

Logistics 4.0: Analysis of the Impact of Countries' Digitalization and Innovation Levels on Logistics Performance with Machine Learning

Lojistik 4.0: Ülkelerin Dijitalleşme ve İnovasyon Düzeylerinin Lojistik Performans Üzerindeki Etkisinin Makine Öğrenmesi ile Analizi

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ABSTRACT

The widespread adoption of globalization and e-commerce has increased the strategic importance of logistics processes, leading to the emergence of the concept of Logistics 4.0 through the integration of Industry 4.0 technologies into the logistics sector. This situation necessitates the strengthening of logistics infrastructures by firms and countries to achieve competitive advantage. In this context, fully determining the impact of digitalization and innovation on logistics performance is of critical importance for policy-making and serves as the starting point of this study. In this study, a machine learning method, the random forest technique, is employed to assess the impact of countries' digitalization and innovation levels on logistics performance and to rank the variables influencing the Logistics Performance Index (LPI) based on their significance. According to the study's findings, research and development (R&D) expenditures, the number of patents, the level of global innovation, high-tech exports, internet usage rate, and e-government development services—considered as indicators of digitalization and innovation—explain a significant portion of the variation in LPI. Among these factors, R&D has been identified as the most critical variable. R&D activities directly influence a country's logistics performance by fostering innovation and technological progress. In this regard, investments in R&D significantly contribute to strengthening logistics infrastructure, improving processes, and enhancing the efficiency of technologies.

JEL Codes: C45, L91, O31, O33

Keywords: Digitalization, Innovation, Logistics 4.0, LPI, Machine Learning

Öz

Küreselleşme ve e-ticaretin yaygınlaşması, lojistik süreçlerin stratejik önemini artırmış ve Endüstri 4.0 teknolojilerinin lojistik sektörüne entegrasyonu ile Lojistik 4.0 kavramı ortaya çıkmıştır. Bu durum, firmaların ve ülkelerin rekabet üstünlüğü sağlamak adına lojistik altyapılarını güçlendirmelerini gerektirmektedir. Bu kapsamda dijitalleşme ve inovasyonun lojistik performans üzerindeki etkisinin tam anlamıyla belirlenmesi, izlenecek politikalar açısından kritik öneme sahiptir ve söz konusu durum çalışmanın çıkış noktasını oluşturmaktadır. Yapılan çalışmada bir makine öğrenmesi yöntemi olan rastgele orman tekniği kullanılarak ülkelerin dijitalleşme ve inovasyon seviyelerinin lojistik performans üzerindeki etkisinin belirlenmesi ve Lojistik Performans Endeksi'ni (LPI) etkileyen değişkenlerin önem derecesine göre sıralanması amaçlanmıştır. Çalışmanın bulgularına göre, modelde dijitalleşme ve inovasyonun göstergesi olarak ele alınan araştırma-geliştirme harcamaları, patent sayısı, küresel inovasyon düzeyi, yüksek teknoloji ihracatı, internet kullanım oranı ve e-devlet geliştirme hizmetleri, LPI'deki değişimin büyük bir kısmını açıklamaktadır. Bununla birlikte Ar-Ge faktörü, en önemli değişken olarak tespit edilmiştir. Ar-Ge faaliyetleri, inovasyonu ve teknolojik ilerlemeyi teşvik ederek bir ülkenin lojistik performansını doğrudan etkileyebilir. Bu doğrultuda, Ar-Ge'ye yapılan yatırımlar, lojistik altyapının güçlendirilmesine, süreçlerin iyileştirilmesine ve teknolojilerin daha verimli hale getirilmesine katkı sağlanmaktadır.

JEL Kodları: C45, L91, O31, O33

Anahtar Kelimeler: Dijitalleşme, İnovasyon, Lojistik 4.0, LPI, Makine Öğrenmesi

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Introduction

The term "Industry 4.0," which refers to the fourth industrial revolution characterized by digital transformation in the manufacturing sector, was first introduced at the Hannover Fair in 2011 and was adopted by the German government to create profound changes by digitalizing production processes and promoting automation (Xu et al., 2018). However, within the framework of Industry 4.0, the digitalization of production processes requires the interconnection and integration of all processes within and outside the enterprise, thus creating a more efficient value chain. In this context, logistics, in particular, is of great importance as it is directly related to the process and connected to other business units (Lai et al., 2010). Therefore, the digitalization of logistics processes within the scope of Industry 4.0 plays a strategic role (Moldabekova et al., 2021).

Logistics is defined as a primary activity in the value chain (Porter, 1980). It is a general acceptance that logistics and its subcomponents play a critical role in the effective implementation of business strategies through distribution flexibility and rapid response ability (Daugherty & Pittman, 1995). The expansion of economic boundaries from the local to the international level under the influence of globalization has caused the logistics sector to take on a very dynamic structure today. This variable and competitive environment directs companies and countries to develop and differentiate their logistics competencies. Within this context, the concept of "Logistics 4.0" has emerged as a result of the integration of Industry 4.0 technologies into the logistics field. Logistics 4.0 is defined as the planning of storage and transportation processes of raw materials, semi-finished products and final products using advanced technology in order to meet customer expectations. Today, digitalization and innovative approaches in logistics processes are considered as the basic elements of differentiating logistics capabilities and achieving high logistics performance (Acar & Günsel, 2010).

Digitalization, which is considered a technological innovation and is essentially an innovation (Çetiner & Bayat, 2023), provides important contributions such as facilitating access to information for the supply chain, optimizing logistics processes, obtaining real-time data, more effective inventory management and increasing transparency (Hettterscheid & Schlüter, 2019). Therefore, it has become an important requirement for companies and

countries to develop their logistics infrastructures in order to increase their logistics performance and obtain a larger share of world trade. In this context, determining the impact of digitalization and innovation on logistics performance is of critical importance in terms of the policies to be followed and this situation constitutes the starting point of the study.

When evaluating the studies in the literature regarding the impact of digitalization and innovation on logistics performance, it has been observed that there is still a lack of sufficient applied research, and the existing applied studies are predominantly conducted at the firm level, with few studies focusing on the country level. In applied studies, the preference of similar analysis methods such as multi-criteria decision-making techniques, regression and correlation analyses has been evaluated as another deficiency. In addition to these, in studies examining the impact of digitalization and innovation on logistics performance at the country level, a single index or data has generally been used as digitalization and innovation indicators, and as in studies on European Union countries, a small number of countries have been evaluated. In this context, the study, which was conducted based on the gap in the literature, aimed to determine the impact of countries' digitalization and innovation levels on logistics performance by using the random forest technique, a machine learning method. In addition, another aim of the study is to rank the variables affecting the LPI according to their importance using the model that shows the highest accurate prediction performance. In the study, the number of patent applications, R&D expenditures and global innovation level as innovation indicators; high-tech exports, percentage of individuals using the internet in the population and e-government development service as digitalization indicators; The LPI was used as the logistics performance indicator and countries with data in all indicators for the years 2010, 2012, 2014, 2016 and 2018 were included in the study. A total of 325 observations were analyzed on a country and year basis and the factors affecting the LPI were ranked according to their importance as a result of the analysis. At the end of the study, determining the most critical factors that countries that want to improve their LPI scores in the context of innovation and digitalization should focus on is an important contribution of the study to the business world and literature.

Logistics 4.0

Throughout history, new technologies and changes in

the way we perceive the world have radically transformed economic and social structures and have always been the trigger for revolutions (Schwab, 2017). The Industrial Revolution was built on the foundations laid by the Agricultural Revolution, which facilitated the transition to industrial production with technological innovations in agriculture (Harding, 2013). The First Industrial Revolution, which began in the mid-17th century, introduced mechanical facilities to the world and mass production began thanks to steam and motorized machines. In addition, the first revolution is also considered the beginning of industrial culture, where small businesses transformed from serving a limited number of customers to a large organization with thousands of employees. Later, the main contribution to the Second Industrial Revolution, which began in the 1870s, was the development of electric machines (Loy et al., 2021). The Third Industrial Revolution (Industry 3.0), which began in the mid-20th century, is characterized by the rise of digital manufacturing technologies. With the integration of computers into production processes, major developments have occurred in production planning, control and management systems (Özsoylu, 2017). Then, Industry 4.0, which started in the 2000s, represents an important beginning in human history. Because the focus is based on digitalization technologies rather than the discovery of a new energy source. It is characterized by comprehensive automation, smart factories and the integration of digital technologies such as robotics, big data and cloud computing, and includes technologies that increase productivity, efficiency, flexibility and intelligent decision-making in production processes (Gurrula & Choudhary, 2024).

One of the sectors where Industry 4.0 has made its greatest impact is logistics. The goal of logistics is to deliver the right goods to the right place at the right time, based on axioms related to the movement of products within time, within the framework of spaces and relationships. Logistics has a more complex structure than other sectors. This complexity is due to the simultaneous sequencing of many steps and their flexible interconnection. Planning logistics distribution systems is one of the most complex tasks of modern information technologies (Hompel & Henke, 2020). Managing global logistics systems and adapting to new demands in a dynamic and customer-oriented manner is becoming increasingly important. Therefore, based on the assumption that Industry 4.0 has realized the mass customization paradigm, a suitable system, Logistics 4.0, is needed (Winkelhaus & Grosse, 2019). According to Winkelhaus and Grosse (2019), who offer a general definition, Logistics 4.0 is a logistics system

that accelerates the digital transformation of industry and trade, maximizes customer satisfaction and prioritizes sustainability. After all, logistics has been seen as the first sector to physically implement Industry 4.0, the Internet of Things and artificial intelligence processes. Smart freight carriers, autonomous and driverless transport systems are the first physical examples of this (Hompel & Henke, 2020).

Digital technologies, particularly artificial intelligence and the internet of things, enable more effective monitoring and management of supply chains and significantly enhance operational efficiency by automating processes, increasing visibility and supporting real-time decision making. These technologies facilitate better resource management and sustainability, ultimately leading to cost savings and competitive advantages (El Baki & Andaloussi, 2024).

Logistics Performance

With the acceleration of globalization, the logistics sector has become an indispensable part of modern economies, playing a critical role in all processes ranging from production to consumption. Including various services such as raw material supply, production, distribution, transportation, customs clearance, storage and inventory management, logistics is the locomotive of the service sector in many countries today (Sezer & Abasis, 2017).

As in any market system, there is competition between market participants, namely countries, on a global scale. Globalization and increasing competition have made logistics one of the basic elements of international trade (Polat et al., 2023). Effective logistics services and advanced infrastructures optimize the international flow of goods, ensuring that products are transported between countries safely, quickly and with cost advantage (Liu, 2024). The importance of logistics lies in its ability to effectively solve transportation, storage and packaging problems. This increases the competitiveness of businesses and therefore countries, and countries increasingly realize the importance of logistics in global trade (Sénquiz-Díaz, 2021).

To develop competitive advantage in logistics, governments need to evaluate the current country-level logistics system, create policies to improve transportation relations (Kabak et al., 2018), and determine which subsystems should be optimized or completely removed (Jhawar et al., 2017). Therefore, the need to develop a special system to measure the logistics performance of

countries and to create strategies to increase country performance has arisen.

Country-based logistics performance assessments contribute to the creation of roadmaps for development by measuring a country's logistics competitiveness. The most notable of logistics performance assessments is the LPI, which measures the perceived logistics performance of nations using the World Bank's biennial survey of shippers and carriers. The LPI is the only measure of national logistics performance for a large number of countries. This index aims to evaluate how countries rank in terms of managerial and physical efficiency and their competitiveness in global trade. Published at regular intervals since 2007 (Arvis et al., 2023), the LPI serves as a crucial tool for identifying differences in logistics performance across countries and analyzing the underlying factors contributing to these disparities. The LPI shows how critical it is for countries to increase their capacity to connect companies, suppliers and consumers, while also creating local-scale assessments for ports and other logistics elements. The index focuses on critical components of logistics processes such as the efficiency of customs procedures, logistics costs and the quality of transportation infrastructure, allowing countries to evaluate the overall status and effectiveness of their logistics infrastructure. The LPI also provides an important statistical contribution in terms of creating a standard scale for all countries to determine the difficulties countries face in bilateral trade and their needs related to existing logistics facilities (Marti et al., 2014). When calculating the LPI, the World Bank defines six indicators in its methodology section as follows (Arvis et al., 2023):

- **Customs:** Measures the efficiency and effectiveness of the customs clearance process, including the speed, simplicity, and predictability of customs procedures and institutions.
- **Infrastructure:** Assesses the quality of transport-related infrastructure, such as telecommunications, information technology, ports, and railways, which support trade and transportation.
- **International Shipments:** Evaluates the ease of arranging competitively priced shipments.
- **Service Quality:** Measures the quality and adequacy of logistics services provided by transport operators and customs brokers.

- **Tracking and Tracing:** Assesses the ability to track shipments and the efficiency of monitoring consignments.

- **Timeliness:** Measures how frequently logistics service providers deliver shipments within the scheduled or expected time frames.

High logistics performance facilitates access to new markets by transporting goods and services faster, more reliably and at lower costs. This increases international trade and encourages business. Therefore, logistics is in a critical position in international competition (Ekici et al., 2016). While high logistics performance is of great importance in increasing the international trade volumes of countries; on the contrary, inadequate logistics infrastructure and services limit the integration in international supply chains, weakening the global competitiveness of countries. Therefore, it is very important for countries to constantly evaluate and compare their logistics performance in order to optimize logistics processes and increase efficiency in international trade (Hadžikadunić et al., 2023).

The Impact of Digitalization and Innovation on Logistics Performance

Digitalization, which is defined as the transformation of the field of activity from physical to virtual (Plekhanov et al., 2023), stands out as a critical disruptive force triggered by Industry 4.0 (the fourth industrial revolution) and radically changing approaches to business processes. Industry 4.0, which is at the center of digitalization and automation (Xu et al., 2018), has rapidly improved production processes, optimized existing methods, enabled the adoption of new technologies, and significantly expanded the size and scale of industrial production. Indeed, the main idea of Industry 4.0 is to create smart factories that perform environmentally friendly, flexible, and efficient production with consistently high quality and low cost by integrating advanced technologies such as the Internet of Things (IoT) and artificial intelligence into business processes (Wang et al., 2016). However, in today's intensely competitive environment, it has been determined as a priority for smart factories to respond quickly to changing demands and to manage material flows dynamically. This flexibility goal necessitates real-time integration between smart factories and logistics processes. In other words, it is not possible to transition to the smart factory model within the framework of Industry 4.0 without logistics processes becoming "smart" (Kagermann, 2015).

Industry 4.0, referred to as the new industrial revolution, necessitates digital transformation in the field of logistics, as well as in all business processes. Digitalization in logistics operations provides companies with a critical advantage in meeting the requirements of the Industry 4.0 era in transportation, inventory management, storage, supply and return processes. These advantages contribute to the improvement of logistics performance, especially by providing high flexibility and efficiency (Sorkun, 2020). As a matter of fact, today, it has become a necessity for countries to develop their logistics processes and infrastructures in order to get a larger share of world trade and increase their competitiveness. Advantages offered by digitalization, such as instant data collection, ease of access to information, more simplified transactions, effective inventory management and transparency, have significantly contributed to the optimization of logistics operations and accelerated the development of infrastructures (Hettterscheid & Schlüter, 2019). In addition, thanks to the digitalization of logistics, digital platforms make it possible to overcome time and space constraints. Through digitalized logistics infrastructures, providers and consumers can access the movement of resources anytime, anywhere. Therefore, digitalization stands out as one of the most effective methods of improving logistics performance (Xu et al., 2023).

A review of the literature reveals that, particularly in recent years, several studies have produced significant findings regarding the relationship between digitalization and logistics performance (Çetiner & Bayat, 2023; Gong et al., 2022; Kayıkçı, 2018; Moldabekova et al., 2021; Parfenov et al., 2021). Parfenov et al. (2021), in their study examining the impact of digitalization on the development of logistics, found that digitalization plays a crucial role in enhancing logistics performance. Their research highlights several benefits, such as reducing cargo waiting times at state borders through electronic customs declarations, decreasing the need for long-term forecast-based supply planning through improved information awareness, and improving infrastructure by integrating e-commerce channels into logistics processes. Gong et al. (2022), in their study on the effects of digitalization in China's logistics sector, found that digitalization enhances resource distribution efficiency and that the increased information sharing and transparency through electronic platforms streamline regulations, thereby reducing bureaucracy. Kayıkçı (2018) examined manufacturing companies and transportation service providers, emphasizing the positive effects of digitalization on economic sustainability in logistics processes, particularly

in terms of delivery time, logistics costs, and flexibility. In the study conducted by Moldabekova et al. (2021), the impact of digitalization on logistics performance was examined, and in this context, data from the Digital Economy and Society Index and the Logistics Performance Index were used. The research concluded that government policies should promote human capital (e.g., information and communication technology specialists), the sustainable use of internet services (such as professional social networks, online sales, etc.), the integration of digital technologies (such as cloud computing, big data, etc.), and digital connectivity (fixed broadband and 4G coverage) to improve logistics performance. Similarly, Çetiner and Bayat (2023), using a simple linear regression analysis with DESI and LPI data, found that the Digital Economy and Society Index explains 32.1% of the variance in the LPI.

Another important concept associated with Industry 4.0 is innovation, and the development of this new industrial revolution with technological advances is made possible by the contributions provided by innovation. Innovation means the development, adoption and implementation of new ideas, products and processes (Najib & Kiminami, 2011). Strengthening the innovation infrastructure and the implementation of different types of innovation accelerate technological advances and increase digitalization in production processes (Shamim et al., 2016). Moreover, while processes and products in the manufacturing sector are being innovatively developed today, the value chain approach has gained prominence as this transformation encourages other firms involved in the value chain. Innovation is also of great significance for the logistics sector. With the globalizing economy and increasing competitive pressure, many companies have focused on innovation in order to improve their logistics performance, provide cost advantage and gain competitive advantage in service (Zhao & Wang, 2010). In other words, while logistics activities play a key role in the successful implementation of business strategies, innovation increases the effectiveness, profitability, customer satisfaction and competitiveness of these activities (Helvacioğlu & Demirkol, 2023). In addition, it is expected that customer demands and needs will be determined accurately and the time between order and delivery will be shortened by increasing operational efficiency thanks to innovation in logistics processes (Griese & Sieber, 2000).

Studies in the literature (Acar & Günsel, 2010; Bakan & Şekkeli, 2016; Burmaoğlu, 2012; Çetiner & Bayat, 2023; Helvacioğlu & Demirkol, 2023) prove that innovation

contributes to the increase in logistics performance at both the country and firm levels. For example, Acar and Günsel (2010) revealed in their study that there is a significant relationship between innovation in logistics services and logistics capabilities, competitive advantage and logistics performance. Similarly, Bakan and Şekkeli (2016) determined in their research that logistics innovation capability is an important element that increases competitive advantage and logistics performance. In another study conducted by Çetiner and Bayat (2023), which compared the logistics performances of countries with their innovation levels, it was found that innovation explains 54.2% of the variation in logistics performance. The study concluded that human capital and research factors, in particular, have a significant impact on logistics performance.

When the studies on the impact of digitalization and innovation on logistics performance were evaluated, it was seen that there were not yet enough applied studies and applied studies were mostly conducted at the firm level, and there were few studies at the country level. Another deficiency was that similar analysis methods such as multi-criteria decision-making techniques, regression and correlation analyses were generally preferred in applied studies. In addition to these, in studies examining the impact of digitalization and innovation on logistics performance at the country level, a single index or data was generally used as digitalization and innovation indicators, and as in studies on European Union countries, a small number of countries were evaluated. In this study, a machine learning method known as the Random Forest technique is employed to determine the impact of countries' levels of digitalization and innovation on logistics performance. Information on the methodology of the research will be detailed in the next section.

Material and Methods

Machine learning, a discipline that allows computers to learn from data, plays an important role in data analysis and modeling processes (Mitchell, 1997). Machine learning algorithms are divided into three main categories: supervised, unsupervised, and reinforcement learning. The main distinction between the two most basic methods, supervised and unsupervised learning, stems from the logic of whether the data it works on is labeled or not. Supervised learning methods work on labeled data. In this study, the Random Forest algorithm, which is one of the supervised learning methods, has been utilized.

Random Forest is an ensemble learning method proposed by Breiman (2001). It is based on the principle of combining multiple decision trees to form a more powerful model. Random Forest is an algorithm that uses decision trees as base models and follows the bagging (bootstrap aggregating) method in ensemble learning. Bagging is a technique where base models are trained on datasets generated through various resampling techniques (bootstrap), and the predictions from these models are then aggregated. "Bagging" is the abbreviation of the term "bootstrap aggregating." Random Forest relies on the concepts of diversity, ensemble decision-making, and randomness. More specifically, in its working principle, random samples with replacement are drawn from the original dataset. Each selected sample is then used to train a different decision tree. During the splitting phase of each decision tree, a random subset of features is used instead of considering all available features. This ensures that trees learn independently from each other (Breiman, 2001). In classification tasks, each tree produces a class prediction, and the class with the highest number of votes (majority voting) is chosen as the final prediction (Liaw & Wiener, 2002). In regression problems, the final prediction is determined by calculating the average of the predictions made by all trees.

Random forest offers many advantages thanks to its underlying logic. The most important of these is its predictive performance. It works effectively especially on high-dimensional datasets and offers high accuracy rates (Hastie et al., 2009). It is also more resistant to overfitting due to the heterogeneity between trees. On the other hand, it provides a useful metric for determining which features are more important in the model's decision-making process. This serves to increase the understandability and clarity of the underlying model, thus facilitating a deeper understanding of its mechanisms and decision-making processes. It can be used in both classification and regression problems. It is robust to incomplete datasets and has the ability to handle both categorical and numerical attributes simultaneously. In addition to these advantages, there are several notable disadvantages. The most important of these is the computational cost. Creating a large number of trees in large datasets is computationally expensive. Creating a significant number of trees in extensive datasets results in significant computational costs. The time required for training can be extended, especially in the case of deep trees and extensive datasets. A large amount of trees combined with large datasets can lead to significant memory consumption (Breiman, 2001).

Data Set and Analysis

The institutions from which the data used in the study were obtained are shown in Table 1. Within the scope of the innovation indicator, it was determined that R&D expenditures, the number of patent applications, and the global innovation level are accepted as standard measures for assessing innovation potential and output in many studies in the literature (Archibugi & Pianta, 1994; Burmaoğlu, 2012; Çetiner & Bayat, 2023; Nasir & Zhang, 2024), and they were included in the study as independent variables. In addition, other independent variables included in the study—high-technology exports, individuals using the internet in the population, and the e-government development service—are frequently used in academic studies (Moldabekova et al., 2021; Özsoy et al., 2022; Usta & Bilici, 2022) to demonstrate the prevalence of digitalization in economic and social spheres. The dependent variable selected was the LPI, as the LPI comprehensively measures key components such as countries' logistics infrastructure, customs, international shipments, tracking and tracing, thereby enabling international comparison of logistics performance (Arvis et al., 2023). To analyze the changes between digitalization and innovation indicators and global logistics performance, the years 2010, 2012, 2014, 2016, and 2018 were taken as the basis, and a total of 325 observations by country and year were analyzed. The countries with no data available for the relevant years have been removed from the dataset. The data of this study are available on the Harvard Dataverse.¹

During the analysis phase, the dataset was first divided into 75% training and 25% testing sets. The base model was trained using the training dataset. The model's prediction performance was evaluated using metrics such as Mean Absolute Error (MAE), Mean Squared Error (MSE), and R-squared (R^2). To improve the model's performance, hyperparameter optimization was conducted. A grid search was performed for the maximum number of nodes (maxnodes) and the number of trees (ntree) parameters. The model trained with the optimal parameters was analyzed using both performance evaluation metrics and visualizations of feature importance levels. Additionally, the model's reliability was assessed through a detailed examination of cross-validation results.

Table 1.

Data Sources

Variables	Source of Data
LPI	World Bank
Number of Patent Applications	World Bank
Global Innovation Level	World Intellectual Property Organization
High Technology Exports Research and Development Expenditure	World Bank
Individuals Using the Internet (% of Population)	World Bank
E-Government Development Service	United Nations

After the hyperparameter optimization process, the best parameters were determined as 80 for the maximum number of nodes and 1300 for the number of trees. The performance metrics of the optimized Random Forest model are presented in Table 2.

Table 2.

Performance Metrics

Metric	Value
Mean Absolute Error (MAE)	0.187
Mean Squared Error (MSE)	0.059
R^2	0.808

These results show that the model provides a fairly good overall fit and achieves high prediction accuracy on the data set. In particular, the R^2 value indicates that the model can explain approximately 80% of the variance in the target variable. This reveals that the optimized parameters are effective in improving the model performance.

Results and Discussion

The study aims to determine the impact of countries' digitalization and innovation levels on logistics performance. The analysis results indicate that the R^2 value of the model in Table 2 demonstrates the proportion of variance in the dependent variable (LPI) explained by the independent variables. In this context, an R^2 value of 0.808 suggests that the model has a high explanatory power. In other words, the fact that R^2 is at the 80% level implies that the R&D expenditures, number of patents, global innovation level, high-tech exports, internet usage rate,

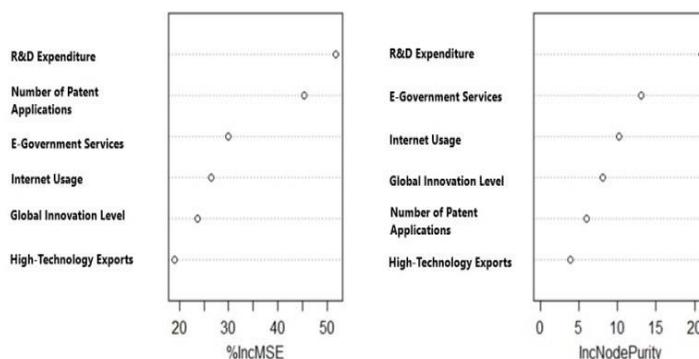
¹ <https://doi.org/10.7910/Dvn/JN5MYA>

and e-government development services—which are used in the model as indicators of digitalization and innovation—explain a significant portion of the variation in LPI. This finding highlights that the selected independent variables have a strong impact on the LPI and that the model possesses a high explanatory capability. As a result, the calculated R^2 value confirms the high reliability of the model and indicates that the independent variables have a significant effect on LPI. Furthermore, the findings align with previous studies in the literature that examine the relationship between digitalization, innovation, and logistics performance at the country level (Burmaoğlu, 2012; Çetiner & Bayat, 2023; Moldabekova et al., 2021).

However, another aim of this study is to rank the variables affecting LPI according to their importance using the model that shows the highest accurate prediction performance. In this context, the analytical importance of each variable integrated into the model was examined by considering both prediction accuracy and structural composition. The evaluation was carried out using two basic measurements. These are; change in mean squared error (%IncMSE) and increase in node purity (IncNodePurity) metrics. %IncMSE shows the effect of each variable on the prediction accuracy of the model. The increase in mean squared error (MSE) in the event of the removal of a variable indicates the relative importance of that variable on the model performance. The variables with the highest value in this metric are the variables that contribute the most to the prediction power of the model. IncNodePurity shows the degree to which each variable increases the node purity in the model. In other words, if the inclusion of a variable facilitates the capacity of the model to make more precise differentiations, it is concluded that the effect of this variable on the purity of the node is important. Both metrics provide different perspectives to evaluate the impact of variables on the effectiveness of the model. The variable importance levels are visualized in Figure 1 using these metrics.

Figure 1.

Importance Levels of Variables



As a result of this analysis, R&D (Research and Development)—included in the study as an innovation indicator—has been identified as the most significant variable in both evaluation metrics. This finding indicates that R&D is the most influential factor in enhancing the model's effectiveness. In other words, R&D is the key determinant of a country's logistics performance. Indeed, R&D activities can have a direct impact on logistics performance by fostering innovation and technological advancements. Investments in R&D contribute significantly to the development of logistics infrastructure, processes, and applied technologies. Similarly, a study conducted by Çetiner and Bayat (2023), which compared countries' logistics performance with their innovation levels, found that innovation explains 54.2% of the variation in logistics performance. The study also concluded that research-related factors, such as human capital, the number of researchers, and research expenditures, have a significant impact on logistics performance.

Although e-government services, internet usage and the number of patents are less important than R&D, they still contribute significantly to the general framework of the model. It can be said that digitalized public services will increase the efficiency of logistics processes by accelerating customs procedures, document management and trade transactions. In this context, countries' e-government systems stand out as one of the critical factors shaping logistics performance. Advanced e-government services create a positive impact on logistics performance by reducing bureaucratic barriers and facilitating cross-border trade. In other words, the use of electronic documents, traceability and digitalization of processes

directly contribute to the increase in LPI. Similarly, Parfenov et al. (2021) investigated the impact of digitalization on the development of logistics and highlighted several benefits. These include the reduction of cargo waiting times at national borders due to electronic customs declarations, a decreased need for long-term forecast-based supply planning as a result of increased information awareness, and the improvement of infrastructure through the integration of e-commerce channels into logistics processes. Gong et al. (2022), in their study on the effects of digitalization in the logistics sector in China, found that digitalization made the distribution of resources more efficient and simplified regulations thanks to increased information sharing and transparency through electronic platforms, which reduced bureaucracy.

The internet's contribution to the digitalization of logistics processes and its expected role in strengthening communication networks is a given. This variable positively impacts logistics performance by supporting fast and reliable data flow. A high internet usage rate in countries allows logistics operations to be carried out more securely and quickly in a digital environment. This not only increases the efficiency of processes but also enhances tracking and traceability. Therefore, it can be said that the internet is a critical infrastructure component for logistics performance. Similarly, Moldabekova et al. (2021), in their study examining the impact of digitalization on logistics performance, utilized data from the digital economy and society index and the LPI. They concluded that government policies aimed at improving logistics performance should support human capital (e.g., information and communication technology specialists), the sustainable use of internet services (professional social networks, online sales, etc.), the integration of digital technologies (cloud computing, big data, etc.), and digital connectivity (fixed broadband and 4G coverage).

Another important variable, the number of patents, can be evaluated together with the R&D factor. Considering that patents reflect the commercialization capacity of innovative technologies and solutions in a country, a high number of patents indicates that original technologies and innovations that can be used in logistics processes have developed. This contributes to the improvement of logistics performance. The adoption of innovative solutions in the logistics sector helps speed up operations and reduce error rates, making processes more efficient.

The variables of high-tech export and global innovation level have a lower effect on the model compared to other

variables. The production and use of high-tech products indicate the existence of a technological infrastructure that supports logistics performance. However, it was determined that this variable has a relatively lower effect compared to other factors. Although it is possible to carry out logistics operations with more advanced technologies in countries where the high-tech sector is developed, it was observed that this element is not as decisive on logistics performance as other variables. This situation reveals that logistics performance depends not only on high technology but also on the efficient management of processes. On the other hand, the global innovation level variable represents a country's general innovation capacity and the level of innovative activities. Countries with a high level of innovation can also gain competitive advantage by adopting more innovative solutions in the field of logistics. This variable can be considered as an indirect factor in increasing logistics performance.

Conclusion and Recommendations

In recent years, digitalization and innovation steps have had a revolutionary impact in various areas of business and industry, including logistics. In the context of globalization and increasing competition, the efficiency of logistics systems is becoming critical to achieving competitive advantage and ensuring the sustainable development of organizations. In line with current technological trends, increasing global competition and rapidly changing customer demands, companies and countries are forced to re-evaluate the opportunities offered by digitalization and innovation in order to better manage their supply chain activities (Golubtsov et al., 2024). Digitalization is seen as a fundamental driving force for the logistics sector in terms of significantly improving logistics efficiency, cost and user experience through innovation and advanced technology.

The logistics sector is undergoing significant transformations as a result of the worldwide digitalization movement. Logistics 4.0 refers to the digital transformation of the logistics sector with technologies such as artificial intelligence, IoT and big data. This transformation increases operational efficiency while making processes smarter and more optimized. Digitalization enables more effective monitoring and management of supply chains by automating logistics processes through the integration of these technologies (El Baki & Andaloussi, 2024). Strengthening the innovation infrastructure and implementing different types of innovation accelerate technological advances and increase digitalization in production processes (Shamim et al., 2016). However, while processes and products are being

developed in an innovative way in the production sector today, the value chain approach comes to the fore as this change encourages other companies included in the value chain, and innovation is of great importance for the logistics sector (Zhao & Wang, 2010).

With the dynamic emergence of Logistics 4.0, country-based logistics performance evaluations can contribute to the creation of roadmaps for improvement by measuring a country's logistics competitiveness. In this context, the study examines the impact of countries' digitalization and innovation levels on their logistics performance. In the literature, it is observed that empirical studies generally prefer similar analytical methods such as multi-criteria decision-making techniques, regression, and correlation analyses. Moreover, in studies investigating the impact of innovation and digitalization on logistics performance, typically a single index or data is used as digitalization and innovation indicators, and the number of countries evaluated remains limited. In this study, however, the random forest technique was used to determine the impact of countries' digitalization and innovation levels on logistics performance and to rank the factors with the most significant impact on logistics performance. According to the findings of the study, R&D expenditures, number of patents, global innovation level, high-tech exports, internet usage rate, and e-government services, which are considered indicators of digitalization and innovation in the model, explain a large portion of the change in the LPI. Furthermore, R&D activities can directly affect a country's logistics performance by promoting innovation and technological advancement. In this regard, investments in R&D contribute significantly to strengthening logistics infrastructure, improving processes, and making the technologies used more efficient. Therefore, countries should prioritize R&D expenditures to enhance logistics performance.

While e-government services, internet usage, and the number of patents are of less importance compared to R&D, they still make a significant contribution to the overall framework of the model. Given that the use of digital documentation and electronic document circulation are key functions of digitalization, it is highly likely that logistics processes can be made more efficient, especially through e-government services and the internet, which ensure traceability of processes. However, the variables of high-tech exports and global innovation level have a lower impact on the model compared to other variables. The lower impact of these two variables on logistics performance may be due to their broader scope compared

to other variables. The study highlights the importance of more specific indicators.

At the end of the study, identifying the most critical factors that countries should focus on to improve their LPI score is believed to make a significant contribution to both business practices and the literature. However, the main limitation of the study is the use of data from only five years. Future studies could examine the impact of variables on the LPI more comprehensively by using newly published data and increasing the number of independent variables. A comprehensive study could be conducted on the impacts of digitalization and innovation tools in terms of green logistics and sustainability.

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Genişletilmiş Özet

Küreselleşme ile birlikte ülkeler arasındaki mal, hizmet, sermaye ve bilgi akışı önem kazanmış ve bu durum dış ticaretin hızlı bir şekilde büyümesine yol açmıştır. Dış ticaretin gelişimi, ülkelerin endüstriyel pazardaki konumunu ve payını etkilemekle birlikte ekonomik büyüme noktasında önemli fırsatlar sunmaktadır. Bununla birlikte son yıllarda e-ticaretin artmasıyla lojistik faaliyetler de daha çok önem kazanmış ve küresel rekabette hız, esneklik, kalite ve maliyet kavramları ön plana çıkmıştır. Bu dinamik ve rekabetçi ortam, firmaları ve ülkeleri lojistik yetkinliklerini geliştirmeye ve farklılaştırmaya yönlendirmektedir. Bu çerçevede, yeni nesil teknolojiler olarak kabul edilen Endüstri 4.0 teknolojilerinin, lojistik alanına entegrasyonu sonucunda Lojistik 4.0 kavramı ortaya çıkmıştır. Lojistik 4.0 teknolojileri temelinde lojistik süreçlerdeki dijitalleşme ve inovatif yaklaşımlar, lojistik yeteneklerin farklılaşmasının ve yüksek lojistik performans elde etmenin temel unsuru olarak değerlendirilmektedir. Dolayısıyla firmaların ve ülkelerin, lojistik performanslarını artırabilmesi ve dünya ticaretinden daha büyük bir pay elde edebilmesi için lojistik altyapılarını geliştirmesi önemli bir gereklilik haline gelmiştir. Bu kapsamda dijitalleşme ve inovasyonun lojistik performans üzerindeki etkisinin tam anlamıyla belirlenmesi, izlenecek politikalar açısından kritik öneme sahiptir ve söz konusu durum çalışmanın çıkış noktasını oluşturmaktadır.

Amaç: Yapılan çalışmada ülkelerin dijitalleşme ve inovasyon seviyelerinin lojistik performans üzerindeki etkisinin belirlenmesi ve Lojistik Performans Endeksi'ni (LPI) etkileyen değişkenlerin önem derecesine göre sıralanması amaçlanmıştır.

Yöntem: Yapılan çalışmada bir makine öğrenmesi yöntemi olan rastgele orman tekniği kullanılmıştır. Çalışmada, inovasyon göstergeleri olarak patent başvurusu sayısı, Ar-Ge harcamaları ve küresel inovasyon düzeyi; dijitalleşme göstergeleri olarak yüksek teknoloji ihracatı, nüfus içinde internet kullanan bireylerin yüzdesi ve e-devlet geliştirme hizmeti; lojistik performans göstergesi olarak ise LPI kullanılmış ve 2010, 2012, 2014, 2016 ve 2018 yıllarına ait tüm göstergelerde verisi bulunan ülkeler çalışmaya dahil edilmiştir. Toplam 325 gözlem ülke ve yıl bazında analiz edilmiş ve analiz sonucunda LPI'yi etkileyen faktörler önemlerine göre sıralanmıştır.

Bulgular: Çalışmanın bulgularına göre, modelde dijitalleşme ve inovasyonun göstergesi olarak ele alınan Ar-Ge harcamaları, patent sayısı, küresel inovasyon düzeyi, yüksek teknoloji ihracatı, internet kullanım oranı ve e-devlet geliştirme hizmetleri, LPI'deki değişimin büyük bir kısmını açıklamaktadır. Bununla birlikte araştırma ve geliştirme (Ar-Ge) faktörü, en önemli değişken olarak tespit edilmiştir.

Sonuç: Ar-Ge faaliyetleri, inovasyonu ve teknolojik ilerlemeyi teşvik ederek bir ülkenin lojistik performansını doğrudan etkileyebilir. Bu doğrultuda Ar-Ge'ye yapılan yatırımlar, lojistik altyapının güçlendirilmesine, süreçlerin iyileştirilmesine ve kullanılan teknolojilerin daha verimli hale getirilmesine önemli katkılar sağlamaktadır. Dolayısıyla ülkeler, lojistik performansı artırma noktasında Ar-Ge harcamalarına öncelik vermelidir.