with mixed product mixes, lacking production data, and different constraints. The use of profitability as the key performance indicator helps the thesis to add to the more comprehensive vision of the dynamics of the manufacturing industry.

The thesis, therefore, contributes to the literature in a number of ways. To begin with, it prolongs the use of stochastic frontier analysis application in Türkiye by building one of the earliest profitability-based frontiers in the two-digit manufacturing industries. This change in ROA to a dependent variable is in line with the trends in frontier modelling in the world, as frontier modelling is becoming a significant measure of managerial performance, resource use and competitiveness within the sector. Second, the thesis contributes to the empirical landscape by incorporating the variables of financial structure, the indicators of innovations, and the risk-management measures into the model of inefficiency directly. Fixed assets to equity, interest-coverage capacity, R&D intensity, and operating-expense pressure are variables that have hardly been researched simultaneously as a coherent frontier in the Turkish manufacturing industry. They include a broader window into the processes by which sectors become less than their optimal profitability. Third, by comparing the estimates of efficiency levels in the entire 2019-2023 span and in the COVID-19 years, the study introduces a new evidence on the way in which crisis circumstances redefine frontiers of profitability. This two-fold comparison does not just show that certain industries proved resiliency but also shows the structural vulnerability of other industries, which is very useful in the policy of industrial and crisis management.

The thesis is methodologically based on the one-step stochastic frontier Battese and Coelli (1995) model that enables estimation of both the profit frontier and determinants of inefficiency simultaneously. ROA becomes the frontier output that reflects the financial aspect of the performance and enables to compare the performance of different industries where various production technologies are relevant. These core determinants of profitability were liquidity, leverage and inventory turnover, with inefficiency modelled by more structural determinants. The data based on the CBRT Company Accounts Statistics offered a balanced panel of twenty two NACE Rev.2 two digit sectors 2019-2023 allowing the measurement of cross-sectional variance as well as the impact of extraordinary economic circumstances.

The results of the empirical study are clear and coherent in terms of giving a vision of the drivers of performance in manufacturing in TürkiyeTürkiye. Frontier estimates indicate that liquidity has a positive effect on profitability in that it alleviates working-capital constraints and exposure to short-term shocks. High profitability is also supported by inventory turnover, which is a regularity of the operational advantages of effective inventory. Conversely leverage has a major negative impact, as it is an indication of how Turkish industries are sensitive to interest-rate volatility, exchange-rate pressures, and increase in borrowing costs. These findings affirm that financial fragility and operational bottlenecks still play significant limitations to the performance of the sector.

The effects of inefficiency have more structural information. Industries that have greater prior support of their operations by fixed assets as compared to equity are expected to be more efficient, implying that a well-built capital structure will minimize the chances of being affected by credit risks and are more stable. Interest-coverage capacity comes out as a very strong driver of efficiency meaning that industries that have the capability to comfortably service debt operate nearer to the profitability frontier. The level of inefficiency significantly decreases by R&D intensity as well, which also cements the key role of innovation and technological modernization to increase competitiveness. Conversely, high operating costs are linked to the inefficiency, which is cost-structure inflexibility and impairments of productivity in traditional, labour-intensive sectors. The pandemic-year dummy proves that COVID-19 significantly increased the inefficiency, which highlights the extreme disruption of supply chains, domestic demand and operational continuity at that time.

The parameters of variance justify the application of stochastic frontier. The large estimation of σ_u^2 means that inefficiency is a real and quantifiable cause of performance dispersion among the Turkish manufacturing industries. The gamma value of about 0.394 implies that the structural inefficiency generates close to 40 percent of the total variation in ROA and not by chance. This confirms the conclusion that systematic variations in financial capacities, innovation abilities, and cost structures influence manufacturing performance in Türkiye.

The results of the analysis are further put into perspective with the analysis of the scores of technical efficiency. The high-technology industries, including electronics, motor vehicles and pharmaceuticals, are constantly at the profitability frontier, that is, there is a benefits in terms of innovation, capital intensity and integration with global value chains. The results in medium-technology industries are more heterogeneous, allowing certain industries to reach moderate levels of efficiency and others falling behind due to unequal patterns of investments or technological divide. The industries with low technology such as textiles, wood products, food production, and clothing are always the most inefficient. Their low efficiency is indicative of long-standing systemic problems, such as low R&D, small size, high labour costs in relation to productivity and reliance on domestic demand conditions. A comparison of efficiency scores in the pre-pandemic and the pandemic period indicates that high-technology sectors proved to be resilient whereas most of the traditional industries were severely hit with efficiency scores which exacerbated their weaknesses.

These cumulative findings, based upon the frontier results, the effects of inefficiency and the efficiency rankings, give rise to some broad findings. The financial structure is decisive in the profitability-based efficiency and excessively leveraged sectors are permanently disadvantaged. Innovation capacity is revealed as a strong competitiveness driver and this confirms the global evidence of technological capability in supporting frontier performance. One of the biggest problems facing various industries is cost management that is specifically very critical in industries that involve a lot of labor or are using outdated production technologies. Moreover, during such crises as the COVID-19 pandemic, the structural weaknesses are multiplied, which increases the efficiency gap between advanced and traditional sectors.

These results have significant implications in industrial policy. Enhancing the mechanisms of equity-based financing would decrease the excessive reliance on debt and enhance the financial resilience. Increasing the incentives on R&D, technology adoption, and extending programs that facilitate digitalization would assist sectors to experience a rise in the profitability frontier. Eliminating the cost-structure issues, by making modernization investments, providing productivity-enhancing programs, and better supply-chain integration would help the industries struggling to close the gaps in their efficiency. Lastly, the data indicate that resilience-building strategies such as risk-management instruments, diverse sources of financing, and crisis-response systems are a necessity in protecting the industrial performance during the volatile times.

To sum up, this thesis contributes to the field of profitability-based efficiency in the Turkish manufacturing sector in terms of its synthesis of financial, operational, and structural determinants in a stochastic frontier. It emphasizes the importance of innovation, financial stability and cost control in maintaining competitiveness and gives empirical backgrounds of policy intervention to enhance resilience and performance of the industry. Further studies may build on this study by adding firm-level micro data, investigating dynamic frontier models, or focusing on the impact of export intensity, environmental performance, and digital transformation on the development of efficiency. Analytical tools that combine financial and structural views like those used in this thesis will be a requirement to inform evidence based policy and strategic decision making as Turkiye continues its transition to an industrialized country.

Appendix

Table 7. Mean Scores (All Years)

Sectors	Mean	Max	Min	SD
29-motor vehicles, trailers and semi-trailers	0.95	0.99	0.92	0.03
26-computer, electronic and optical products	0.94	0.98	0.84	0.06
21-basic pharmaceutical products and pharmaceutical preparations	0.89	0.94	0.75	0.08
28-machinery and equipment n.e.c.	0.71	0.89	0.56	0.14
30-other transport equipment	0.67	0.91	0.42	0.19
33-Repair and installation of machinery and equipment	0.63	0.88	0.48	0.19
20-chemicals and chemical products	0.62	0.74	0.47	0.10
27-electrical equipment	0.59	0.68	0.48	0.09
25-fabricated metal products, except machinery and equipment	0.59	0.75	0.50	0.10
24-basic metals	0.55	0.79	0.38	0.17
17-paper and paper products	0.51	0.64	0.38	0.10
16-wood and of products of wood and cork	0.47	0.58	0.33	0.12
13-textiles	0.47	0.52	0.43	0.03
22-rubber and plastic products	0.46	0.53	0.40	0.05
11-beverages	0.42	0.84	-0.20	0.38
23-other non-metallic mineral products	0.41	0.59	0.23	0.16
31-furniture	0.41	0.55	0.28	0.11
10-food products	0.38	0.51	0.26	0.11
32-Other manufacturing	0.35	0.37	0.32	0.02
18-Printing and reproduction of recorded media	0.33	0.43	0.23	0.08
14-wearing apparel	0.32	0.45	0.23	0.09
15-leather and related products	0.26	0.39	0.18	0.09

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