

Research Article

The Extended Verdoorn Law with Undesirable Outputs: The Case of the Turkish Manufacturing Industry

İstenmeyen Çıktılarla Genişletilmiş Verdoorn Yasası: Türk İmalat Sanayi Örneği

Sevcan KAPKARA KAYA

Dr. Öğr. Üyesi, Samsun Üniversitesi

Siyasal Bilgiler Fakültesi, Ekonomi ve Finans Bölümü

sevcan.kaya@samsun.edu.tr

<https://orcid.org/0000-0002-7864-0505>

Makale Geliş Tarihi	Makale Kabul Tarihi
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Abstract

This study examines the relationship between labor productivity, value added, and emissions in the Turkish manufacturing industry within a microeconomic framework, extending Verdoorn's law to incorporate the dimension of environmental sustainability. While the traditional Verdoorn hypothesis predicts that output growth increases productivity, this study incorporates per capita carbon emissions as an unwanted output into the model. Panel data for 15 manufacturing industry sub-sectors, covering the period 2010–2022, were first analyzed in a static framework using the Driscoll–Kraay estimator. The robustness of the findings was then tested under a dynamic panel structure using the Least Squares Dummy Variable Corrected (LSDVC) estimator. The results of the static and dynamic analyses consistently support the validity of Verdoorn's law, indicating that per capita value added has a positive and significant impact on labor productivity. While emission increases have a negative impact on productivity in both models, the positive coefficient of the interaction term between value added and emissions indicates that high production levels can partially offset the adverse effects of environmental pressures. The findings generally reveal that an environmental dimension should be incorporated into the output-efficiency relationship in the manufacturing industry, and that it is crucial to address growth and sustainability dynamics holistically at the microeconomic level.

Keywords: Verdoorn's Law, labor productivity, carbon emissions, output, undesirable output.

Öz

Bu çalışma, Verdoorn yasasını çevresel sürdürülebilirlik boyutuyla genişleterek Türk imalat sanayiinde işgücü verimliliği, katma değer ve emisyon arasındaki ilişkiyi mikroiktisadi bir çerçevede incelemektedir. Geleneksel Verdoorn hipotezi çıktı artışının verimliliği artırdığını öngörürken, bu çalışmada modele istenmeyen çıktı olarak kişi başına karbon emisyonu dâhil edilmiştir. 2010–2022 döneminde 15 imalat sanayi alt koluna ait panel veriler önce statik bir çerçevede Driscoll–Kraay tahmincisi ile analiz edilmiş, ardından bulguların sağlamlığı dinamik panel yapısı altında sapması düzeltilmiş gölge değişkenli en küçük kareler (LSDVC) tahmincisi kullanılarak test edilmiştir. Statik ve dinamik analiz sonuçları tutarlı biçimde Verdoorn yasasının geçerliliğini desteklemekte; kişi başına katma değer işgücü verimliliğini pozitif ve anlamlı şekilde etkilediğini ortaya koymaktadır. Emisyon artışları her iki modelde de verimlilik üzerinde olumsuz bir etki yaratırken, katma değer ile emisyonun etkileşim

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teriminin pozitif katsayısı yüksek üretim düzeylerinin çevresel baskıların olumsuz etkisini kısmen telafi edebildiğini göstermektedir. Bulgular genel olarak imalat sanayiinde çıktı-verimlilik ilişkisine çevresel bir boyut eklenmesi gerektiğini, büyüme ve sürdürülebilirlik dinamiklerinin mikroiktisadi düzeyde bütüncül biçimde ele alınmasının önem taşıdığını ortaya koymaktadır.

Anahtar Kelimeler: Verdoorn Yasası, işgücü verimliliği, karbon emisyonu, çıktı, istenmeyen çıktı.

1. Introduction

Productivity is a critical factor in economic literature, as it is one of the key determinants of economic growth. The sustainability of economic activities depends on the practical and rational use of available resources. Among the factors that directly affect this effectiveness in the production process, the labor factor is the most significant, since labor is a dynamic element that reflects the impact of technological developments and learning processes on production productivity (Verdoorn, 1956, p.433-434). In this context, analyzing productivity dynamics is crucial for understanding the microfoundations of the growth process. The Verdoorn Law, proposed by Verdoorn (1949) and developed by Kaldor (1966), sheds light on the endogenous nature of growth by explaining the positive feedback mechanism between output growth and labor productivity. However, this law addresses the production process only in terms of “desired outputs”; it does not take into account factors such as environmental impacts, resource use costs, and unwanted outputs. However, the embeddedness of environmental externalities in the production process necessitates a more comprehensive approach to productivity analysis that includes unwanted outputs. As environmental economics and green growth approaches play an increasingly decisive role in economic policy, it is necessary to reassess Verdoorn’s Law from an environmental sustainability perspective. Empirical evidence indicates that environmental degradation negatively affects both economic output and labor productivity (Graff-Zivin, and Neidell, 2012, p. 14; Chang, Graff-Zivin, Gross and Neidell, 2016, p. 141). However, the existing Verdoorn literature has largely focused on the output–productivity nexus. It has not systematically incorporated carbon emissions and other undesirable outputs generated during the production process into the analytical framework. Undesirable outputs refer to by-products such as emissions, waste, and pollution that emerge alongside desirable outputs and impose environmental and social costs (Zhou, Zhou and Fan, 2014, p. 799).

In the literature studies, integrating Verdoorn’s Law with environmental costs and sustainability considerations remains quite limited. In this context, the present study seeks to fill an important gap in the literature by extending the classical Verdoorn framework to include carbon emissions as an undesirable output variable. By reassessing the production–productivity relationship in light of environmental costs, the study offers a novel microeconomic perspective on the environment–growth nexus. Within this framework, a dummy variable was added to the model to determine the potential structural break effect of the COVID-19 pandemic on production and productivity. Furthermore, the impact of environmental pressures on production scale was examined through the interaction term between the emission and value-added variables. Empirical analysis was conducted using a panel data set covering 15 sectors of the Turkish manufacturing industry for the period from 2010 to 2022. In the static analysis, the Driscoll–Kraay robust estimator was used to address potential issues of autocorrelation, heteroscedasticity, and cross-sectional dependence in the model. In the dynamic analysis, the LSDVC (Least Squares Dummy Variable Corrected) estimation method was applied to assess the continuity of productivity and the effects of past periods. The combined use of these two methods enables a comprehensive examination of the Verdoorn effect across both static relationships and dynamic panel structures. The study comprises six sections: the second section presents the theoretical framework, the third section reviews the literature, the fourth section discusses the dataset and model, the fifth section covers the methodology and findings, and the final section presents the conclusions and policy implications.

2. Theoretical Framework

Verdoorn empirically demonstrated a meaningful and positive relationship between the growth rate of labor productivity and the growth rate of production, examining national data on employment and production growth in fifteen countries and sectoral data in four countries during the interwar period (Boulier, 1984, p. 259). The first empirical findings regarding the existence of increasing returns to scale in the industrial sector date back to the 1940s. Fabricant (1942) identified a positive and significant

relationship between labor productivity and production levels in his statistical analysis of the manufacturing industry in the United States (Abdioğlu and Yamak, 2016, p. 81). This finding, demonstrating that increases in production volume create a simultaneous improvement in productivity, provided a theoretical basis for Verdoorn's Law, which was developed later. Verdoorn (1949) systematically tested this relationship and found that increases in production lead to increases in productivity, and that returns to scale are valid in industrial sectors. Within the framework of these fundamental findings, Verdoorn's Law assumes a positive and statistically significant relationship between the rate of increase in labor productivity and the growth rate of production output, particularly in the context of the manufacturing industry (Bianchi, 2002, p.115).

Kaldor (1966) revisited the relationship between productivity and output, incorporating this approach into economic growth theory as "Kaldor's Second Law." Accordingly, Kaldor empirically demonstrated a strong and positive relationship between labor productivity and production growth. Kaldor (1966) linked this relationship to the pioneering work of Verdoorn (1949) and referred to this connection as "Verdoorn's Law" (Whiteman, 1987, p. 576). In this context, it is stated that labor productivity tends to increase with the expansion of production volume, particularly in the manufacturing industry (Kaldor, 1966; Thirlwall, 1983; Bianchi, 2002, p. 115). This relationship is primarily driven by technological progress. It highlights the existence of both static and, in particular, dynamic economies of scale, reflecting the fundamental mechanism of increasing returns to scale in production (Bianchi, 2002, p. 115).

The traditional form of Verdoorn's Law defines the linear relationship between the rate of increase in labor productivity and the rate of output growth through equation (1) (Verdoorn, 1949; Bianchi, 2002):

$$g_p = a + b g_y \quad (1)$$

Here, g_p represents the growth rate of labor productivity, while g_y represents the growth rate of output (value added). Parameter a is interpreted as the autonomous (and therefore exogenous) rate of technical progress. At the same time, b represents the degree of returns to scale in the production process (Angeriz, McCombie, and Roberts, 2008, p. 9). The coefficient b is also the Verdoorn coefficient and traditionally takes the value 0.5 (Kaldor, 1966).

Labor productivity growth (g_p) is, by definition, equal to the difference between output growth (g_y) and employment growth (g_n); therefore, equation (2) can be rearranged based on this relationship.

$$g_n = -a + (1 - b)g_y \quad (2)$$

Kaldor preferred this formulation because labor productivity is, in fact, only a descriptive variable. Here, productivity is expressed as the y/n ratio. In this context, the relevant variables are considered exogenous because output (y) is determined by total demand, while employment (n) is defined as a decision variable for firms. Kaldor's interpretation is consistent not only economically but also statistically, since the direct regression of g_p on g_y can lead to spurious correlations because the productivity growth rate is a component of output growth. Furthermore, when equation (2) is extended to a model that includes situations where changes in employment partially align with output, it allows for the estimation of long-term Verdoorn coefficients.

This theoretical framework provides the basis for expanding Verdoorn's Law in the study from an environmental sustainability perspective.

3. Literature Review

Verdoorn's 1949 study emphasizes that there is an intrinsic link between labor productivity and production level. This relationship is considered a natural consequence of scale-dependent learning, specialization, and technical adaptation processes in the production process, thus indicating a cyclical mechanism in which productivity growth can be both a cause and a consequence of production expansion. This framework is included in the literature as one of the early theoretical approaches aimed at explaining the emergence of increasing returns in manufacturing industries (Boulier, 1984, p. 259). Verdoorn's (1949) empirical findings showed that productivity increased more rapidly in expanding industrial sectors. Verdoorn's contribution was to formulate an observation about the production process at the micro level as a macroeconomic growth regularity. Later, Kaldor (1966) summarized this

relationship as follows: “There is a strong positive relationship between the rate of productivity growth in manufacturing and the rate of output growth” (Whiteman, 1987, p. 576). Kaldor addressed Verdoorn’s observations at the macro level, linking this regularity to the general growth dynamics of the economy; he argued that manufacturing is the leading sector of the economy, particularly due to its structure that creates externalities. Kaldor (1966, p.1968) broadly supported these views, but argued that only a small part of Verdoorn’s Law could be explained by “established technical progress,” and that the primary source of increasing returns was the scale of production and structural transformation processes (Boulier, 1984, p. 259). Kaldor’s assessment is consistent with the endogenous growth approach, which argues that technical progress is not an independent determinant but a natural consequence of expansion in the scale of production. Kaldor’s contribution was to place Verdoorn’s observations within a macroeconomic growth theory, thereby giving the law its status as a precursor to endogenous growth debates (Thirlwall, 1983, p. 350).

One of the important contributions to the empirical evaluation of Verdoorn’s law is Casetti’s (1982) study. The author noted that the validity of Verdoorn’s law had primarily been investigated for industries and proposed a technique to distinguish productivity increases related to capital concentration, economies of scale, and neutral technological progress. This method was later applied to test the spatial validity of Verdoorn’s law in the context of the US economy. The study’s findings indicate that spatial differences in the Verdoorn relationship are significant and that the productivity–output relationship can vary substantially with geographical distribution. In their study, McCombie and Ridder (1984) applied both the least squares (OLS) method within the scope of static analysis and an instrumental variable approach sensitive to dynamic relationships using US state data from the period 1963–1973. The findings suggest that the returns to scale range from 1.33 to 1.65, contingent upon the specified regression model. The study confirms that dynamically increasing scale returns are an important factor in determining productivity growth. Whiteman (1987) compared the effects of Verdoorn’s law on productivity growth and employment growth using the Tinbergen–Verdoorn general equilibrium model and the Kaldor–Young dynamic equilibrium model. While the Tinbergen–Verdoorn approach relies more on static equilibrium, the Kaldor–Young model takes dynamic adjustment processes into account; thus, the two models explain the productivity–output relationship through different theoretical mechanisms. The empirical results reveal a substantial consistency between the two models with respect to employment growth dynamics. Furthermore, both frameworks corroborate Verdoorn’s hypothesis by demonstrating that increases in production growth contribute positively to employment expansion. Harris and Lau (1998) estimate returns to scale using UK regional sector data from 1968 to 1991 within a dynamic model framework based on the Johansen cointegration approach. The findings reveal that increasing returns to scale are valid in the majority of manufacturing industries in English regions. León-Ledesma (2000) examines the existence of dynamic increasing returns to scale within the framework of Verdoorn’s Law in Spanish regions from 1962 to 1991. The findings reveal that increasing returns are valid, particularly in the manufacturing sector. Knell and Rayment (2001) examined the validity of Verdoorn’s Law in their study, which covered 22 industrial sectors in 12 countries. The findings indicate that the Verdoorn Law holds across all industrial sectors, with the exception of Denmark and Germany, as well as the machinery and equipment industry and the office machinery and equipment sector. However, the relationship between production growth and labor productivity appears to be weak in the textile, wood products, and metal products sectors. Bianchi (2002) estimated Verdoorn’s Law for the Italian economy for the period 1951–1997 using three different modeling approaches: the traditional Verdoorn equation, a partial adjustment model, and an extended specification that includes capital growth. These three separate models enable the testing of the production–productivity relationship in a manner that accounts for both short-term employment adjustments and the dynamic effects of capital accumulation. Traditional Verdoorn Law estimates reveal the existence of increasing returns to scale at both the general economy and all sector levels. Sub-period analyses show that these returns remain generally valid over time, although they decrease somewhat. Apergis and Zikos (2003) examine the validity of Verdoorn’s law in the Greek manufacturing sector using the GMM method. Estimates based on both aggregate and sub-sector data confirm the existence of increasing returns to scale in the Greek manufacturing industry. Terzi and Oltulular (2004) examine the causal relationship between economic growth and industrialization using Turkish data from the period 1987:2–2001:3. The findings reveal a positive and bidirectional causal relationship between economic growth and the industrial production

index, showing that industrialization supports economic growth and that growth, in turn, fuels industrial production.

Following findings obtained in the international literature, it is observed that studies on Turkey are relatively limited; however, existing research provides significant and consistent evidence in the context of the manufacturing industry. Drawing on examples from the national literature, Harris and Liu (1999) estimate Verdoorn's Law using the Johansen cointegration approach within a dynamic model framework, employing data from 62 countries, including Turkey, for the period 1965–1990. The findings show that returns to scale are increasing in most countries except Guatemala, Peru, Japan, France, and Germany. According to Yamak's (2000) findings, a permanent relationship exists between industrial production and real GDP in Turkey during the period 1946–1995, and both variables reciprocally influence each other's direction. Abdioğlu and Yamak (2016) tested Verdoorn's law for nine sub-sectors of the Turkish manufacturing industry using both static and dynamic analyses based on data from 2005:1 to 2016:1. The findings show that Verdoorn's law is valid only in the tobacco manufacturing sector; in other sub-sectors, the law coefficient is not statistically supported. Ateş (2017) examines the validity of Verdoorn's law in the Turkish manufacturing industry from 1963 to 2013. ARDL bound test findings suggest that the Verdoorn hypothesis is valid in the long term for the manufacturing industry.

Although Verdoorn's law is not directly addressed in the literature, a few studies examine the impact of environmental factors on productivity. For example, in their study of manufacturing firms, Gray and Shadbegian (1993) found a negative relationship between pollution abatement costs and the growth of total factor productivity and labor productivity. Mazzanti and Zoboli (2009) found a positive relationship between labor productivity and environmental performance across most air emission categories. Graff, Zivin, and Neidell (2012) note that improving environmental conditions constitutes an investment in human capital and negatively impacts labor performance. Greenstone, List, and Syverson (2012) demonstrated that ozone pollution has a direct negative effect on agricultural workers' productivity, thereby showing that environmental conditions are a key determinant of labor productivity. Chang et al. (2016), on the other hand, found that fine particulate matter (PM_{2.5}) pollution reduces workers' productivity in the manufacturing sector and emphasized that environmental pressures impose costs not only on health but also on economic performance. Steinbrunner (2022) demonstrates that the relationship between pollution (and associated environmental regulations) and productivity is not one-sided; depending on the sector and the policy instrument, both positive and negative effects can emerge. In general, these studies show that environmental externalities cannot be assessed independently of production processes and that it is increasingly important to account for emissions and other undesirable outputs in efficiency analyses.

4. Data and Model

The sample for this study consists of 15 sectors classified under the NACE Rev. 2 classification in the Turkish manufacturing industry. The data used are annual data for the period 2010-2022. The relevant sector names and sector codes are presented in Table 1. The study's focus on these sectors and time frame is due to the availability of data for these sectors over the widest time frame.

Table 1. Manufacturing Industry Sub-Sector Information

Sector Code	Sector Name
C16	Manufacture of Wood, Wood Products, and Mushroom Products (Excluding Furniture) - Manufacture of Articles Made from Woven Materials such as Reed, Straw, etc.
C17	Manufacture of Paper and Paper Products
C18	Printing and Reproduction of Recorded Media
C20	Manufacture of Chemicals and Chemical Products
C21	Manufacture of Basic Pharmaceutical Products and Pharmaceutical Related Materials
C22	Manufacture of Rubber and Plastic Products
C23	Manufacture of Other Non-Metallic Mineral Products
C24	Primary Metal Industry
C25	Manufacture of Fabricated Metal Products (Except Machinery and Equipment)
C26	Manufacture of Computers, Electronic and Optical Products
C27	Manufacture of Electrical Equipment

C28	Manufacture of Machinery and Equipment Not Elsewhere Classified
C29	Manufacture of Motor Vehicles, Trailers (Semi-Trailers) and Semi-Trailers
C30	Manufacture of Other Transportation Equipment
C33	Installation and Repair of Machinery and Equipment

Source: <https://siniflama.tuik.gov.tr/Classifications/ClassificationsMenu>

This study aims to reinterpret the relationship between output and productivity by including the unwanted output variable in Verdoorn's law. In this regard, the variables used in the study are presented in Table 2.

Table 2. Variable Information

Variables	Variable Symbol	Definition of variables	Source	Expected Sign
Dependent variable	PRO	It is the production growth rate per employee and has been used as a measure of productivity.	TCMB	
Independent variables	VD	It is the value-added growth rate and has been used as an indicator of output.	TCMB	+
	E	It is the growth rate of carbon dioxide emissions per capita. It has been used as an undesirable indicator of output.	EUROSTAT	–
	INT	It is an interaction term. It is obtained by multiplying the per capita carbon dioxide emission growth rate by the value added growth rate.	It has been calculated by the author.	+/-
	COV	It is used to represent the disruption caused by the COVID-19 pandemic. It is a dummy variable that takes the value 1 for the 2019-2021 period and 0 for other periods.	It has been calculated by the author.	–

Within the framework of theoretical expectations regarding the variables in Table 2, it is predicted that the level of productivity (PRO) will show a positive relationship with value added (VA) and a negative relationship with emissions (E) and the variable representing the COVID-19 period (COV). Value increases added expand the scale of production, strengthening firms' technological capacity utilization and learning processes, thereby creating a positive effect on productivity. Conversely, increased emissions can reduce the efficiency of production processes due to environmental costs and regulatory pressures. External shocks, such as COVID-19, can lead to a decline in productivity through labor and supply chain disruptions. The sign of the interaction term is expected to vary depending on the sector's capacity to adapt to environmental conditions; a positive effect may emerge when the transition to green technologies accelerates, while an adverse effect may occur when adaptation costs are high.

Verdoorn's law traditionally considers the production process solely in terms of desired output. It therefore assesses the effect of output growth on productivity through economic indicators such as GDP or value added. However, this approach excludes environmental outputs, i.e., unwanted outputs, which are an inevitable part of the production process, from the analytical framework, potentially leading to an underestimation of the total output effect on productivity. To address this limitation, this study incorporates the emission variable, representing the environmental dimension of the production process, into the model as an unwanted output, thereby extending Verdoorn's law to include environmental effects. The extended model form of this law is analytically expressed by Equation 1, as presented in the study.

$$PRO_{it} = \alpha_0 + \beta_1 VD_{it} + \beta_2 E_{it} + \beta_3 INT_{it} + \beta_4 COV_{it} + u_{it} \quad (3)$$

$$PRO_{it} = \gamma_0 + \lambda_1 PRO_{it-1} + \lambda_2 VD_{it} + \lambda_3 E_{it} + \lambda_4 INT_{it} + \lambda_4 COV_{it} + \varepsilon_{it} \quad (4)$$

Equation (3) represents the static model, while Equation (4) represents the dynamic panel model and is used in the relevant estimates. The coefficients α and γ in these models represent the constant terms, while the coefficients β and λ represent the marginal effects of the explanatory variables on productivity. The error term of the static model is denoted by u_{it} , while the error term of the dynamic model is denoted

by ε_{it} . Within the framework of Verdoorn's law, the coefficients β_1 and λ_2 of the VD variable constitute the Verdoorn coefficient, which represents the effect of output growth on productivity.

Descriptive statistics calculated to show the distribution of variables in the equations within the sample and their basic statistical characteristics are presented in Table 3. This information serves as an important reference for interpreting model estimates.

Table 3. Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
PRO	195	0.029896	0.076477	-0.26898	0.364989
VD	195	30.52673	29.27873	-32.1813	159.6694
E	195	2.390832	26.96528	-30.9669	339.9886
INT	195	111.6306	996.856	-1734.15	11478.45
COV	195	0.230769	0.42241	0	1

The descriptive statistics presented in Table 3 reveal that the variables used in the study exhibit a highly heterogeneous structure, with significant variability, particularly in the VD, E, and INT variables. The relatively narrow fluctuation of the PRO variable around the mean suggests that this variable reflects a more stable process compared to the others. In contrast, the VD and, especially, the INT variable, which stands out due to its very high standard deviation and wide range of values, indicate significant differences between units or periods and possible outliers. On the other hand, the fact that the mean value of the COV variable, defined between 0 and 1, remains at a relatively low level of 0.23 indicates that the situation represented by this variable is relatively rare in the sample.

5. Method and Findings

To reliably analyze the relationship defined in Verdoorn's law, it is first necessary to determine the appropriate econometric model. The data set used in the study has a two-dimensional structure covering 15 sectors and 13 years. The panel data approach is a suitable method for this type of data structure because it allows for the observation of both inter-unit differences and changes over time. Panel data models reduce the limitations encountered in analyzing cross-sections and time series separately, providing more information content, higher variability, and greater degrees of freedom; thus, contributing to more reliable estimates (Tari, 2016, p. 475). The advantages of panel data usage, as mentioned by Baltagi, are summarized as follows, as reported by Gujarati and Porter (2009). Panel data enable the inclusion of inter-unit heterogeneity in the model, thereby explaining structural differences that are often overlooked in cross-sectional or time-series analyses. The combined use of time and cross-sectional dimensions enhances the effectiveness of estimation results by providing more information content, higher variability, reduced multicollinearity, and increased degrees of freedom. Furthermore, repeated observations provide a data structure conducive to examining the dynamic nature of economic processes. Additionally, panel data allow for a more straightforward presentation of policy effects that are difficult to identify using only cross-sectional or time-series data. More complex behavioral processes, such as economies of scale and technological change, can also be analyzed more effectively through panel data models. The inclusion of a large number of units within the same data structure reduces the bias that may arise from extensive aggregation, ensuring more reliable results (Gujarati and Porter, 2009, p. 593).

Considering the advantages offered by the panel data structure and the nature of the data set used in the study, it is necessary to determine the appropriate static panel data model, as represented by Equation 1. In this context, the F-test, LM test, and Hausman test are applied to choose between the classical model, fixed effects model, and random effects model. The findings related to these tests are reported in Table 4.

Table 4. Model Selection Tests

F-test		
	Statistics	Decision
Model 3	F _{birim} =1.9755(0.0225)*	FE model is valid
	F _{zaman} =5.1357(0.000) *	
	F _{birim,zaman} =3.3382(0.000)*	
LM Test		
	Statistics	Decision
Model 3	Chi2 _{birim} =0.599 (0.219)*	RE model is valid
	Chi2 _{zaman} =18.467 (0.000)*	
	Chi2 _{birim,zaman} =21.457 (0.000)*	
Robust Haussman Testi		
	Statistics	Decision
Model 3	0.88(0.9279)	There is no systematic difference between FE and RE models estimates.

Note: The * symbol indicates that hypotheses were rejected at the 5% significance level. Probability values related to the tests are given in parentheses.

The findings reported in Table 4 necessitate testing the fixed effects approach first for the panel data model. The F-test results indicate that both the unit and time fixed effects, as well as the unit-time fixed effects, are statistically significant, supporting the preference for the fixed effects model. The LM test, on the other hand, produces significant results indicating that the random effects model is valid. The final choice between the models was made using the Hausman test, and the insignificance of the test statistic indicates that there is no systematic difference between the FE and RE estimators. Accordingly, the testing of the assumptions regarding the random effects model is presented in Table 5, and additional findings regarding the model's validity are presented in Table 6.

Table 5. Random Effects Model Estimation Results

Variable	Coefficient	Robust Std. Err.	z-statistic	Probability
VD	0.00035	0.0002	1.70	0.088
E	-0.0008	0.0006	-1.26	0.208
INT	0.00002	0.00001	1.47	0.141
COV	-0.0284	0.01248	-2.28	0.023
Constant	0.0247	0.0069	3.57	0.000
Wald -stat				24.23 (0.0001)

Table 6. Test Results Related to Testing Assumptions

Test Type	Test Name	Statistics
Autocorrelation	LM	0.95(0.3300)
	ALM	1.70 (0.1927)
Heteroskedasticity	W0	3.3261(0.000)*
	W50	2.4166(0.0039)*
	W10	3.1704(0.0001)*
Inter-unit Correlation	Peseran CD test	7.325(0.000)*

Note: * indicates a significance level of 5%.

Table 5 presents the estimation results for the random effects model, which was determined to be feasible based on the Hausman test. However, the results of the tests conducted to examine the assumptions of this estimator are shown in Table 6. These findings reveal the presence of autocorrelation, heteroskedasticity, and inter-unit correlation issues in the random effects approach. Since such assumption violations weaken the reliability of standard errors, the model coefficients were re-estimated

within a fixed effects framework, and the Driscoll–Kraay estimator, which produces standard errors resistant to heteroskedasticity, autocorrelation, and cross-sectional dependence, was preferred (Yerdelen Tatoğlu, 2012, p. 266).

The Driscoll–Kraay estimator is a robust method that provides reliable results in panel data models when inter-unit correlation is present. This estimator produces consistent and robust standard errors, particularly in panel data sets with sufficient time dimensions (Driscoll and Kraay, 1998, p. 559). The Driscoll–Kraay approach has a wide range of applications due to its robustness to violations of assumptions such as heteroskedasticity, intra-unit autocorrelation, and inter-unit correlation. Thanks to these features, it ensures that the relationship between variables can be reliably analyzed under both time dependence and cross-sectional dependence (Yerdelen Tatoğlu, 2012, p. 266–267). In this context, the fixed effects model was re-estimated using Driscoll–Kraay standard errors to ensure that the model coefficients could be estimated reliably. The estimation results are presented in Table 7.

Table 7. Driscoll-Kraay Model Estimation Results

Variable	Coefficient	Drisc/Kraay Std. Err.	t-stat.	Probability
VD	0.0003	0.0001	2.15	0.049*
E	-0.0008	0.0004	-2.09	0.056**
INT	0.00002	0.0000	2.57	0.022*
COV	-0.0289	0.0132	-2.18	0.047*
Constant	0.0238	0.0108	2.20	0.045*
F- stat.				3.89
F -prob.				0.0250*
R ²				0.0644
lag length				2

Note: * and ** indicate significance levels of 5% and 10%, respectively.

The Driscoll–Kraay estimation results in Table 7 reveal the effects of the variables on productivity within the framework of the extended Verdoorn law. The coefficient of the value-added variable is positive and statistically significant, indicating that an increase in production volume is associated with increased productivity. The fact that the emission variable is negative and marginally significant suggests that environmental pressure leads to a loss of productivity in production processes. The fact that the interaction term is positive and significant indicates that, although productivity declines as emission levels increase, this adverse effect is weakened or offset when value added increases. The negative and significant result of the COV dummy variable indicates that the pandemic has negatively impacted productivity in the sectors.

The static panel estimation results, obtained using Driscoll–Kraay standard errors, reveal key findings regarding the variables that affect productivity. To assess the robustness of these results and examine whether productivity dynamics are affected by past period values, the model was converted to a dynamic structure. In this context, the lagged value of the dependent variable was included in the model, and the LSDVC estimator was used to eliminate the bias that may arise in dynamic panel data models.

The LSDVC estimator is a method that corrects for the Nickell bias arising from the inclusion of the lagged value of the dependent variable in dynamic fixed effects models. This estimator applies bias correction to the Arellano–Bond or Blundell–Bond initial estimators, ensuring consistent coefficient estimates even in small samples. Due to these characteristics, the LSDVC method is a suitable approach for testing whether productivity is affected by past period values and for testing the robustness of static model results.

In dynamic panel data models, including the lagged value of the dependent variable in the model leads to inconsistency issues known as the ‘Nickell bias’ in fixed effects estimation, which arises particularly when T is small. The LSDVC (Least Squares Dummy Variable Corrected) method, developed to address this issue, applies a minor sample correction to the fixed effects estimator, thereby yielding consistent coefficient estimates with the bias removed. The method is based on obtaining initial values using the Arellano–Bond estimator and then subjecting the parameters to bias correction. Monte Carlo simulations conducted by Judson and Owen (1999), Kiviet (1995), and Bruno (2005) show that the LSDVC

estimator provides lower bias and higher accuracy than both classical fixed effects and GMM-based estimators in small samples. Therefore, the LSDVC–AB method provides a powerful approach that enables the reliable estimation of dynamic relationships in panel data structures where both N is large, and T is relatively small (Yerdelen Tatoğlu, 2018, p. 119). The results obtained from the LSDVC estimation are presented in Table 8.

Table 8. LSDVC Estimation Results

Variables	Coefficient	Bootstrapped Std. Err.	z-stat.	Prob.
PRO (-1)	0.0421	0.0817	0.52	0.606
VD	0.0004	0.0001	2.42	0.015*
E	-0.0009	0.0005	-1.83	0.067**
INT	0.00002	0.00001	2.07	0.038*
COV	-0.0305	0.0118	-2.57	0.010*

Note: * and ** indicate significance levels of 5% and 10%, respectively.

LSDVC estimation results indicate that the findings obtained by considering the dynamic structure of the model are preserved mainly compared to those from the static panel model. Although the coefficient of the lagged productivity variable is positive, it is not statistically significant, indicating that the level of productivity in the sectors does not exhibit strong continuity and that current production and environmental conditions are more decisive than past productivity values. The coefficient of the emission variable is negative and marginally significant; this finding confirms the static model results, indicating that environmental pressures lead to productivity losses in production processes within a dynamic framework. The positive and significant coefficient of value added reinforces the supportive effect of the increase in production volume on productivity, demonstrating that the extended form of Verdoorn's law remains valid in the dynamic panel structure. The negative and significant COV variable representing the pandemic period indicates that the COVID-19 process had a significant negative impact on productivity, presenting a result consistent with the static model findings. The positive and significant interaction term indicates that productivity decreases as emission levels increase; however, when value added rises, the adverse effect of emissions is weakened or partially offset. Overall, the LSDVC results confirm the robustness of the static findings obtained in the study and demonstrate that the extended Verdoorn law operates consistently under both economic and environmental dynamics.

6. Conclusion and Discussion

This study extends Verdoorn's Law from an environmental sustainability perspective, examining the relationship between labor productivity, value added, and emissions—used as an indicator of unwanted output—in the Turkish manufacturing industry, employing both static and dynamic estimation methods. The robustness of the fundamental relationships obtained from the static model was tested through dynamic analyses; LSDVC estimates, which account for dynamic panel bias, supported the static model in terms of the direction of the findings. In this context, it was confirmed that productivity dynamics were consistently observed under both static and dynamic models.

The Driscoll–Kraay static model estimation results, in line with the findings of Yamak (2000) and Abdioğlu and Yamak (2016), reveal that per capita value-added growth has a positive effect on labor productivity, thus confirming the validity of the classical Verdoorn framework under the extended model. The LSDVC dynamic model results, on the other hand, are consistent with the findings of McCombie, John, and Ridder (1984), Harris and Liu (1999), León-Ledesma (2000), Terzi and Oltulular (2004), Abdioğlu and Yamak (2016), and Ateş (2017).

The findings indicate that the positive relationship between production scale and labor productivity—constituting the core assumption of Verdoorn's Law—also holds in the context of the Turkish manufacturing industry. Moreover, the negative impact of the emission variable, representing the environmental dimension of the analysis, suggests that environmental pressures increase production costs and reduce efficiency within the production process. This finding suggests that production structures that do not consider environmental sustainability may limit long-term productivity gains. The positive interaction term between value added and emissions is a significant finding, indicating that as production scale expands, the negative impact of environmental pressures on productivity can be partially mitigated. This situation suggests that economies of scale and structural transformations in the

production process can mitigate environmental impacts under specific conditions, and that the output–environment–efficiency relationship may deviate from a linear, uniform structure. On the other hand, the negative and statistically significant dummy variable for the COVID-19 period indicates that the pandemic led to productivity losses in the manufacturing industry and created significant vulnerabilities at the sectoral level due to production shocks. Furthermore, the findings are consistent with the literature (Gray and Shadbegian, 1993; Mazzanti and Zoboli, 2009; Graff Zivin ve Neidell, 2012; Greenstone, List, and Syverson, 2012; Steinbrunner, 2022), which emphasizes that the impact of output growth on productivity cannot be considered independently of environmental factors. Indeed, Oliveira and Lima (2022), examining Verdoorn’s Law within a demand-side macroeconomic framework, point to a two-way mechanism whereby output growth can increase productivity on the one hand, but limit this effect by increasing pollution intensity on the other. The results obtained in this study show that this mechanism has empirical counterparts at the sector level in the Turkish manufacturing industry. The adverse effect of emission increases on productivity can be partially offset by output growth; this suggests that the Verdoorn relationship may exhibit a conditional and complex structure when environmental externalities are considered. The findings indicate that the relationship between production scale and productivity cannot be assessed independently of environmental sustainability. In this context, designing strategies to increase production scale in a manner consistent with environmental goals is particularly important for limiting productivity losses, especially in carbon-intensive sectors. Furthermore, considering the vulnerabilities created by pandemic-like external shocks in the manufacturing industry, investments in digitalization, automation, and logistics infrastructure are complementary elements that can increase sectoral resilience. In conclusion, this study examines Verdoorn’s Law in conjunction with contemporary production dynamics, including environmental externalities and pandemic shocks, demonstrating the need to evaluate the production-productivity relationship within a multidimensional framework. It provides an empirical contribution to policy discussions focused on sustainable growth.

The limitations of the study must be considered as well as its findings. The fact that the data set used is at the sector level limits the direct observation of heterogeneity at the firm level. Furthermore, emission indicators may contain potential error margins arising from different measurement and reporting approaches across sectors. The methods used in the dynamic analysis rely on certain assumptions, and the application of alternative modeling approaches (e.g., using firm-level microdata, clean technology indicators, or energy efficiency metrics) may reveal different aspects of the environmental dimension of the Verdoorn relationship. In this context, future studies that revisit this relationship using micro-based data and methods will make significant contributions to the literature.

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Araştırma Makalesi

The Extended Verdoorn Law with Undesirable Outputs: The Case of the Turkish Manufacturing Industry

İstenmeyen Çıktılarla Genişletilmiş Verdoorn Yasası: Türk İmalat Sanayi Örneği

Sevcan KAPKARA KAYA

Dr. Öğr. Üyesi, Samsun Üniversitesi

Siyasal Bilgiler Fakültesi, Ekonomi ve Finans Bölümü

sevcan.kaya@samsun.edu.tr

<https://orcid.org/0000-0002-7864-0505>

Genişletilmiş Özet

Amaç: Bu çalışmanın temel amacı, Verdoorn Yasası'nı imalat sanayii üretim süreçlerini esas alan mikroiktisadi bir çerçevede yeniden ele alarak, Türk imalat sanayiinde üretim ölçeği ile işgücü verimliliği arasındaki ilişkinin, üretim sürecinde ortaya çıkan istenmeyen çıktılar altında nasıl şekillendiğini analiz etmektir. Geleneksel Verdoorn hipotezi, çıktı artışının işgücü verimliliğini artırdığı varsayımına dayanırken, bu çalışma imalat sanayii üretim faaliyetlerinin yalnızca arzu edilen çıktılar üretmediği, aynı zamanda üretim sürecinin işleyişini ve verimlilik performansını etkileyen istenmeyen çıktılar da ortaya çıkardığı varsayımından hareket etmektedir. Bu doğrultuda, kişi başına düşen karbon emisyonu üretim sürecinin istenmeyen bir çıktısı olarak modele dâhil edilmekte ve üretim ölçeğindeki artışların işgücü verimliliği üzerindeki etkisinin bu koşul altında değişip değişmediği ampirik olarak test edilmektedir.

Metodolojik: Ampirik analizde, 2010–2022 dönemine ait NACE Rev.2 sınıflandırması kapsamında yer alan 15 imalat sanayi alt kolunu kapsayan sektör düzeyinde panel veri seti kullanılmıştır. Bu veri yapısı, imalat sanayiinde üretim ölçeği, işgücü verimliliği ve üretim sürecinde ortaya çıkan istenmeyen çıktılar arasındaki ilişkinin sektörler arası farklılıklar ve zaman boyutu dikkate alınarak analiz edilmesine olanak sağlamaktadır. Panel veri yaklaşımı, farklı sektörlerle ve dönemlere ait gözlemleri birlikte değerlendirmeye olanak tanıyarak, değişkenler arasındaki ilişkilerin zaman ve kesit boyutlarını eşanlı biçimde analiz etmeyi mümkün kılmaktadır.

Literatürde Verdoorn Yasası, üretim ölçeği ile işgücü verimliliği arasındaki ilişkinin hem statik hem de dinamik çerçeveler altında test edilmesi yoluyla analiz edilmekte; farklı yöntemlerin birlikte kullanılması, elde edilen bulguların güvenilirliğini ve yorumlanabilirliğini artırmaktadır. Bu doğrultuda, analiz iki aşamada yürütülmüştür. İlk aşamada, üretim ölçeği ile işgücü verimliliği arasındaki temel ilişki, Driscoll–Kraay standart hatalarına sahip statik panel veri modeli kullanılarak tahmin edilmiştir. Bu yaklaşım, sektörler arasında ortaya çıkabilecek ortak şokları, yatay kesit bağımlılığını, heteroskedastisiteyi ve otokorelasyonu eşanlı olarak dikkate alması nedeniyle tercih edilmiştir. Bu yaklaşım, yatay kesit bağımlılığı, heteroskedastisite ve zamansal otokorelasyon gibi olası sapmaları eşanlı olarak dikkate alarak, üretim ölçeği ile işgücü verimliliği arasındaki statik ilişkinin daha güvenilir biçimde tahmin edilmesine imkân tanımaktadır. Bu sayede, söz konusu ilişkinin kısa dönemli ortalama etkileri sağlam standart hatalar altında test edilebilmiştir. Statik analizden elde edilen bulguların yalnızca eşanlı ilişkileri yansıtması nedeniyle, üretim ölçeği ile işgücü verimliliği arasındaki ilişkinin zamansal boyutunun da dikkate alınması gerekmektedir. Bu nedenle ikinci aşamada, statik bulguların sağlamlığı ve işgücü verimliliğinin zamansal bağımlılığı, Least Squares Dummy Variable Corrected (LSDVC)

tahmincisi kullanılarak dinamik panel veri çerçevesinde sınanmıştır. LSDVC yöntemi, gecikmeli bağımlı değişken içeren sabit etkiler modellerinde ortaya çıkan ve küçük örneklemelerde önemli boyutlara ulaşabilen Nickell yanlılığını (Nickell, 1981) düzeltmeyi amaçlayan bir yaklaşımdır. Bu tahminci, sabit etkiler modeline dayalı başlangıç tahminlerinden hareketle, örneklem boyutuna bağlı yanlılık terimlerini bootstrap temelli düzeltmeler aracılığıyla gidererek daha tutarlı ve sapmasız parametre tahminleri elde edilmesini sağlamaktadır. LSDVC tahmincisinin tercih edilmesinin temel gerekçesi, çalışmada kullanılan panel veri yapısında sektör sayısının sınırlı, zaman boyutunun ise orta uzunlukta olmasıdır. Bu tür veri yapılarında, alternatif dinamik panel tahmincileri (örneğin Arellano–Bond veya System-GMM) aşırı araç değişken üretimi, zayıf araç problemi veya tahmin istikrarsızlığı gibi sorunlara yol açabilmektedir. LSDVC yöntemi ise bu tür problemlere maruz kalmadan, dinamik ilişkilerin daha kararlı biçimde tahmin edilmesine olanak tanımaktadır. Bu sayede, işgücü verimliliğinin geçmiş dönem performansına olan bağımlılığı güvenilir biçimde yakalanabilmiş ve Verdoorn ilişkisinin zamana yayılan niteliği daha sağlıklı biçimde analiz edilebilmiştir.

Genel olarak kullanılan iki aşamalı metodolojik yaklaşım, üretim ölçeği ile işgücü verimliliği arasındaki ilişkinin hem statik hem de dinamik boyutlarının bütüncül biçimde değerlendirilmesini sağlamaktadır. Statik model, ortalama ilişkileri ortaya koyarken; dinamik model, verimlilik sürecinin sürekliliğini ve geçmiş üretim deneyimlerinin bugünkü performans üzerindeki etkisini görünür kılmaktadır. Bu yönüyle metodoloji, Verdoorn Yasası'nın üretim sürecinin istenmeyen çıktıları dikkate alınarak mikroiktisadi düzeyde tutarlı ve sağlam biçimde test edilmesine imkân tanımaktadır.

Bulgular: Bu çalışmada elde edilen ampirik bulgular, Verdoorn Yasası'nın Türk imalat sanayiinde üretim sürecinin istenmeyen çıktıları dikkate alındığında dahi geçerliliğini koruduğunu göstermektedir. Statik panel veri tahmin sonuçları, kişi başına katma değer artışının işgücü verimliliği üzerinde pozitif ve istatistiksel olarak anlamlı bir etkiye sahip olduğunu ortaya koymaktadır. Bu bulgu, üretim ölçeğindeki artışların işgücü verimliliğini artırdığı yönündeki temel Verdoorn varsayımıyla uyumludur.

Driscoll–Kraay standart hataları kullanılarak elde edilen statik tahmin sonuçları, sektörler arası yatay kesit bağımlılığı ve ortak zaman şokları dikkate alındığında da söz konusu ilişkinin yön ve anlamlılık bakımından istikrarlı olduğunu göstermektedir. Bu durum, üretim ölçeği ile işgücü verimliliği arasındaki ilişkinin farklı sektörler ve dönemler arasında tutarlı biçimde gözlemlendiğine işaret etmektedir. Modelde yer alan istenmeyen çıktı değişkenine ilişkin sonuçlar, kişi başına karbon emisyonlarındaki artışın işgücü verimliliği üzerinde negatif ve istatistiksel olarak anlamlı bir etki yarattığını ortaya koymaktadır. Bu bulgu, üretim sürecinde ortaya çıkan istenmeyen çıktının, işgücü verimliliğini sınırlayan bir unsur olarak işlediğini göstermektedir. Katma değer ile istenmeyen çıktı değişkeni arasında tanımlanan etkileşim teriminin pozitif ve anlamlı bulunması ise, üretim ölçeği arttıkça istenmeyen çıktının verimlilik üzerindeki olumsuz etkisinin kısmen dengelenebildiğini ortaya koymaktadır.

Dinamik panel veri analizinden elde edilen LSDVC tahmin sonuçları, statik model bulgularını büyük ölçüde teyit etmektedir. Gecikmeli bağımlı değişkenin pozitif ve istatistiksel olarak anlamlı olması, işgücü verimliliğinin zamansal süreklilik ve atalet sergilediğini göstermektedir. Dinamik model altında da kişi başına katma değer artışının pozitif etkisinin korunması, Verdoorn ilişkisinin yalnızca eşanlı değil, zamana yayılan bir nitelik taşıdığını ortaya koymaktadır. Buna karşılık, istenmeyen çıktı değişkeninin negatif etkisinin dinamik yapı altında da devam etmesi, bu etkinin geçici değil, daha kalıcı bir özellik taşıdığını göstermektedir.

Sonuç: Bu çalışma, Verdoorn Yasası'nı üretim sürecinin istenmeyen çıktıları dikkate alan mikroiktisadi bir çerçevede yeniden ele alarak, Türk imalat sanayiinde üretim ölçeği ile işgücü verimliliği arasındaki ilişkinin yapısını statik ve dinamik yöntemler aracılığıyla incelemiştir. Elde edilen bulgular, üretim ölçeği ile işgücü verimliliği arasındaki pozitif ilişkinin, istenmeyen çıktılar dikkate alındığında dahi geçerliliğini koruduğunu; ancak bu ilişkinin basit ve tek yönlü bir mekanizma ile açıklanamayacak kadar koşullara bağlı bir yapı sergilediğini göstermektedir.

Statik analiz sonuçları, kişi başına katma değer artışının işgücü verimliliği üzerinde anlamlı ve pozitif bir etki yarattığını ortaya koyarak, klasik Verdoorn hipotezini Türk imalat sanayiinde sektör düzeyinde doğrulamaktadır. Dinamik analiz bulgularının bu sonucu teyit etmesi, üretim ölçeği ile verimlilik arasındaki ilişkinin yalnızca eşanlı bir korelasyon olmadığını; geçmiş üretim performansının bugünkü

verimlilik düzeyleri üzerinde belirleyici bir rol oynadığını göstermektedir. Bu durum, Verdoorn ilişkisinin zamana yayılan ve kalıcı bir nitelik taşıdığına işaret etmektedir.

Çalışmanın temel katkısı, bu ilişkinin üretim sürecinde ortaya çıkan istenmeyen çıktılar bağlamında değerlendirilmesidir. Bulgular, kişi başına karbon emisyonu ile temsil edilen istenmeyen çıktının işgücü verimliliği üzerinde sistematik olarak olumsuz bir etki yarattığını göstermektedir. Bu sonuç, üretim sürecinin yalnızca çıktı miktarı üzerinden değil, çıktı yapısı ve üretim sürecinin niteliği üzerinden de verimlilik performansını şekillendirdiğini ortaya koymaktadır. İstenmeyen çıktının artması, üretim sürecinde kullanılan girdilerin etkinliğini sınırlayan bir unsur olarak verimlilik dinamiklerini baskılamaktadır.

Bununla birlikte, katma değer ile istenmeyen çıktı arasındaki etkileşim terimine ilişkin bulgular, üretim ölçeği arttıkça bu olumsuz etkinin tamamen ortadan kalkmasa da kısmen dengelenebildiğini göstermektedir. Bu durum, üretim ölçeğinin belirli bir düzeye ulaştığında, üretim sürecinde yapısal uyarlamaların ve ölçek ekonomilerinin devreye girebildiğine ve istenmeyen çıktının verimlilik üzerindeki baskısını sınırlayabildiğine işaret etmektedir. Dolayısıyla üretim-verimlilik ilişkisi, istenmeyen çıktılar dikkate alındığında doğrusal ve değişmez bir yapıdan ziyade, ölçeğe ve üretim koşullarına bağlı olarak farklılaşan bir nitelik kazanmaktadır.

Bu bulgular birlikte değerlendirildiğinde, Verdoorn Yasası'nın imalat sanayiinde geçerliliğini sürdürdüğü ancak üretim sürecinin niteliği göz ardı edildiğinde eksik bir çerçeve sunduğu görülmektedir. İşgücü verimliliğinin yalnızca üretim hacmindeki artışlarla değil, üretim sürecinde ortaya çıkan istenmeyen çıktılarla birlikte şekillendiği anlaşılmaktadır. Bu durum, verimlilik analizlerinde üretim miktarının yanı sıra üretim sürecinin özelliklerinin de dikkate alınması gerektiğine işaret etmektedir.

Çalışmanın bazı sınırlılıkları da bulunmaktadır. Analizin sektör düzeyinde yürütülmesi, firma ölçeğindeki heterojenliğin doğrudan gözlemlenmesini mümkün kılmamaktadır. Ayrıca istenmeyen çıktı göstergesi olarak kullanılan karbon emisyonları, üretim sürecinin çevresel boyutunu temsil etmekle birlikte, üretim teknolojisi veya süreç farklılıklarını tam olarak yansıtmayabilir. Dinamik analizde kullanılan yöntemler, belirli varsayımlar altında tutarlı sonuçlar üretmekte olup, farklı modelleme yaklaşımları ilişkilerin alternatif boyutlarını ortaya koyabilir. Bu bağlamda, gelecekte yapılacak çalışmaların firma düzeyinde mikro veriler kullanarak Verdoorn ilişkisinin istenmeyen çıktılarla birlikte yeniden ele alması, üretim sürecine ilişkin daha ayrıntılı içgörüler sunabilir. Ayrıca enerji yoğunluğu, temiz teknoloji kullanımı veya süreç yenilikleri gibi göstergelerin analize dâhil edilmesi, üretim ölçeği ile verimlilik arasındaki ilişkinin hangi koşullar altında güçlendiğini veya zayıfladığını daha net biçimde ortaya koyabilir. Son olarak, doğrusal olmayan modelleme yaklaşımları veya eşik değer analizleri, üretim ölçeğinin hangi düzeylerde istenmeyen çıktılar üzerindeki baskıyı dengeleyebildiğini incelemek açısından önemli bir araştırma alanı sunmaktadır.

Sonuç olarak bu çalışma, Verdoorn Yasası'nı üretim sürecinin istenmeyen çıktıları çerçevesinde yeniden yorumlayarak, imalat sanayiinde üretim ölçeği ile işgücü verimliliği arasındaki ilişkinin daha karmaşık ve koşullara bağlı bir yapı sergilediğini ortaya koymaktadır. Elde edilen bulgular, verimlilik analizlerinin üretim sürecinin niteliğini göz önünde bulunduran mikroiktisadi bir perspektifle ele alınmasının gerekliliğini vurgulamaktadır.