ISSN 2560-421X

UDK 33+502/504

ECONOMICS

of Sustainable Development

1

Vol. IX

Niš, 2025

ECONOMICS OF SUSTAINABLE DEVELOPMENT
ЕКОНОМИКА ОДРЖИВОГ РАЗВОЈА

ДРУШТВО ЕКОНОМИСТА "ЕКОНОМИКА" НИШ
SOCIETY OF ECONOMISTS "EKONOMIKA", NIS

The Journal is issued two times a year. Year IX, I-VI 2025, Vol. 1

ECONOMICS
OF SUSTAINABLE DEVELOPMENT

PUBLISHER: Society of Economists "Ekonomika", Nis

EDITORIAL BOARD

Lector
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Bank Account: 160-19452-17

Printed by:
“MEDIVEST”
18000 Niš
Copies: 200

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ECONOMICS OF SUSTAINABLE DEVELOPMENT

Vol. 9, January-June 2025, № 1
UDK 33+502/504
ISSN 2560-421X

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P. 1-28
ORIGINAL SCIENTIFIC ARTICLE
10.5937/ESD2501001P
Received: August 25, 2024
Accepted: January 19, 2025

ARTIFICIAL INTELLIGENCE ADOPTION AND ITS INFLUENCE ON CIRCULAR MATERIAL USE: AN EU CROSS-COUNTRY ANALYSIS

Abstract

This research study examines the relationship between Artificial Intelligence (AI) adoption and Circular Material Use Rate across 27 EU member states (2021-2023). Using panel data econometrics and Random Forest machine learning, it analyzes the direct and non-linear effects of AI adoption on circular economy outcomes. Results show no statistically significant direct impact of AI on circular material use rate (CMUSE) when controlling for economic factors. Resource Productivity emerges as the strongest predictor, with GDP per capita playing a crucial moderating role. The Random Forest model explains 48.58% of CMUSE variance. The study provides evidence that AI investments should align with initiatives of increasement of resource efficiency and with economic development policies. The findings emphasize the need for tailored interventions considering technological readiness and economic capacity variations across EU states, contributing to sustainable development policy design.

Keywords: *Artificial Intelligence, Circular Economy, Circular Material Use Rate, European Union, Resource Productivity, Sustainable Development*

JEL classification: *O33, Q55, O52, Q56*

УСВАЈАЊЕ ВЕШТАЧКЕ ИНТЕЛИГЕНЦИЈЕ И ЊЕН УТИЦАЈ НА ЦИРКУЛАРНУ УПОТРЕБУ МАТЕРИЈАЛА: АНАЛИЗА ЗЕМАЉА ЕУ

Апстракт

Овај рад анализира однос вештачке интелигенције и стопе циркуларне употребе материјала у 27 држава ЕУ (2021-2023). Комбинованим приступом економетрије панел података и Random Forest машинског учења, истражени су директни и нелинеарни ефекти вештачке интелигенције на резултате циркуларне економије. Резултати овог истраживања показују да вештачка интелигенција нема статистички значајан утицај на стопу циркуларне употребе материјала

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(CMUSE) при контроли економских фактора. Продуктивност (ефикасност) ресурса је најзначајнији предиктор, док бруто домаћи производ по глави становника има кључну модераторску улогу. Random Forest модел објашњава 48,58% варијансе CMUSE. Ово истраживање је показало да улагања у вештачку интелигенцију треба ускладити са иницијативама за повећање ефикасности ресурса и са политикама привредног развоја, наглашавајући потребу за прилагођеним интервенцијама које узимају у обзир технолошку спремност и економске капацитете држава чланица ЕУ.

Кључне речи: *вештачка интелигенција, циркуларна економија, стопа циркуларне употребе материјала, Европска унија, продуктивност ресурса, одрживи развој*

1. Introduction

Due to resource limitations and environmental devastation, the 21st century has brought forth the dual imperatives of technological transformation and environmental sustainability as defining priorities for modern economies. These challenges are particularly prominent within the European Union (EU), which has positioned itself as a global leader in addressing sustainability concerns, with particular emphasis on resource scarcity and energy efficiency and driving the digitalization of industries. The circular economy (CE) has emerged as a comprehensive framework to mitigate resource depletion and environmental degradation and devastation. At its core, the CE shifts from the dominant, linear "take-make-dispose" model to regenerative systems that prioritize resource efficiency, waste minimization, and material recovery (Geissdoerfer et al., 2017; Kirchherr et al., 2017). By integrating practices such as sustainable product design, reuse, recycling, and recovery, CE aligns economic growth with ecological resilience, representing a cornerstone of the EU's strategy for sustainable development (Ghisellini et al., 2016; MacArthur, 2013).

Simultaneously, artificial intelligence (AI) has evolved as a transformative force in contemporary business, and the speed of its development has forced policymakers, especially in the EU, to adapt fast. AI's capabilities in real-time data processing, predictive analytics, and optimization have enabled innovative solutions across critical sectors, including manufacturing, logistics, and energy management (Jabbour et al., 2022; Lasi et al., 2014). Its potential to enhance CE practices is profound and foundationally transformative. Machine learning algorithms can optimize resource flows (Ghisellini et al., 2016), predictive maintenance systems extend product lifespans (Frank et al., 2019), and advanced robotics improve recycling and waste management (Ramos et al., 2019; Roberts et al., 2022). This synergy between CE and AI creates unprecedented opportunities to address sustainability challenges while fostering economic competitiveness (Wautelet, 2020).

The EU's leadership in CE and digital transformation emphasizes the urgency of understanding how these domains intersect. Policies such as the European Green Deal and the Circular Economy Action Plan (CEAP) set ambitious targets, including increasing the EU's circular material use rate (CMUSE) from 11.7% in 2020 to 25% by 2030 (European Commission, 2020a; Eurostat, 2023). Simultaneously, the Coordinated Plan on AI and the proposed AI Act emphasize ethical and widespread AI adoption to enhance economic and environmental resilience (European Commission, 2020b). These overlapping policy priorities highlight the strategic importance of understanding how AI adoption can bolster CE outcomes, providing a timely context for this research.

However, despite the theoretical promise of AI in advancing CE practices, its empirical impacts remain underexplored, particularly at the macroeconomic level. While case studies and sectoral analyses have demonstrated AI's role in improving resource productivity and enabling circular business models (Popović & Milijić, 2021; Tutore et al., 2024), systematic cross-country evidence is scarce. Popović (2020) notes that research on the implications of Industry 4.0 technologies, including AI, often neglects their potential to achieve sustainable development outcomes like those tied to CE. This gap is particularly pronounced in the EU, where variations in technological readiness, economic development, and industrial structure may influence the effectiveness of AI in promoting CE outcomes. Moreover, the relationship between AI adoption and CMUSE may not be linear, with diminishing returns or threshold effects at higher levels of AI implementation (Platon et al., 2024). Without strong empirical evidence, policymakers and business leaders face uncertainties in leveraging AI to meet CE objectives.

Understanding the interplay between AI adoption and CMUSE is essential for advancing both academic inquiry and policy design. Insights into this relationship can support policymakers in aligning the EU's digital transformation and environmental sustainability agendas. Programs like NextGenerationEU, which allocates €723.8 billion for green and digital transitions, and Horizon Europe, with a €95.5 billion budget for research and innovation, underscore the importance of evidence-based strategies to maximize the impact of these investments (European Commission, 2021c, 2021d). Popović et al. (2023) emphasize that tailored policies accounting for national contexts - such as disparities in technological infrastructure and economic capacity - are crucial for achieving CE targets. For business leaders, identifying how AI can enhance CE practices offers pathways to operational efficiency and competitive advantage.

This research contributes to bridging these gaps by providing macroeconomic-level evidence on the relationship between AI adoption and CMUSE. By focusing on the EU - a global leader in CE and AI adoption - this study contributes to broader discussions on sustainable technological innovation. Moreover, exploring non-linearities and contextual moderating factors enriches the theoretical understanding of how digital and environmental transitions intersect.

The primary goal of this research is to investigate the relationship between AI adoption and CMUSE across EU member states. Four specific objectives support this aim:

1. *Quantifying the causal impact of AI adoption on CMUSE.*
2. *Identifying potential non-linear relationships and threshold effects.*
3. *Analyzing how economic development and technological readiness moderate this relationship.*
4. *Developing evidence-based policy recommendations to enhance CE outcomes through AI adoption.*

The study addresses the following research questions:

1. *How does AI adoption influence circular material use (CMUSE) in EU member states?*

2. *What is the nature of this relationship - linear, non-linear, or threshold-based?*
3. *How do economic development and technological readiness affect this relationship?*

This research employs a mixed-method quantitative approach, integrating panel data econometrics with machine learning techniques to explore the relationship between AI adoption and CMUSE. Using data from 27 EU member states for 2021 and 2023, the analysis captures a pivotal period in the region's digital and circular transitions. Fixed-effects regression models address unobserved heterogeneity among countries and enable causal estimation while controlling for factors such as GDP per capita, resource productivity, and industrial value-added. Additionally, quadratic terms test for potential non-linearities, such as threshold effects or diminishing returns from AI adoption (Platon et al., 2024).

Machine learning complements the econometric analysis by validating results and uncovering complex interactions. Random forest models evaluate variable importance and identify nuanced patterns, providing insights that traditional regression methods might overlook (Breiman, 2001). Partial dependence plots further illustrate the interplay between AI adoption and contextual factors, revealing heterogeneity in impacts across member states. This hybrid approach addresses limitations in prior studies, such as endogeneity concerns and the inability to model non-linear effects (Acerbi et al., 2021).

By integrating econometrics and machine learning, this research advances understanding of the magnitude and nature of AI's influence on CMUSE. The findings align with crucial EU policy frameworks, such as the European Green Deal and CEAP, offering actionable insights for tailoring strategies to enhance the EU's dual transitions in sustainability and digitalization.

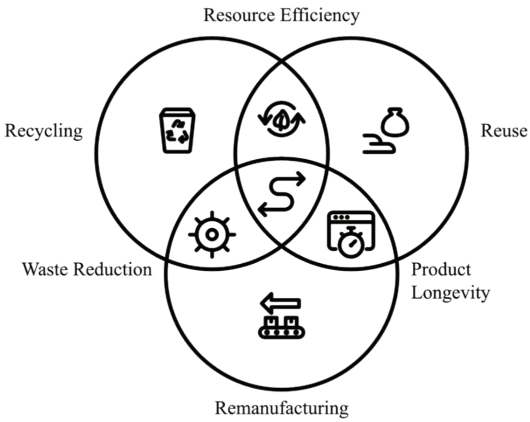
The remainder of this paper is organized to initially review the relevant literature on AI and CE, emphasizing existing gaps and outlining the methodological framework, data sources, and variable selection. Further, it presents empirical findings, including econometric results and machine learning validation, and discusses the implications for policy and practice. Finally, it concludes with key insights and future research directions.

This research makes several contributions to academic literature and policy discussions. First, it provides novel empirical evidence on the relationship between AI adoption and CE outcomes at a macroeconomic level, addressing a critical gap in existing research. Second, it introduces a hybrid methodological approach that combines econometric analysis with machine learning, offering a robust framework for policy analysis. Third, it delivers actionable insights for policymakers and business leaders, aligning with the EU's strategic goals for digital transformation and environmental sustainability. By bridging theoretical understanding and practical application, this research advances the discourse on leveraging AI for sustainable development.

2. Theoretical Background

The integration of circular economy (CE) principles with technological innovation, particularly artificial intelligence (AI), has emerged as a focal point in contemporary discussions on sustainable development. The resource-based view (RBV) and the dynamic capabilities framework provide foundational theories for understanding how organizations can leverage resources and competencies to respond to environmental challenges through resource optimization and technological advancements (Barney, 1991; Teece et al., 1997). Haas et al. (2015) highlight the inefficiencies of the global linear economic model, noting that out of 62 gigatons (Gt) of processed materials, only 4 Gt are recycled annually. This significant disparity underscores the urgent need for a fundamental shift toward circular material flows, aligning with Kirchherr et al. (2017), who emphasize the centrality of CE principles - recycling, reuse, and remanufacturing - in addressing resource scarcity and mitigating environmental degradation and devastation. Figure 1 illustrates the dimensions of the circular economy.

Figure 1: Dimensions of Circular Economy



Source: Author's illustration based on Kirchherr et al. (2017)

Aleksić et al. (2023) extend this perspective by linking sustainable product lifecycle strategies to CE principles. Their study demonstrates that compliance with CE frameworks not only fosters environmental benefits but also enhances profitability. By adopting sustainable design and adhering to CE principles, companies can reduce resource consumption and waste generation, thereby improving their overall economic performance. This integration of theoretical foundations with practical applications emphasizes the imperative for technological innovations, such as AI, to facilitate the transition from linear to circular economic systems.

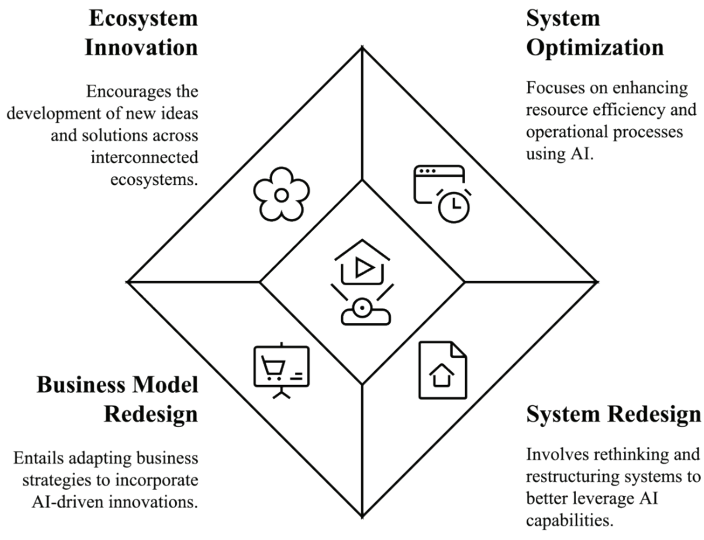
Digital transformation plays a pivotal role in enabling CE practices by leveraging technological solutions to close resource loops, optimize supply chains, and monitor material flows. Technologies such as the Internet of Things (IoT), blockchain, and advanced analytics are instrumental in this domain. Popović et al. (2022) highlight the transformative potential of digital platforms in fostering circular business models like product-as-a-service and extended producer responsibility. These models promote resource efficiency and accountability across value chains, which are essential components in achieving CE goals.

However, the interplay between digital transformation and circularity is complex and often non-linear. Nham and Ha (2022) suggest that while digital technologies offer benefits like precision tracking of materials and enhanced resource recovery, these advantages may diminish beyond a certain threshold. This non-linear dynamic indicates the necessity of aligning technological interventions with strategic policy frameworks to ensure sustained progress toward CE objectives.

In specific industry contexts, Radukić et al. (2023) provide a case study on the textile industry, focusing on H&M's transition toward circularity. Their analysis reveals significant reductions in waste and improvements in operational efficiency through the adoption of digital technologies and CE principles. However, they also highlight the challenges faced by smaller firms and those in resource-limited economies, emphasizing the need for supportive policies and access to technological resources to facilitate broader adoption.

Artificial intelligence has emerged as a transformative enabler in advancing CE practices, offering capabilities in real-time decision-making, predictive analytics, and process optimization. Tutore et al. (2024) propose a four-stage framework for AI integration into CE actions: system optimization, system redesign, business model redesign, and ecosystem innovation. This framework, presented in Figure 2 illustrates the diverse applications of AI, from improving resource efficiency at the operational level to fostering innovation across entire ecosystems.

Figure 2: AI Integration Framework



Source: Author's illustration based on Tutore et al. (2024)

Platon et al. (2024) emphasize the substantial positive impact of AI on CE development, particularly when combined with eco-investments. Their panel regression analysis across 27 EU member states demonstrates that while eco-investment has a greater impact, AI adoption significantly contributes to the advancement of CE outcomes. However, they also note that the extent of this impact varies by industry, organizational maturity, and national policy frameworks.

Similarly, Ghoreishi and Happonen (2020) explore AI's role in sustainable product design, emphasizing how advanced analytics and real-time data can enhance circular manufacturing processes. Their qualitative study suggests that integrating AI techniques in the product design phase leads to improved sustainability and cost savings, although they acknowledge limitations due to the lack of empirical validation.

Despite these promising findings, challenges to AI adoption persist. Cubric (2020) identifies barriers such as data availability, trust issues, and the lack of technical expertise as significant impediments to broader AI implementation. Kelley (2022) further highlights organizational factors, including communication, management support, and ethical considerations, as critical to the successful adoption of AI-driven CE practices.

The European Union (EU) is recognized as a global leader in advancing CE principles, particularly through its focus on circular material use rate (CMUSE). Defined as the percentage of recovered materials reintegrated into the economy, CMUSE serves as a vital indicator of progress toward circularity. According to Eurostat (2023), the EU-wide CMUSE rate was 11.7% in 2020, but this aggregate figure masks significant disparities among member states. Nations with advanced industrial structures and comprehensive policy frameworks, such as Germany and the Netherlands, exhibit higher CMUSE rates, while countries in Eastern and Southern Europe lag due to weaker institutional capacities and technological infrastructure (Popović & Milijić, 2021).

The Circular Economy Action Plan (CEAP), part of the European Green Deal, outlines ambitious goals to increase the CMUSE rate to 25% by 2030 (European Commission, 2020a). Achieving these targets requires innovative approaches, including the adoption of AI, to accelerate the transition to a circular economy. Popović et al. (2023) emphasize that overcoming structural barriers - such as inefficient waste management systems, limited cross-sector collaboration, and uneven technological diffusion - is critical for realizing these objectives.

The application of AI in CE practices has evolved from theoretical explorations to broader implementations across various industries. AI technologies contribute to CE objectives through several mechanisms:

1. Enhanced Waste Sorting: Machine learning and computer vision technologies enable precise identification and separation of waste materials, significantly improving recycling rates. Agrawal et al. (2021) discuss how AI-powered systems can classify materials with greater accuracy and speed than traditional methods, reducing contamination and enhancing the quality of recycled outputs.
2. Predictive Maintenance: AI-driven predictive analytics prolong the lifecycle of products and machinery by identifying potential failures before they occur. Acerbi et al. (2021) emphasize the transformative impact of predictive maintenance on reducing material consumption, particularly in manufacturing and logistics sectors.
3. Supply Chain Optimization: Advanced AI algorithms optimize supply chains by minimizing waste, reducing transportation inefficiencies, and aligning production with demand. Ramos et al. (2018) highlight AI's potential to lower environmental footprints by improving resource allocation and enabling real-time adjustments to supply chain dynamics.

However, scalability challenges persist. While AI has demonstrated significant success at the micro-level (individual firms), its integration at the meso-level (industry networks) and macro-level (regional or national economies) is often limited by regulatory hurdles, infrastructure gaps, and varying levels of technological readiness (Acerbi et al., 2021; Popović et al., 2023). Acerbi et al. (2021) note that the exploitation of AI in circular manufacturing is more advanced at the micro-level compared to meso- and macro-levels, suggesting the need for coordinated efforts to scale AI applications across sectors and regions.

The efficacy of AI in advancing CMUSE is heavily influenced by economic development and institutional quality within EU member states. Wealthier countries with developed institutional frameworks are better positioned to leverage AI technologies for CE objectives. For example:

- Economic Development: Advanced economies like Germany and Sweden have the financial resources and technological infrastructure to invest in AI innovation, enabling more effective implementation of circular strategies (Platon et al., 2024; Popović et al., 2022).
- Institutional Quality: Institutional frameworks that promote collaboration between government, academia, and industry foster environments conducive to AI adoption. Popović et al. (2023) highlight that countries with strong governance and clear CE policies achieve higher rates of technology-driven circularity.

Conversely, less-developed regions face significant barriers, including inadequate infrastructure, limited financial resources, and fragmented policy support. These challenges exacerbate disparities in CMUSE and hinder AI's potential to contribute meaningfully to circular transitions across the EU (Popović & Milijić, 2021). Addressing these disparities requires tailored policy interventions that consider the unique economic and institutional contexts of each member state.

Despite the growing body of literature on AI and CE, notable research gaps persist:

1. Macro-Level Analysis of AI and CMUSE: Current studies predominantly focus on micro-level (firm-specific) or sectoral analyses, neglecting broader macroeconomic dynamics. Popović et al. (2023) underscore the need for cross-country studies that consider the influence of AI adoption on national CMUSE rates, particularly within diverse institutional and economic conditions.
2. Non-Linear Dynamics and Threshold Effects: The relationship between AI adoption and CMUSE may exhibit non-linear characteristics, such as diminishing returns or threshold effects. Nham and Ha (2022) suggest that beyond a certain level of digital technology adoption, the incremental benefits to circularity may decrease, indicating the importance of identifying optimal levels of AI integration.
3. Technological Readiness and Policy Alignment: Platon et al. (2024) emphasize that technological readiness must be complemented by policy frameworks that encourage sustainable AI adoption. Without such alignment, AI's potential to drive CE objectives remains underutilized.

These research gaps inform the methodological choices of this paper. By employing a mixed-method quantitative approach that combines econometric modeling with machine learning validation, this research addresses the limitations of prior studies. Econometric analysis allows for hypothesis testing and estimation of causal relationships, while machine learning techniques capture complex, non-linear interactions and provide robustness checks (Athey & Imbens, 2019). This methodological triangulation enhances the reliability of findings and offers a comprehensive understanding of how AI adoption influences CMUSE across diverse EU contexts.

The scalability of AI applications and their implications for CMUSE across diverse EU contexts are critical considerations. The mixed-method approach enables the examination of both direct effects and detailed interactions between AI adoption and CMUSE. By analyzing data from all 27 EU member states over multiple years, the research captures variations in economic development, technological readiness, and institutional quality. This comprehensive analysis addresses the scalability challenge by identifying patterns and relationships that are generalizable across different contexts.

Moreover, the incorporation of non-linear models and machine learning algorithms allows for the detection of threshold effects and diminishing returns, providing insights into optimal levels of AI adoption for maximizing CMUSE. This is particularly important for policymakers aiming to design interventions that are both effective and efficient.

The literature underscores the transformative potential of AI in advancing CE objectives, particularly in enhancing CMUSE. However, the realization of this potential is contingent upon various factors, including economic development, institutional quality, and strategic policy alignment. The identified research gaps highlight the need for macro-level analyses that consider the complex, non-linear relationships between AI adoption and CMUSE. By addressing these gaps through a robust methodological framework, the present study aims to contribute to both academic discourse and practical policy solutions in promoting sustainable development within the EU.

3. Research Methodology

This research employs a mixed-method quantitative approach to investigate the relationship between Artificial Intelligence (AI) adoption and the Circular Material Use Rate (CMUSE) across the 27 European Union (EU) member states. By integrating traditional econometric techniques with advanced machine learning methods - specifically, panel data econometrics and Random Forest regression – this paper aims to capture both linear and non-linear dynamics in this relationship. This methodological triangulation addresses the limitations of prior studies that often rely solely on linear models or lack robustness checks for complex interactions (Acerbi et al., 2021; Nham & Ha, 2022).

3.1. Data Sources and Sample Selection

The analysis utilizes a balanced panel dataset covering all 27 EU member states over two pivotal years: 2021 and 2023. This period coincides with significant developments in the EU's digital transformation and circular economy initiatives, such as the implementation of the European Green Deal and the Circular Economy Action Plan (CEAP) (European Commission, 2020a). By focusing on this timeframe, the research aims to capture the contemporary dynamics between AI adoption and circular economy outcomes.

The data is sourced from authoritative and harmonized databases to ensure consistency and comparability:

- Eurostat: Provides data on CMUSE, Resource Productivity (RESP), and other circular economy indicators (Eurostat, 2023). Specifically, variables such as Waste Generation per Capita (WASTPC), and Recycling Rates are included.
- European Commission's Surveys: Supplies information on AI adoption rates and digital technology usage, including E-commerce Sales (ECOMS), Cloud Computing Services (CCOMP), and Use of Robotics (ROBOTICS), based on harmonized EU-wide enterprise surveys (European Commission, 2022).
- World Bank and OECD Databases: Provide supplementary macroeconomic data

such as GDP per Capita (GDPpc), Unemployment Rates (UNEMP), Industrial Value Added (INDVA), and Renewable Energy Consumption (RENWENG) for validation and robustness checks.

By concentrating on the EU context, this paper controls for overarching policy frameworks and institutional settings, thereby addressing scalability challenges and ensuring that variations in the data are attributable to differences in national characteristics rather than global disparities (Popović et al., 2023).

3.2. Variables and Operationalization

Dependent Variable: Circular Material Use Rate (CMUSE) measures the share of material recycled and reintroduced into the economy, thus reducing the need for extracting primary raw materials. It is defined as the ratio of the circular use of materials to the overall material use and is expressed as a percentage (%) (Eurostat, 2023).

Independent Variable: Artificial Intelligence Adoption Rate (AI) represented by the percentage of enterprises employing at least one AI technology, such as machine learning, natural language processing, or computer vision. This data is collected from enterprises with 10 or more employees across various sectors, excluding agriculture, forestry, fishing, and mining (European Commission, 2022).

Control Variables: To account for country-specific characteristics and potential confounding factors, several control variables are included:

- E-commerce Sales (ECOMS): Percentage of enterprises making sales via e-commerce, serving as a proxy for digital infrastructure and technological readiness (Eurostat, 2023).
- Cloud Computing Services (CCOMP): Percentage of enterprises buying cloud computing services used over the Internet, indicating the level of digital adoption (European Commission, 2022).
- Resource Productivity (RESP): Calculated as gross domestic product (GDP) divided by domestic material consumption (DMC), expressed in Euro per kilogram. This variable captures the efficiency of resource utilization (Eurostat, 2023).
- Industrial Value Added (INDVA): Represents the contribution of the industrial sector (including construction) to GDP, expressed as a percentage (%). It controls for structural economic differences across countries (World Bank, 2024).
- GDP per Capita (GDPpc): Gross domestic product divided by midyear population, measured in current U.S. dollars. It accounts for the level of economic development (World Bank, 2024).
- Renewable Energy Consumption (RENWENG): The share of renewable energy in total final energy consumption, expressed as a percentage (%). It reflects a country's commitment to sustainable energy practices (World Bank, 2024).

Additional Variables: For robustness checks and supplementary analysis, the analysis includes:

- Waste Generation per Capita (WASTPC): Total waste generated per capita, including major mineral wastes, measured in kilograms (Eurostat, 2023).
- Recycling Rates: Including Recycling Rate of Municipal Waste (RECMWASTE) and Recycling Rate of Electronic Waste (RECREW), expressed as percentages (%), to assess specific aspects of waste management efficiency.

- Unemployment Rate (UNEMP): The share of the labor force without work but available for and seeking employment, expressed as a percentage (%). This variable controls for labor market conditions (World Bank, 2024).

All variables are carefully operationalized and standardized where appropriate to ensure comparability and to mitigate issues of scale and multicollinearity (Wooldridge, 2010).

3.3. Data Preparation and Processing

Data was collected from the respective databases to ensure the most recent and relevant information was utilized. Each variable is matched with its short definition, date of collection, and source link for transparency and reproducibility.

The dataset is structured as a balanced panel (Croissant & Millo, 2008), with countries as individual units and years as time periods. This structure allows us to control for unobserved heterogeneity and capture both cross-sectional and temporal variations.

Variable Transformation:

- Standardization: Continuous variables are standardized using z-scores to address scale differences and facilitate the interpretation of coefficients.
- Log Transformation: The natural logarithm of GDP per capita (lgdp) is taken to linearize the relationship and reduce heteroscedasticity.
- Composite Indices: Where appropriate, composite indices are created using Principal Component Analysis (PCA) to capture underlying constructs such as technological readiness or environmental sustainability.

All analyses are conducted using R statistical software version 4.4.0 (R Core Team, 2024), utilizing packages such as plm for panel data econometrics (Croissant & Millo, 2008), randomForest for machine learning models (Liaw & Wiener, 2002), and ggplot2 for data visualization (Wickham, 2016). The use of R ensures transparency, reproducibility, and accessibility.

3.4. Empirical Strategy and Model Specifications

Stage 1 - Linear Panel Data Analysis: The analysis begins with a fixed-effects panel regression model to estimate the direct relationship between AI adoption and CMUSE:

$$\mathrm{CMUSE\_std}_{it} = \beta_1 \mathrm{AI\_std}_{it} + \beta_2 \mathrm{lgdp}_{it} + \beta_3 \mathrm{RESP\_std}_{it} + \beta_4 \mathrm{INDVA\_std}_{it} + \alpha_i + \epsilon_i \quad (1)$$

- $\mathrm{CMUSE\_std}_{it}$: Standardized Circular Material Use Rate for country iii at time ttt.
- $\mathrm{AI\_std}_{it}$: Standardized AI Adoption Rate.
- Lgdp_{it}: Natural logarithm of GDP per capita.
- $\mathrm{RESP\_std}_{it}$: Standardized Resource Productivity.
- $\mathrm{INDVA\_std}_{it}$: Standardized Industrial Value Added.
- α_i\alpha_iαi: Country-specific fixed effects.
- ϵ_{it}: Error term.

The fixed-effects model accounts for unobserved heterogeneity by allowing each country to have its own intercept, thus controlling for time-invariant characteristics (Baltagi, 2008).

Stage 2 - Non-linear Relationship Analysis: To explore potential non-linearities and threshold effects, the analysis extends the model by including a quadratic term for AI adoption:

$$CMUSE\_std_{it} = \beta_1 AI\_std_{it} + \beta_2 AI\_std^2_{it} + \beta_3 lgdp_{it} + \beta_4 RESP\_std_{it} + \beta_5 INDVA\_std_{it} + \alpha_i + \epsilon_{it} \quad (2)$$

This specification allows us to test whether the impact of AI adoption on CMUSE changes at different levels of AI adoption, addressing the possibility of diminishing returns or acceleration effects (Nham & Ha, 2022).

Stage 3 - Machine Learning Validation: To complement the econometric analysis and capture complex interactions, the analysis employs a Random Forest regression model:

- Dependent Variable: CMUSE_std.
- Independent Variables: AI_std, lgdp, RESP_std, INDVA_std, and additional variables such as ECOMS_std and CCOMP_std.
- Model Parameters: 500 trees with variable importance measures.

The Random Forest model is particularly suitable for handling non-linear relationships and interactions without imposing restrictive functional form assumptions (Breiman, 2001). Variable importance is assessed based on the increase in mean squared error when a variable is permuted, providing insights into the relative influence of each predictor.

3.5. Diagnostic Tests and Robustness Checks

Econometric Model Diagnostics included:

- Hausman Test: Determines the appropriateness of the fixed-effects model over the random-effects model (Hausman, 1978). The test results support the fixed-effects specification, indicating that country-specific effects are correlated with the explanatory variables.
- Heteroscedasticity Test: The Breusch-Pagan test is conducted to detect heteroscedasticity. Robust standard errors are employed using the Huber-White sandwich estimator to address any issues (White, 1980).
- Multicollinearity Check: Variance Inflation Factors (VIFs) are calculated to assess multicollinearity among the regressors. All VIFs are below the threshold of 5, indicating no severe multicollinearity (Gujarati & Porter, 2009).

Machine Learning Model Evaluation was performed through:

- Model Performance Metrics: Mean Squared Error (MSE) and the Percentage of Variance Explained are used to evaluate model accuracy.
- Variable Importance: Analyzed through the %IncMSE, providing a ranking of predictors based on their impact on model performance.
- Visualization: Actual vs. predicted plots and variable importance graphs are generated to visualize model fit and predictor influence.

3.7. Addressing Research Gaps through Methodological Choices

This paper's methodological approach directly addresses the research gaps identified in the literature:

- Macro-Level Analysis: By encompassing all EU member states, the paper provides a comprehensive macro-level perspective, extending beyond micro-level studies (Popović et al., 2023).

- Non-Linear Dynamics: Incorporating quadratic terms and utilizing Random Forest regression allows this research to capture non-linear relationships and threshold effects (Nham & Ha, 2022).
- Scalability and Contextual Factors: Analyzing countries with varying levels of economic development and technological readiness helps explore the scalability of AI applications and their implications for CMUSE (Acerbi et al., 2021).

3.8. Ethical Considerations and Limitations

While this study offers valuable insights, certain limitations must be acknowledged:

- Temporal Scope: The analysis covers two years, which may not fully capture long-term trends or lagged effects.
- Data Availability: The reliance on secondary data sources may introduce inconsistencies due to reporting practices across countries.
- Measurement Errors: Variables based on surveys, such as AI adoption rates, may be subject to self-reporting biases.

Despite these limitations, the combination of rigorous econometric analysis and machine learning techniques enhances the robustness of the findings.

4. Research Results

Building upon the methodological framework outlined earlier, this section presents the empirical findings of this research on the relationship between Artificial Intelligence (AI) adoption and the Circular Material Use Rate (CMUSE) within the European Union (EU). The analysis encompasses descriptive statistics, econometric modeling, diagnostic tests, and machine learning validation. The results offer insights into the dynamics of AI adoption in promoting circular economy practices across diverse EU contexts.

4.1. Descriptive Statistics

Table 1 presents the summary statistics for the key variables used in the analysis. The dataset comprises observations from 27 EU member states over two years (2021 and 2023), totaling 54 observations.

Table 1: Summary Statistics of Key Variables

Variable	Mean	Median	Std. Dev.	Min	Max
ECOMS	24.63	23.3	7.83	11.8	40.2
ECOMV	18.07	17.7	7.14	4.3	37.9
AI	7.96	7.45	4.57	1.4	23.9
CCOMP	44.71	43.25	16.79	12.8	78.3
MUSE	18.98	17.31	8.26	7.46	48.02
RESP	1.97	1.56	1.26	0.34	5.46
CMUSE	10.1	8.7	6.88	1.3	30.6
GDPpc	41,328	32,420	26,640	12,219	133,712
INDVA	22.46	22.74	6.2	10.47	38.47

Source: Own calculations.

The mean AI adoption rate across EU countries is approximately 7.96%, with a wide range from 1.4% to 23.9%, indicating significant disparities in AI utilization among member states. This suggests that while some countries are at the forefront of AI implementation, others are still in the nascent stages of adoption.

Similarly, the average CMUSE is 10.10%, with values ranging from 1.3% to 30.6%, reflecting varying levels of circular economy implementation across the EU. The wide range indicates that some countries have made significant progress in recycling and reusing materials, while others have considerable room for improvement.

Assessing the distributional properties of the variables is essential for selecting appropriate statistical techniques and interpreting results accurately. Shapiro-Wilk and Kolmogorov-Smirnov normality tests were conducted for all variables used in the models, and the results are presented in Table 2.

Table 2: Normality Test Results for Variables Used in the Models

Variable	SW (W)	SW (p-value)	KS Stat. (D)	KS (p-value)	Skew.	Kurt.
AI	0.9325	0.0046	0.1165	0.0652	0.904	3.995
CMUSE	0.9012	0.0003	0.1378	0.0122	1.033	3.525
RESP	0.9226	0.0019	0.1619	0.0012	0.805	2.893
ECOMS	0.9578	0.0547	0.1128	0.0837	0.277	2.033
CCOMP	0.9798	0.4918	0.0660	0.8065	0.114	2.184
GDPpc	0.8020	0.0000	0.1738	0.0003	1.803	6.292
INDVA	0.9786	0.4422	0.0700	0.7336	0.179	3.109

Source: Own calculations.

The Shapiro-Wilk test results indicate that variables like AI, CMUSE, RESP, and GDP per Capita (GDPpc) significantly deviate from normality ($p < 0.05$).

AI adoption rate exhibits positive skewness (0.904) and kurtosis (3.995), indicating a right-skewed distribution with heavier tails than a normal distribution. This suggests that a majority of countries have AI adoption rates below the mean, with a few countries having significantly higher rates.

CMUSE also shows positive skewness (1.033) and kurtosis (3.525), implying that most countries have lower circular material use rates, with some outliers at the higher end.

Variables like ECOMS and INDVA do not significantly deviate from normality based on the Shapiro-Wilk test ($p > 0.05$), suggesting that parametric tests assuming normality may be appropriate for these variables.

The Kolmogorov-Smirnov test (KS test) generally supports the findings of the Shapiro-Wilk test, with significant deviations from normality for variables like CMUSE and GDPpc ($p < 0.05$).

Given the deviations from normality for key variables, the research proceeded with caution in the econometric analysis, using robust statistical methods that do not strictly rely on the assumption of normality (Wooldridge, 2010).

To examine the relationships among all the key variables in this research, Pearson correlation coefficients were computed. The comprehensive correlation matrix is presented in Figure 3.

Figure 3: Correlation Matrix

	Year	ECOMS	ECOMV	AI	CCOMP	MUSE	RESP	WASTPC	MWASTE	WASTE	PACWASTE	PLASWASTE	RECMWASTE	RECPACW	RECREW	CMUSE	RECFTR	CEINV	CEGVA	PATENTS	CONSFP	GDPpc	UNEMP	INDVA	RENWENG
RENWENG	0.02	0.40	0.41	0.54	0.53	0.04	0.34	0.11	0.37	-0.14	0.37	0.16	0.62	0.59	0.09	0.36	-0.00	0.42	0.42	0.21	0.53	0.37	-0.23	-0.03	1.00
INDVA	0.04	0.17	0.40	-0.17	0.04	0.05	-0.19	-0.09	-0.22	0.07	0.18	0.42	0.31	0.07	0.30	-0.23	-0.24	-0.17	0.19	0.13	-0.37	-0.08	-0.28	1.00	-0.03
UNEMP	-0.17	0.05	-0.21	-0.16	-0.18	-0.09	0.01	-0.07	-0.14	-0.10	-0.12	-0.05	-0.22	0.09	-0.24	-0.18	-0.19	-0.33	-0.21	-0.10	0.06	-0.12	1.00	-0.28	-0.23
GDPpc	0.03	0.26	0.52	0.61	0.41	0.18	0.72	0.31	0.62	-0.38	0.59	0.48	0.41	0.34	-0.04	0.16	-0.09	0.33	0.12	0.12	0.70	1.00	-0.12	-0.08	0.37
CONSFP	0.16	0.36	0.34	0.60	0.53	0.18	0.49	0.16	0.62	-0.38	0.53	0.31	0.20	0.30	-0.10	0.12	0.12	0.26	0.36	0.09	1.00	0.70	0.06	-0.37	0.53
PATENTS	0.05	-0.09	0.07	0.16	0.09	-0.22	0.39	-0.04	0.06	-0.21	0.55	0.21	0.46	0.30	-0.07	0.37	-0.16	0.22	0.18	1.00	0.09	0.12	-0.10	0.13	0.21
CEGVA	-0.01	0.40	0.20	0.13	0.37	-0.25	0.18	-0.21	0.21	-0.05	0.42	0.47	0.09	-0.08	0.08	0.16	0.37	0.38	1.00	0.18	0.36	0.12	-0.21	0.19	0.42
CEINV	0.01	0.14	0.16	0.35	0.12	-0.17	0.43	-0.03	0.47	-0.07	0.41	0.17	0.39	0.16	-0.16	0.50	0.19	1.00	0.38	0.22	0.26	0.33	-0.33	-0.17	0.42
RECFTR	-0.08	0.08	-0.17	0.06	0.16	-0.06	-0.05	0.16	0.01	0.15	-0.11	-0.11	-0.35	-0.32	0.03	0.24	1.00	0.19	0.37	-0.16	0.12	-0.09	-0.19	-0.24	-0.00
CMUSE	0.03	0.09	0.09	0.30	0.38	-0.39	0.61	0.06	0.17	0.01	0.25	-0.07	0.35	0.40	-0.22	1.00	0.24	0.50	0.16	0.37	0.12	0.16	-0.18	-0.23	0.36
RECREW	-0.19	-0.18	0.01	-0.08	-0.04	0.22	-0.28	0.07	0.06	0.11	-0.17	-0.18	0.13	0.06	1.00	-0.22	0.03	-0.16	0.08	-0.07	-0.10	-0.04	-0.24	0.30	0.09
RECPACW	0.01	0.11	0.37	0.32	0.34	0.04	0.38	0.19	0.33	0.00	0.25	0.07	0.63	1.00	0.06	0.40	-0.32	0.16	-0.08	0.30	0.30	0.34	0.09	0.07	0.59
RECMWASTE	0.03	0.20	0.45	0.49	0.23	-0.05	0.45	-0.03	0.37	-0.27	0.50	0.20	1.00	0.63	0.13	0.35	-0.35	0.39	0.09	0.46	0.20	0.41	-0.22	0.31	0.62
PLASWASTE	0.01	0.33	0.56	0.08	0.24	-0.15	0.38	-0.14	0.10	-0.23	0.77	1.00	0.20	0.07	-0.18	-0.07	-0.11	0.17	0.47	0.21	0.31	0.48	-0.05	0.42	0.16
PACWASTE	0.04	0.15	0.47	0.34	0.31	-0.10	0.61	-0.08	0.28	-0.40	1.00	0.77	0.50	0.25	-0.17	0.25	-0.11	0.41	0.42	0.55	0.53	0.59	-0.12	0.18	0.37
WASTE	0.01	-0.32	-0.35	-0.40	-0.24	0.17	-0.47	0.42	-0.37	1.00	-0.40	-0.23	-0.27	0.00	0.11	0.01	0.15	-0.07	-0.05	-0.21	-0.38	-0.38	-0.10	0.07	-0.14
MWASTE	-0.04	0.26	0.31	0.59	0.27	0.05	0.47	-0.01	1.00	-0.37	0.28	0.10	0.37	0.33	0.06	0.17	0.01	0.47	0.21	0.06	0.62	0.62	-0.14	-0.22	0.37
WASTPC	0.01	-0.07	0.02	0.24	0.27	0.69	-0.05	1.00	-0.01	0.42	-0.08	-0.14	-0.03	0.19	0.07	0.06	0.16	-0.03	-0.21	-0.04	0.16	0.31	-0.07	-0.09	0.11
RESP	0.06	0.23	0.34	0.52	0.34	-0.40	1.00	-0.05	0.47	-0.47	0.61	0.38	0.45	0.38	-0.28	0.61	-0.05	0.43	0.18	0.39	0.49	0.72	0.01	-0.19	0.34
MUSE	0.00	-0.04	0.07	0.18	0.17	1.00	-0.40	0.69	0.05	0.17	-0.10	-0.15	-0.05	0.04	0.22	-0.39	-0.06	-0.17	-0.25	-0.22	0.18	0.18	-0.09	0.05	0.04
CCOMP	0.12	0.62	0.50	0.58	1.00	0.17	0.34	0.27	0.27	-0.24	0.31	0.24	0.23	0.34	-0.04	0.38	0.16	0.12	0.37	0.09	0.53	0.41	-0.18	0.04	0.53
AI	0.06	0.50	0.49	1.00	0.58	0.18	0.52	0.24	0.59	-0.40	0.34	0.08	0.49	0.32	-0.08	0.30	0.06	0.35	0.13	0.16	0.60	0.61	-0.16	-0.17	0.54
ECOMV	0.00	0.57	1.00	0.49	0.50	0.07	0.34	0.02	0.31	-0.35	0.47	0.56	0.45	0.37	0.01	0.09	-0.17	0.16	0.20	0.07	0.34	0.52	-0.21	0.40	0.41
ECOMS	0.04	1.00	0.57	0.50	0.62	-0.04	0.23	-0.07	0.26	-0.32	0.15	0.33	0.20	0.11	-0.18	0.09	0.08	0.14	0.40	-0.09	0.36	0.26	0.05	0.17	0.40
Year	1.00	0.04	0.00	0.06	0.12	0.00	0.06	0.01	-0.04	0.01	0.04	0.01	0.03	0.01	-0.19	0.03	-0.08	0.01	-0.01	0.05	0.16	0.03	-0.17	0.04	0.02

Source: Own calculations.

Based on the correlation matrix above, the analysis provided the following observations:

- CMUSE and AI Adoption: There is a positive correlation between CMUSE and AI adoption ($r = 0.295$). Although this correlation is moderate and not statistically significant at conventional levels, it suggests that higher AI adoption rates may be associated with increased circular material use.
- CMUSE and Resource Productivity: CMUSE is strongly and positively correlated with Resource Productivity (RESP) ($r = 0.610$, $p < 0.01$). This indicates that countries with higher resource efficiency tend to have higher circular material use rates, emphasizing the importance of resource productivity in advancing circular economy practices.
- AI Adoption and GDP per Capita: AI adoption is significantly correlated with GDP per Capita ($r = 0.612$, $p < 0.01$). This suggests that wealthier countries are more likely to adopt AI technologies, possibly due to better access to capital, infrastructure, and skilled labor.
- AI Adoption and Resource Productivity: There is a significant positive correlation between AI adoption and Resource Productivity ($r = 0.517$, $p < 0.01$). This implies that countries adopting AI tend to have higher resource efficiency, potentially leveraging AI for optimizing resource use.
- CMUSE and Cloud Computing Services: CMUSE is positively correlated with Cloud Computing Services (CCOMP) ($r = 0.383$, $p < 0.05$). This indicates that digital infrastructure may play a role in facilitating circular economy activities.
- CMUSE and Circular Economy Investments: A strong positive correlation exists between CMUSE and Circular Economy Investments (CEINV) ($r = 0.501$, $p < 0.01$), suggesting that higher investments in circular economy initiatives are associated with greater circular material use.

- INDVA (Industrial Value Added) shows negative correlations with both CMUSE ($r = -0.228$) and AI adoption ($r = -0.170$), although these correlations are not statistically significant. This might imply that a higher share of traditional industrial activities is not necessarily aligned with higher AI adoption or circular economy practices.

Additionally, based on the analysis, the following insights should be showcased:

- Digitalization and AI: AI adoption is positively correlated with E-commerce Sales (ECOMS) ($r = 0.502$, $p < 0.01$) and Cloud Computing Services (CCOMP) ($r = 0.577$, $p < 0.01$). This highlights the interconnectedness of digital technologies and suggests that countries embracing digital transformation are more inclined to adopt AI.
- Economic Development Factors: GDP per Capita is significantly correlated with RESP ($r = 0.724$, $p < 0.01$) and Consumption Footprint (CONSFP) ($r = 0.700$, $p < 0.01$). This indicates that wealthier countries tend to have higher resource productivity and consumption footprints, reflecting both efficient resource use and higher consumption levels.
- Renewable Energy Use: CMUSE has a positive correlation with Renewable Energy Use (RENWENG) ($r = 0.364$, $p < 0.05$), suggesting that countries focusing on renewable energy also tend to have higher circular material use rates.

The correlations suggest a network of relationships where AI adoption, resource productivity, economic development, and digital infrastructure interact to influence circular material use. The positive associations among these variables warrant further investigation through econometric modeling to determine causal relationships and the magnitude of these effects.

Multicollinearity was assessed among the independent variables by calculating Variance Inflation Factors (VIFs). All VIF values were below 2, well under the common threshold of 5 (Gujarati & Porter, 2009). This indicates that multicollinearity is not a significant concern in the regression models.

The correlation analysis highlights the interconnectedness of AI adoption, resource productivity, economic development, and circular economy practices. While there are significant positive correlations among key variables, the moderate correlations and acceptable VIF values suggest that multicollinearity is not a major issue, allowing us to proceed confidently with the econometric modeling.

4.2. Econometric Modeling Results

The correlation analysis highlights the interconnectedness of AI adoption, resource productivity, economic development, and circular economy practices. While there are significant positive correlations among key variables, the moderate correlations and acceptable VIF values suggest that multicollinearity is not a major issue, allowing us to proceed confidently with the econometric modeling.

The fixed-effects panel regression model (1) was estimated to examine the direct effect of AI adoption on CMUSE, controlling for key economic and industrial factors. The results are presented in Table 3.

Table 3: Fixed-Effects Regression Results

Variable	Coefficient	Std. Error (Robust)	t-value	p-value
AI_std	-0.013	0.068	-0.197	0.845
lgdp	0.041	0.31	0.132	0.896
RESP_std	0.475**	0.134	3.547	0.002
INDVA_std	0.11	0.143	0.774	0.447
Intercept	Included			
R-squared	0.407			
F-statistic	3.943	(df = 4; 23)		0.014

Note: ** indicates significance at the 0.01 level. Robust standard errors are used to account for heteroskedasticity.

Source: Own calculations.

The following interpretation is derived from the results presented in the Table 3:

- AI Adoption (AI_std): The coefficient for AI adoption is -0.013 with a robust standard error of 0.068. This negative coefficient suggests that, holding other factors constant, an increase in AI adoption is associated with a slight decrease in CMUSE. However, the effect is not statistically significant (p = 0.845), indicating that there is no evidence of a meaningful linear relationship between AI adoption and CMUSE within the sample period.
- GDP per capita (lgdp): The coefficient is 0.041 with a robust standard error of 0.310. This positive but insignificant coefficient (p = 0.896) suggests that higher GDP per capita is not significantly associated with changes in CMUSE when controlling for other variables.
- Resource Productivity (RESP_std): The coefficient is 0.475, and it is statistically significant at the 1% level (p = 0.002). This indicates that a one standard deviation increase in resource productivity is associated with a 0.475 standard deviation increase in CMUSE. This strong positive relationship suggests that countries utilizing resources more efficiently tend to have higher circular material use rates.
- Industrial Value Added (INDVA_std): The coefficient is 0.110 with a p-value of 0.447, indicating no statistically significant effect of the industrial sector's contribution to GDP on CMUSE within the sample.

The R-squared value of 0.407 implies that approximately 40.7% of the within-country variance in CMUSE is explained by the model. This indicates a moderate level of explanatory power. The F-statistic of 3.943 (p = 0.014) suggests that the model is statistically significant overall, meaning that the independent variables, collectively, have a significant effect on CMUSE.

To explore potential non-linear relationships between AI adoption and CMUSE, the quadratic term for AI adoption was included in the model (2). The results of the regression for the Model 2 are presented in Table 4.

Table 4: Fixed-Effects Regression with Quadratic Term

Variable	Coefficient	Std. Error (Robust)	t-value	p-value
AI_std	-0.1	0.111	-0.903	0.376
AI_std^2	0.026	0.026	0.987	0.335
lgdp	0.145	0.327	0.443	0.662
RESP_std	0.488**	0.135	3.626	0.001
INDVA_std	0.12	0.143	0.84	0.41
Intercept	Included			
R-squared	0.432			
F-statistic	3.345	(df = 5; 22)		0.021

Note: ** indicates significance at the 0.01 level. Robust standard errors are used.

Source: Own calculations.

The following interpretation is derived from the results presented in Table 4:

- AI Adoption (AI_std): The coefficient for the linear term is -0.100, while the quadratic term (AI_std^2) has a coefficient of 0.026. The negative coefficient on the linear term and the positive coefficient on the quadratic term suggest a U-shaped relationship between AI adoption and CMUSE. However, both coefficients are not statistically significant ($p = 0.376$ and $p = 0.335$, respectively).
- Resource Productivity (RESP_std): Remains statistically significant ($\beta = 0.488$, $p = 0.001$), reinforcing its positive impact on CMUSE.
- GDP per capita (lgdp) and Industrial Value Added (INDVA_std): Both variables remain statistically insignificant, consistent with the linear model.

The R-squared increases slightly to 0.432, indicating that the model explains about 43.2% of the within-country variance in CMUSE. This marginal improvement suggests that adding the quadratic term does not substantially enhance the model's explanatory power. The F-statistic is 3.345 ($p = 0.021$), indicating that the model is statistically significant overall.

To ensure the reliability of the regression results, several diagnostic tests were conducted. The Hausman test was conducted to determine the suitability of the fixed-effects model over the random-effects model. The test yielded a chi-square statistic of 14.57 with 4 degrees of freedom and a p-value of 0.0057, which was significant at the 5% level. This result supports the use of the fixed-effects model (Hausman, 1978). At the same time, the Breusch-Pagan test indicated the presence of heteroskedasticity (Chi-square = 10.84, $p = 0.0285$). Accordingly, robust standard errors were employed using the Huber-White sandwich estimator to ensure reliable inference (White, 1980).

4.3. Machine Learning Validation

To complement the econometric analysis and capture potential non-linear relationships and complex interactions among variables, the Random Forest regression model was employed using the same set of predictor variables: AI adoption (AI_std), GDP per Capita (lgdp), Resource Productivity (RESP_std), and Industrial Value Added (INDVA_std). Random Forest is an ensemble machine learning method that constructs multiple decision trees during training and outputs the average prediction of the individual trees, which helps in handling non-linearities and interactions without the need to specify them explicitly (Breiman, 2001).

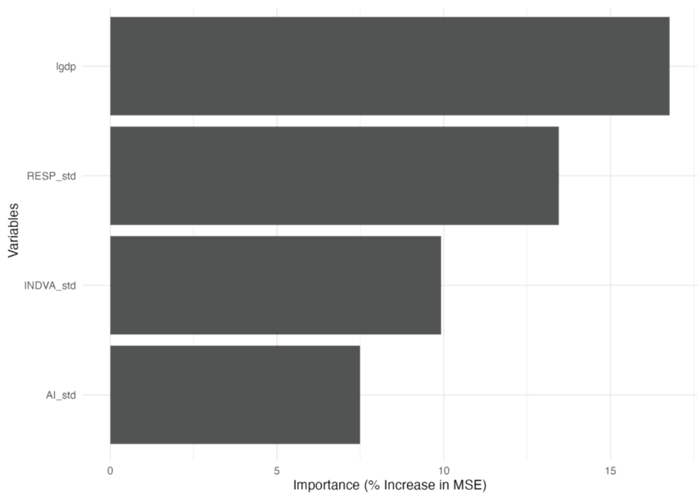
The Random Forest model was trained on the dataset comprising 54 observations. The performance metrics of the model are as follows:

- Mean Squared Error (MSE): 0.505
- Percentage of Variance Explained: 48.58%

These metrics indicate that the Random Forest model explains approximately 48.6% of the variance in CMUSE, which is slightly higher than the R-squared values obtained from the econometric models (40.7% and 43.2% for the linear and quadratic models, respectively). This suggests that the Random Forest model captures additional variance potentially due to non-linear relationships and interactions among variables.

To understand the contribution of each predictor to the model, the variable importance measures were examined based on the percentage increase in MSE when each variable is permuted. Figure 4 illustrates the importance of each variable.

Figure 4: Variable Importance in Random Forest Model



Source: Own calculations.

The variable importance scores are as follows:

1. GDP per capita (lgdp): 14.31% increase in MSE
2. Resource Productivity (RESP_std): 10.28% increase in MSE
3. Industrial Value Added (INDVA_std): 8.96% increase in MSE
4. AI Adoption (AI_std): 6.71% increase in MSE

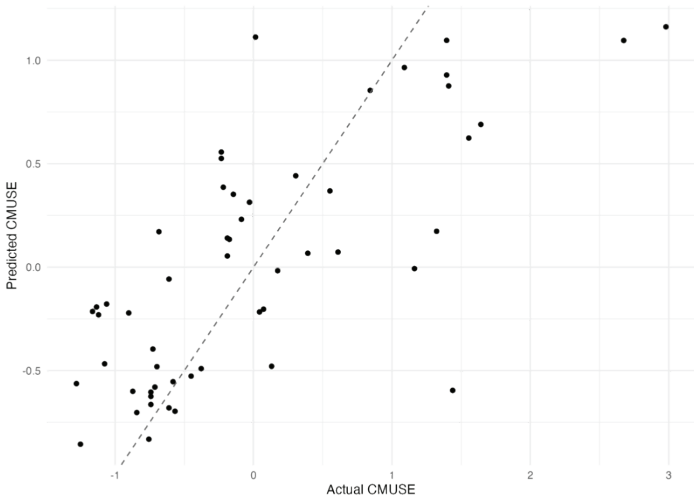
The following interpretation is derived from the results presented in Figure 4:

- GDP per capita (lgdp) is identified as the most important predictor in the Random Forest model. This suggests that economic development levels play a significant role in determining a country’s circular material use rate. Wealthier countries may have more resources to invest in circular economy initiatives and advanced technologies.

- Resource Productivity (RESP_std) remains a key predictor, consistent with the econometric analysis. Its high importance underscores the critical role of efficient resource utilization in enhancing circular material use.
- Industrial Value Added (INDVA_std) also contributes significantly to the model, indicating that the structure of the economy and the industrial sector's share may influence CMUSE.
- AI Adoption (AI_std), while contributing to the model, has a lower relative importance compared to the other variables. This aligns with the econometric results, where AI adoption did not have a statistically significant impact on CMUSE.

To assess the predictive accuracy of the Random Forest model, the actual versus predicted values of CMUSE were plotted.

Figure 5: Actual vs. Predicted CMUSE Values from Random Forest Model



Source: Own calculations.

The scatter plot in Figure 2 displays the actual CMUSE values on the x-axis and the predicted values from the Random Forest model on the y-axis. The dashed line represents the ideal 45-degree line where the predicted values equal the actual values.

The following interpretation is derived from the results presented in Figure 5:

- The data points are reasonably aligned along the 45-degree line, indicating that the model predictions are generally consistent with the actual CMUSE values.
- Some deviations are observed, which is expected given the complexity of the factors influencing CMUSE and the relatively small sample size.
- The visualization confirms that the Random Forest model provides a satisfactory fit to the data, capturing a significant portion of the variability in CMUSE.

To ensure the reliability of the Random Forest results, the following robustness tests were conducted:

- Cross-Validation:
  - A 5-fold cross-validation yielded an average MSE of 0.5425, confirming the model's predictive stability.
  - Additional metrics from cross-validation include an average RMSE of 0.7289 and an average R-squared of 0.5048, demonstrating consistent performance across folds.
- Alternative Specifications:
  - The inclusion of interaction terms and quadratic terms marginally improved model performance.
  - The variable importance rankings remained consistent, reinforcing the robustness of the original results.
- Hyperparameter Tuning:
  - The model's hyperparameters were tunned, including the number of variables sampled at each split.
  - The optimized model achieved a final MSE of 0.0838, with variable importance rankings consistent with the base model.

The machine learning validation provides valuable insights into the factors influencing CMUSE and corroborates the conclusions of the econometric analysis. The Random Forest model's ability to handle complex relationships adds depth to the understanding of the interplay between AI adoption, economic development, resource productivity, and circular economy outcomes.

The empirical analysis demonstrates that while there is a positive correlation between AI adoption and CMUSE, AI adoption does not have a statistically significant direct impact on CMUSE when controlling for other factors. Resource Productivity consistently emerges as a significant and robust predictor across both econometric and machine learning models, underscoring its critical role in advancing circular economy practices. Additionally, GDP per Capita plays a vital role, suggesting that higher levels of economic development enable countries to invest more effectively in circular economy initiatives and advanced technologies. These findings imply that policies aimed at enhancing resource efficiency and supporting economic growth may be more immediately effective in promoting circular material use within the EU. Further research with extended time frames and more detailed data could uncover delayed or sector-specific effects of AI adoption on the circular economy.

5. Discussion

The present study sought to investigate the relationship between Artificial Intelligence (AI) adoption and the Circular Material Use Rate (CMUSE) across the European Union (EU) member states. By employing a mixed-method quantitative approach that integrated econometric modeling and machine learning validation, the research aimed to address three primary research questions:

1. How does AI adoption influence CMUSE in EU member states?
2. What is the nature of this relationship—linear, non-linear, or threshold-based?
3. How do economic development and technological readiness affect this relationship?

This discussion interprets the empirical findings in light of these research questions, connecting them to the theoretical frameworks and previous literature presented earlier. The paper also explored the implications for policy and practice, acknowledging the study's limitations and proposing directions for future research.

5.1. The Influence of AI Adoption on CMUSE

The econometric analysis revealed that AI adoption does not have a statistically significant direct impact on CMUSE when controlling for other factors such as GDP per Capita, Resource Productivity, and Industrial Value Added. Specifically, the fixed-effects regression models showed negative but insignificant coefficients for AI adoption, both in linear and non-linear specifications (Tables 3 and 4). Similarly, the Random Forest model assigned a lower relative importance to AI adoption compared to other predictors (Figure 4).

These findings contrast with the theoretical expectations and prior studies that emphasize AI's potential to enhance circular economy practices (Tutore et al., 2024; Platon et al., 2024). The lack of a significant direct impact may be attributed to several factors:

- Temporal Lag: The effects of AI adoption on CMUSE may require more time to materialize. Given the relatively recent surge in AI implementation across industries, especially in the EU, the benefits for circular material use might not yet be observable at the macroeconomic level.
- Scale of Adoption: The average AI adoption rate among EU countries is 7.96%, with significant disparities (Table 1). Such low adoption levels may not be sufficient to produce measurable impacts on CMUSE across the entire economy.
- Micro vs. Macro-Level Effects: Previous research has often focused on firm-level or sector-specific benefits of AI in promoting circularity (Acerbi et al., 2021; Ghoreishi & Happonen, 2020). The aggregation to the national level may dilute these effects due to heterogeneity among industries and firms.
- Complementary Factors: The effectiveness of AI in advancing CE objectives may depend on complementary infrastructures, such as advanced waste management systems, regulatory support, and cross-sector collaboration (Popović et al., 2023). The absence of these enablers could hinder AI's potential impact on CMUSE.

5.2. Nature of the Relationship Between AI Adoption and CMUSE

The inclusion of a quadratic term for AI adoption in the fixed-effects model aimed to capture potential non-linearities or threshold effects. However, both the linear and quadratic terms of AI adoption remained statistically insignificant (Table 4). The Random Forest model, designed to handle complex non-linear relationships, also did not identify AI adoption as a significant predictor compared to GDP per Capita and Resource Productivity.

The absence of significant non-linear effects suggests that within the observed range of AI adoption rates, there is no evidence of diminishing returns or threshold levels that significantly influence CMUSE. This finding challenges the propositions by Nham and Ha (2022) and Platon et al. (2024), who suggested possible non-linear dynamics in the relationship between digital technology adoption and circularity outcomes.

The possible explanations for the results include:

- Homogeneity in AI Adoption Levels: The relatively narrow range and low average of AI adoption rates may not provide sufficient variation to detect non-linear effects.

- Dominance of Other Factors: The influence of economic development and resource productivity may overshadow any subtle non-linear impacts of AI adoption on CMUSE.
- Measurement Limitations: The use of aggregated AI adoption rates may not capture the nuances of different AI applications and their varying impacts on circular practices.

5.3. The Role of Economic Development and Technological Readiness

Both the econometric and machine learning analyses highlighted the significant roles of GDP per Capita and Resource Productivity in influencing CMUSE. While GDP per Capita was not statistically significant in the econometric models, it was identified as the most important predictor in the Random Forest model (Figure 4). Resource Productivity consistently showed a strong positive and significant effect on CMUSE across all models. The interpretation of these results is presented in the lines below.

- Economic Development (GDP per Capita): The importance of GDP per Capita aligns with the notion that wealthier countries possess more resources to invest in circular economy initiatives and advanced technologies (Platon et al., 2024; Popović et al., 2022). Higher economic development facilitates infrastructure development, research and innovation, and the adoption of sustainable practices.
- Resource Productivity: The significant impact of Resource Productivity underscores the critical role of efficient resource utilization in advancing circular economy objectives (Kirchherr et al., 2017; Ghisellini et al., 2016). Countries that manage resources more efficiently tend to have higher rates of material recycling and reuse.
- Technological Readiness: The positive correlations between CMUSE and indicators of digital infrastructure, such as Cloud Computing Services (CCOMP) and E-commerce Sales (ECOMS), suggest that technological readiness contributes to circular economy practices. This supports findings by Popović et al. (2022) and Tutore et al. (2024), who emphasized the enabling role of digital technologies in implementing CE principles.

The research results have broad and deep implications, which include:

- Policy Alignment: The results highlight the necessity of aligning technological advancement with economic and resource efficiency policies. Investments in AI and digital technologies should be complemented by efforts to enhance resource productivity and economic development to maximize their impact on CMUSE.
- Tailored Interventions: The disparities in economic development and technological readiness among EU member states indicate the need for tailored policy interventions. Less affluent countries may require additional support to build the necessary infrastructure and capabilities for effective AI integration into circular economy strategies (Popović & Milijić, 2021).

5.4. Integration with Theoretical Frameworks, Limitations and Future Research

The study's findings resonate with the Resource-Based View (RBV) and the Dynamic Capabilities Framework, which emphasize the importance of leveraging resources and competencies to achieve competitive advantage and adapt to environmental changes (Barney, 1991; Teece et al., 1997). The significant role of Resource Productivity suggests that countries effectively utilizing their resources can enhance their circular economy performance.

Moreover, the results align with the CE dimensions outlined by Kirchherr et al. (2017) and the sustainable product lifecycle strategies discussed by Aleksić et al. (2023). The emphasis on resource efficiency and economic development reinforces the interconnectedness of environmental sustainability and economic competitiveness.

This research provides valuable insights into the complex relationship between AI adoption and circular material use within the EU. While AI adoption does not exhibit a significant direct impact on CMUSE in the short term, the critical roles of Resource Productivity and Economic Development are evident and consistent across both econometric and machine learning models. These findings emphasize the importance of focusing on resource efficiency and economic growth as primary drivers of circular economy practices. Additionally, the lack of significant non-linear effects suggests that the benefits of AI adoption on CMUSE may either require a longer timeframe to manifest or depend on complementary factors not captured in this study. Future research should explore these dimensions further to fully understand the potential of AI in fostering sustainable economic transitions.

6. Conclusion

This research provides a comprehensive examination of the relationship between Artificial Intelligence (AI) adoption and the Circular Material Use Rate (CMUSE) within the European Union (EU). By employing a mixed-method approach integrating econometric modeling and machine learning validation, the research offers nuanced insights into the interplay between digital transformation and circular economy practices. The findings contribute to the growing body of literature on sustainable development, addressing critical gaps in understanding how emerging technologies influence macroeconomic indicators of sustainability.

The econometric results reveal that AI adoption does not have a statistically significant direct effect on CMUSE. This outcome contrasts with theoretical expectations and highlights the complexity of translating technological advancements into measurable circular economy outcomes at the macroeconomic level. While AI's transformative potential has been widely discussed, its impact on circular practices may depend on factors such as the scale and maturity of adoption, temporal lags, and the presence of complementary infrastructures. The analysis suggests that the benefits of AI adoption for circular material use might manifest more strongly at the microeconomic level - within specific industries or firms - than in aggregated national-level data.

The machine learning validation reinforces the econometric findings by demonstrating that AI adoption while contributing to the explanatory model, has relatively lower importance compared to other predictors such as GDP per Capita and Resource Productivity. These results emphasize the critical roles of economic development and resource efficiency in shaping circular economy outcomes. Wealthier countries with advanced infrastructures and institutional capacities are better positioned to leverage technological innovations for sustainability. Similarly, countries with higher resource productivity are more likely to achieve greater material circularity, underscoring the need for policies that prioritize efficient resource utilization alongside technological investments.

The absence of significant non-linear or threshold effects of AI adoption on CMUSE further challenges assumptions in prior studies, which posited that diminishing returns or acceleration effects might influence this relationship. Within the observed range of AI adoption rates, there is no evidence to suggest such dynamics. This finding points to the potential limitations of aggregated AI adoption metrics and the need for future research to consider more granular data that captures the diversity of AI applications and their sector-specific impacts.

The implications of this study are important for both academic inquiry and policy design. For researchers, the findings highlight the importance of integrating macroeconomic analyses with sectoral and micro-level studies to uncover the mechanisms through which AI adoption influences sustainability. The combination of econometric and machine learning approaches in this study demonstrates the value of methodological pluralism in capturing both linear and complex non-linear dynamics. Future research should build on this foundation by extending the temporal scope, exploring industry-specific applications, and examining mediating factors such as policy frameworks, institutional quality, and cultural attitudes toward sustainability.

For policymakers, the results suggest that investments in AI technologies should be complemented by initiatives that enhance resource productivity and economic development. The findings underscore the necessity of aligning digital transformation strategies with sustainability goals to ensure that technological advancements translate into tangible environmental benefits. Tailored policy interventions are particularly critical for less-developed EU member states, where disparities in economic capacity and technological readiness may hinder the realization of AI's potential to advance circular economy objectives. Collaborative frameworks that facilitate knowledge sharing and capacity building across the EU could help bridge these gaps and promote more equitable progress toward circularity.

Finally, this research reaffirms the centrality of economic development and resource efficiency in driving circular economy practices, while raising critical questions about the current and potential role of AI adoption in this process. Although AI's transformative potential remains undeniable, its direct impact on CMUSE is contingent upon a range of contextual and systemic factors that merit further exploration. By providing robust empirical evidence and actionable insights, this research contributes to the ongoing discourse on leveraging technological innovation for sustainable development. It underscores the need for integrated strategies that balance economic, technological, and environmental priorities, offering a pathway for the EU and beyond to achieve a more sustainable and resilient future.

Acknowledgements:

This research was supported by the Ministry of Education, Science and Technological Development. Contract Number: 451-03-66/2024-03/200371.

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ЭЕ
ECONOMICS OF SUSTAINABLE DEVELOPMENT

Vol. 9, January-June 2025, № 1
UDK 33+502/504
ISSN 2560-421X

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P. 29-38
ORIGINAL SCIENTIFIC ARTICLE
10.5937/ESD2501029M
Received: September 12, 2024
Accepted: January 11, 2025

ANALYSIS OF POVERTY IN THE EUROPEAN UNION: A CLUSTER APPROACH

Abstract

The purpose of this paper is to group the countries of the European Union according to selected poverty indicators. To this end, a cluster analysis based on the most recent annual data available (2023) was applied, which divides all European Union Member States into four clusters, as homogeneous units. The results show that the most successful countries belong to Central, Western and Northern Europe, which form a separate cluster (Cluster 1). On the other hand, the countries of Southern Europe, the Balkan countries as well as the Baltic countries, achieve poor performance and are classified into three clusters (Cluster 2, Cluster 3, and Cluster 4). The results will be useful to the creators of economic and social policy at the level of the Member States, but also at the level of the entire European Union. It is a new study of poverty in the European Union, which uses an original set of indicators in a cluster analysis of this phenomenon.

Keywords: *poverty, social exclusion, cluster analysis, European Union.*

JEL classification: *I32, C38*

АНАЛИЗА СИРОМАШТВА У ЕВРОПСКОЈ УНИЈИ: КЛАСТЕРСКИ ПРИСТУП

Апстракт

Сврха рада је да групише земље Европске Уније према одабраним индикаторима сиромаштва. У том циљу, примењена је кластер анализа на основу најновијих доступних годишњих података (2023), која све земље чланице Европске Уније дели у четири кластера, као хомогене целине. Резултати показују да најуспешније земље припадају централној, западној и северној Европи које формирају засебан кластер (Кластер 1). Са друге стране, земље Јужне Европе, земље Балкана, као и Балтичке земље остварују лоше перформансе и класификују се у три кластера (Кластер 2, Кластер 3 и Кластер 4). Резултати ће користити креаторима економске и социјалне политике на нивоу држава чланица, али и на нивоу целе

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Европске Уније. Ради се о новој студији сиромаштва у Европској Унији, која користи оригинални сет индикатора у кластер анализи овог феномена.

Кључне речи: *сиромаштво, социјална искљученост, кластер анализа, Европска Унија.*

1. Introduction

Sustainable development of society is unthinkable without the eradication of poverty. Poverty reduction is one of the main Millennium Development Goals (Kalinowski & Kiełbasa, 2017). The related global goals of sustainable development are eradicating hunger, achieving greater coverage of people through education, as well as improving the health status of the population. Poverty is a challenge faced by all countries of the world (Belu et al., 2024), so all countries are making efforts to reduce poverty. Social prosperity in the narrow sense relies on economic growth. However, an important link in achieving overall social development is social sustainability, in which solving the problem of poverty plays one of the main roles (Marković, 2024).

The main factor of poverty is a lack of income, i.e. material resources. Not having money to meet basic needs and ensure a decent standard of living is the first visible cause of poverty. However, poverty also implies the inability to have non-financial resources such as health, education, social and cultural resources (Iftimoaei, Baciu & Gabor, 2021). Therefore, the observation of poverty without including other indicators of material deprivation (social exclusion) is inadequate. An important determinant of poverty in a country is the unemployment rate, which can be the result of inadequate education of individuals, labour market disruptions, global market developments, or poor government economic policies.

Observing and measuring poverty in the European Union is significant because of the nature of this economic integration. The complexity is reflected in the fact that enlargements took place slowly, over a longer period, as well as in the fact that countries differ in basic social and economic indicators. This was especially evident after the last largest enlargement of the European Union, when the countries of Eastern Europe joined this integration (Fahey, 2005). Although this economic integration is considered one of the most developed and advanced of all others, the risk of poverty and social exclusion persists, especially after the economic crisis of 2008, as well as the social crises of recent years. Just as the goal at the world level is to reduce the number of people living in poverty, so in the European Union it is one of the leading social goals. Unfortunately, the 2020 poverty targets were not met by even 20% (Aranguiz, 2022). Poverty also has a special place in the Europe 2030 strategy. By 2030, the number of people in poverty is expected to be reduced by 15 million people compared to 2020 (European Commission, 2021). In all earlier development strategies, the European Union focused on the social dimension of development, which is reflected in the constant promotion of full employment, fostering high social protection, emphasis on social inclusion, as well as increased participation in education, training, and health care services (Akarçeşme et al., 2023).

The aim of this paper is to identify advanced economies according to the level of poverty, and on the other hand, countries that need greater financial and social support to fight poverty. Continuous monitoring and analysis of poverty is the first step in defining measures to alleviate it and build a fairer society and social sustainability, especially in the light of previous crises such as the COVID-19 pandemic and the military conflict in Ukraine.

The paper consists of several parts, respecting the usual structure in scientific research - IMRAD. After the introduction, the data sources, material, and approach are described in the Methodology section. The results of the research, in addition to presenting the findings, include tables and graphs based on the conducted cluster analysis, while the Discussion section reveals the most important findings. The paper ends with concluding remarks.

2. Methodology

Poverty is a multidimensional phenomenon, which means that it can be represented by many indicators (Palaščáková & Stepaniuk, 2016). In the European Union, persons are at risk of poverty (relative poverty) if they have an income lower than 60% of the national median equivalent disposable income (Iftimoaei, Baciu & Gabor, 2021). It is the “At-risk-of-poverty rate” indicator. However, the degree of poverty of an individual cannot be assessed solely on the basis on realized income (material factor), which is indeed the most common indicator of poverty. Access to health care services, the level of long-term unemployment, social exclusion, the percentage of people who are severely materially deprived, etc. are also important. That is why it is necessary to apply several indicators in the analysis of poverty (in addition to the “At-risk-of-poverty rate”), such as: “Severe material and social deprivation rate”, “Self-reported unmet need for medical examination and care”, and “Long-term unemployment rate”. One gets the impression that poverty is often associated with different forms of social exclusion, which can be economic, cultural, and political exclusion. These non-material factors can be seen as a consequence of poverty because individuals who are socially excluded have fewer opportunities to acquire adequate education, meet some medical needs, which leads them to marginalization in every sense (Marković et al., 2022). In addition, having a job does not mean that such individuals can afford to meet basic needs, so the inclusion of the “In work at-risk-of-poverty rate” indicator in this study is justified. This may be due to the increasing number of fixed-term contracts, as well as temporary and occasional jobs, which has been a widespread practice in recent years (Aranguiz, 2022). Because of all this, the concept of poverty is also described as a composite concept (Frączek, 2022).

Based on the available literature and the Eurostat database, the author selected the following indicators of poverty: “At-risk-of-poverty rate”, “Severe material and social deprivation rate”, “In work at-risk-of-poverty rate”, “Self- reported unmet need for medical examination and care”, and “Long-term unemployment rate”. The data for these indicators are in percentages and refer to the last available year in the database used (2023).

To group the countries of the European Union by clusters, the author applied hierarchical cluster analysis (Everitt et al., 2011), while Ward’s method (object grouping method) was used as the clustering method (Nardo et al., 2005), and the squared Euclidean distance was used as a measure of distance between objects (Janković-Milić, Lepojević & Stanković, 2019).

3. Research results and Discussion

Table 1 shows descriptive statistics of the poverty indicators used in the research. Descriptive statistics refer to data on the minimum, maximum and mean values of indicators. Also, the size of the standard deviation was calculated.

The data from Table 1 show that the largest deviations from the mean are in the "Severe material and social deprivation rate" indicator, while, on the other hand, the lowest standard deviation is present in the "Long-term unemployment rate" indicator. The countries of the European Union differ the most in terms of the percentage of severe material and social deprivation, from 2% in Slovenia to as much as 19.80% in Romania. The poverty risk rate is the highest in Estonia and Latvia, while the Czech Republic records the lowest value of the same indicator (9.80%). It must be pointed out that it is the only country in the European Union that in 2023 achieved a poverty rate lower than 10%. Furthermore, Finland has the lowest rate of poverty among people who are employed. On the other hand, Romania again has the worst value of this indicator. According to Eurostat data, Malta and Cyprus stand out as the countries where the highest percentage of the population has their needs for medical (health) care and protection met, while Estonia is at the bottom. The latter indicator measures the long-term unemployment rate. Long-term unemployment is the highest in Greece, while Denmark and the Netherlands both have the same long-term unemployment rate of just 0.50%. Romania and Estonia have the worst poverty scores for two indicators.

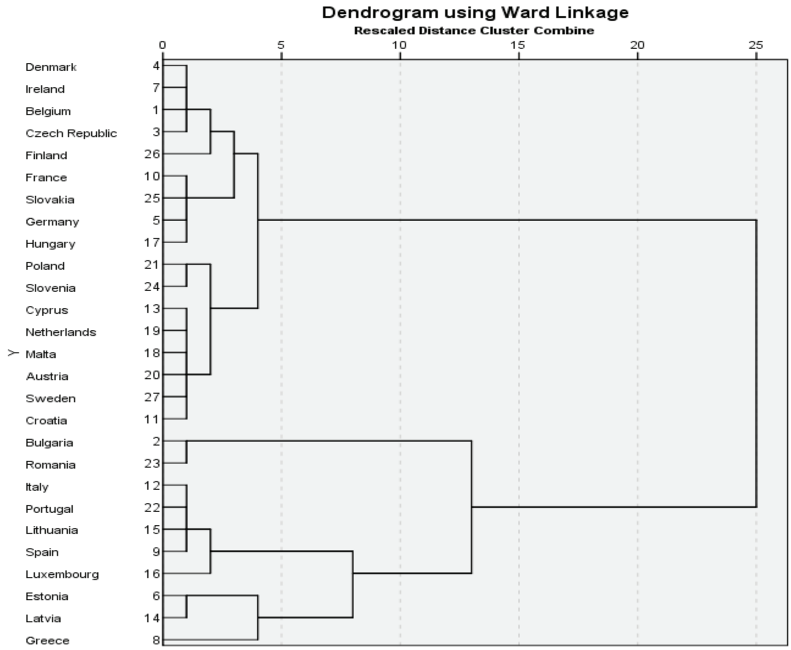
Table 1: Descriptive statistics of poverty indicators

Indicator	Minimum	Maximum	Mean	Std. Deviation
At-risk-of-poverty rate	9,80 (Czech Republic)	22,50 (Estonia, Latvia)	16,2556	3,62452
Severe material and social deprivation rate	2,00 (Slovenia)	19,80 (Romania)	6,0630	4,60695
In work at-risk-of-poverty rate	2,80 (Finland)	15,00 (Romania)	8,1444	2,98088
Self-reported unmet need for medical examination and care	0,10 (Malta, Cyprus)	12,90 (Estonia)	3,1148	3,36334
Long-term unemployment rate	0,50 (Denmark, Netherlands)	6,20 (Greece)	1,9630	1,31388

Source: IBM SPSS 22 according to Eurostat data, 2024.

Figure 1 displays the dendrogram, as a result of the applied hierarchical cluster analysis, Ward's method and squared Euclidean distance. In the figure, at a distance of 5, four clusters of European Union countries can be clearly identified according to the state of poverty as a social indicator.

Figure 1: Dendrogram (Hierarchical cluster analysis)



Source: Authors' presentation based on Eurostat data (2024) and IBM SPSS 22 program

Table 2 presents the number of countries by formed clusters, i.e. the structure of clusters. The first cluster comprises the largest number of countries. It is also the cluster with the countries that achieve the lowest poverty rates because they have the most favourable value indicators. Other clusters include countries that have worse indicators. The worst is Cluster 2, which consists of Romania and Bulgaria.

Table 2: Grouping of European Union countries into clusters according to poverty indicators

Clusters	Countries
Cluster 1 (17 countries)	Denmark, Ireland, Belgium, Czech Republic, Finland, France, Slovakia, Germany, Hungary, Poland, Slovenia, Cyprus, Netherlands, Malta, Austria, Sweden, Croatia
Cluster 2 (2 countries)	Bulgaria, Romania
Cluster 3 (5 countries)	Italy, Portugal, Lithuania, Spain, Luxembourg
Cluster 4 (3 countries)	Estonia, Latvia, Greece

Source: Authors' presentation, IBM SPSS 22

Table 3 offers a more detailed insight into the clusters, by calculating the mean, minimum and maximum values of the observed indicators within each of them.

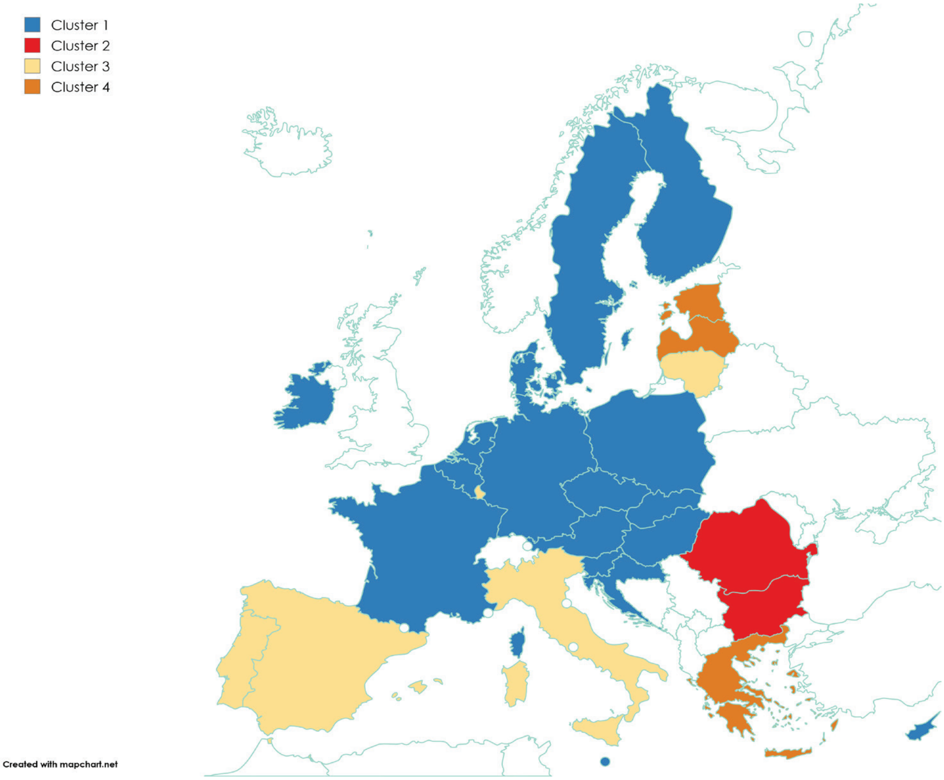
Table 3: Mean, maximum and minimum values of poverty indicators within individual clusters

Cluster	Indicator 1	Indicator 2	Indicator 3	Indicator 4	Indicator 5
Cluster 1					
Mean	13,99	4,5	6,42	2,03	1,42
Max	19,3	10,4	9,1	7,9	3,8
Min	9,8	2,0	2,8	0,1	0,5
Cluster 2					
Mean	20,85	18,9	13,35	3,15	2,25
Max	21,1	19,8	15,0	5,2	2,3
Min	20,6	18,0	11,7	1,1	2,2
Cluster 3					
Mean	19,1	5,44	10,82	2,2	3,0
Max	20,6	9,0	14,8	3,8	4,3
Min	17,0	2,5	8,1	0,8	1,7
Cluster 4					
Mean	21,3	7,4	9,97	10,77	3,1
Max	22,5	13,5	10,6	12,9	6,2
Min	18,9	2,5	9,5	7,8	1,3

Source: Authors' calculations
Note: Indicator 1 - At-risk-of-poverty rate; Indicator 2 - Severe material and social deprivation rate; Indicator 3 - In work at-risk-of-poverty rate; Indicator 4 - Self-reported unmet need for medical examination and care; Indicator 5 - Long-term unemployment rate.

Cluster 1 achieves the lowest mean values for all indicators, so since all the attributes of poverty are of the cost type, this cluster is in the best position regarding poverty. This cluster of countries is the largest and includes most of the countries of the European Union (17), which is a positive circumstance. Cluster 3 consists of five countries. It performs slightly worse compared to the group of countries from the previous cluster. The countries in this cluster have particularly good indicators for Indicator 2 (At-risk-of-poverty rate) and Indicator 4 (In work at-risk-of-poverty rate). Cluster 4 and Cluster 2 gather the countries with the worst poverty indicator rates. They include most of the Baltic countries, as well as the Balkan countries (Greece, Bulgaria, and Romania). Figure 2 clearly shows the spatial distribution of countries by cluster in order to more easily see the extent of poverty at the level of the European Union.

Figure 2: Geographical distribution of clusters on the map of the European Union



Source: The map was generated using Map Chart (mapchart.net)

According to other research, the countries of Southern Europe are also the most affected by poverty in the European Union (Sompolska-Rzechuła & Kurdyś-Kujawska, 2022). In addition to the Southern European countries (Spain, Portugal, Italy, Greece), the Baltic countries (Estonia, Latvia, and Lithuania), as well as Bulgaria and Romania, are in a bad position. The last two countries are the Balkan countries that (excluding Croatia) joined the European Union at the latest.

Although underdeveloped countries are more vulnerable, it is necessary to point out that poverty affects all countries, regardless of their level of economic development (Janković-Milić, Lepojević & Stanković, 2019). An interesting example is Luxembourg. Luxembourg stands out in terms of poverty compared to the other Benelux countries and had worse indicators in the earlier period (2016) according to the results of the cluster analysis of other researchers, who used a similar set of poverty indicators in the European Union (Palaščáková & Stepaniuk, 2016). Many readers would expect Luxembourg to be classified in Cluster 1. But, on the other hand, we should be careful in drawing conclusions, because being poor in Luxembourg and Spain is not the same (given the different absolute values of the poverty thresholds). Future research should focus on the interdependence of the level of poverty and inequality in income distribution since Luxembourg has a relatively high GINI coefficient. Other studies show similar results. Portugal, Greece, and Italy have still not recovered from the public debt crisis triggered by the 2008 global economic and financial crisis. It should be noted that the state of poverty may be the result of ineffective income redistribution measures or inadequate policies to combat poverty in these countries. The level of social benefits, the degree of economic development and the measures of social and economic policy of individual countries are factors that significantly influence the differences in the level of poverty and social exclusion among European countries (Frączek, 2022).

Conclusion

Social progress is often conditioned by the prevention of social risks, including poverty. Tackling poverty is the key to sustainable socio-economic development. The at-risk-of-poverty rate focuses on relative poverty, therefore, often this indicator alone is not adequate in international comparisons. That is why other indicators were also considered in this analysis. For example, material deprivation considers absolute poverty, as do most of the other indicators used that refer to some non-economic factors. It is highly likely that individuals living in poverty will have lower human rights, face the impossibility of finding a well-paid job, and more difficult to meet their health needs.

The paper assessed poverty in the European Union based on the classification of member countries into clusters. It is a problem that creates social costs and makes it impossible to achieve sustainable development of society. Social costs are most often reflected in social benefits (social aid, unemployment benefits and increased health care expenditures). Secondly, the increase in taxes, to finance public expenditures for the fight against poverty, can act as a disincentive on economic activities. It is especially dangerous if there is an inefficiency of social transfers, i.e. if they are not allocated to the most vulnerable population categories. Therefore, it is necessary to constantly monitor the state of poverty in the country and at the supranational level (European Union) and take appropriate financial and non-financial measures. Of course, improving the economic environment is imperative for the poverty relief in the long term.

Acknowledgments:

This research was financially supported by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia (Agreements on the implementation and financing of scientific research in 2024 - Contracts No. 451-03-66/2024-03/200371 and No. 451-03-66/2024-03/200100).

This paper is part of the research done within the international project "*Twinning for excellence in Smart and Resilient Urban Development: Advanced Data Analytics Approach*" (UR DATA) that has received funding from the European Union's Horizon Europe Framework programme (HORIZON-WIDERA-2021-ACCESS-02) under Grant Agreement No. 101059994. Usual disclaimers apply.

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ЭЕ
ECONOMICS OF SUSTAINABLE DEVELOPMENT
Vol. 9, January-June 2025, № 1
UDK 33+502/504
ISSN 2560-421X

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P. 39-50
ORIGINAL SCIENTIFIC ARTICLE
10.5937/ESD2501039S
Received: April 17, 2024
Accepted: October 11, 2024

SERVITIZATION STRATEGY AND FINANCIAL PERFORMANCE OF MANUFACTURING COMPANIES IN THE REPUBLIC OF SERBIA: A PRELIMINARY STUDY

Abstract

Intending to identify the relation between Serbian manufacturing companies' performance and the servitization strategy, the paper presents research that was carried out on a sample of 10 medium and large companies. The results suggest that there is a positive correlation between the level of servitization and the financial performance of manufacturing companies, as well as between the company's experience in implementing this strategy and its profits. Although the direction of the correlation corresponds to the hypothesized one, the results are not statistically significant. A small and geographically undiversified sample is seen as a primary reason for this. As a preliminary, this study should actualize servitization as a field of research and initiate the interest of practitioners in this strategy.

Keywords: *competitiveness, manufacturing, services, performance*

JEL classification: M11, L25

СТРАТЕГИЈА СЕРВИТИЗАЦИЈЕ И ФИНАНСИЈСКЕ ПЕРФОРМАНСЕ ПРОИЗВОДНИХ ПРЕДУЗЕЋА У РЕПУБЛИЦИ СРБИЈИ: ПРЕЛИМИНАРНА СТУДИЈА

Апстракт

Са циљем да се идентификује однос између стратегије сервитизације и перформанси производних предузећа у Републици Србији, у раду је презентовано истраживање које је реализовано на узорку од 10 средњих и великих предузећа. Резултати спроведеног истраживања указују на то да између нивоа сервитизације и финансијских перформанси производних предузећа, као и између искуства предузећа у имплементацији ове стратегије и профита, постоји позитивна корелациона веза. Иако идентификовани смер корелационе везе одговара смеру који је дефинисан истраживачким хипотезама, изостала је статистичка значајност добијених резултата, за шта се примарни разлог види у малом и географски недиверзификованом узорку. И поред тога, као прелиминарна, ова студија

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треба да актуелизује сервитизацију као истраживачко поље и иницира интересовање практичара за ову стратегијску опцију.

Кључне речи: *конкурентност, производња, услуге, перформансе*

Introduction

The competitiveness of manufacturing companies is a complex phenomenon, determined by a range of factors located in the internal and external environment (Benedettini et al., 2015; Opresnik & Taisch, 2015). Strategic analysis of manufacturing companies highlights the importance of external threats and internal weaknesses for their competitiveness (Rabetino et al., 2017; Feng et al., 2021). Strengthening the position of consumers as one of the competitive forces, intensifying competition, maturing and saturation of the market, technology development, fluidity of industry boundaries and new competitors are some of the factors that weaken the competitive potential of manufacturing companies (Vandermerwe & Rada, 1988; Gaiardelli et al., 2014; Tao & Qi, 2019). Internally, the competitive position of manufacturing companies is threatened due to their insufficient flexibility and agility, investment in employee development, risk aversion, as well as inert business models (Xing Liu et al., 2017; Karatzas et al., 2020; Simonsson & Agarwal, 2021).

Responding to the challenges of threatened competitiveness, manufacturing companies seek to improve their business potential by undertaking a series of measures and practices, such as co-creating value with consumers (Cao et al., 2015), specialization, and close cooperation with key stakeholders (Tongur & Engwall, 2014), as well as a strategic turn, or innovation of their strategic portfolio (Rabetino et al., 2017; Tao & Qi, 2019). With all of the above, a servitization strategy is recognized as one of the possible paths that manufacturing companies can take to improve their competitive position (Martinez et al., 2010; Kowalkowski et al., 2017; Adrodegari & Saccani, 2020).

With the servitization strategy, the manufacturers are transforming and innovating their businesses toward offering an integrated bundle of products and services to deliver a total value for their customers (Vandermerwe & Rada, 1988; Baines et al., 2009; Martinez et al., 2010; Opresnik & Taisch, 2015). The servitization strategy is seen as a successful way to achieve a differentiated competitive advantage (Opresnik & Taisch, 2015). Successful implementation of this strategy supports the sustainable growth of manufacturing companies by enabling greater customer satisfaction and loyalty leading to an increase in the firm's revenues and profits (Bustinza et al., 2015; Kowalkowski et al., 2017).

Although the beginnings of the practical application of the servitization strategy in manufacturing companies can be traced back to the middle of the 20th century (Feng et al., 2021), academic interest in this strategic option is more recent (Garcia Martin et al., 2019; Chen et al., 2022). Along with the efforts to conceptually frame the servitization (Vandermerwe & Rada, 1988; Ulaga & Reinartz, 2011), the attention of researchers is also focused on internal and external drivers and motives for implementing this strategy (Kowalkowski et al., 2015; Rabetino et al., 2018; Tao & Qi, 2019), the supply chain environment in which this implementation takes place (Martinez et al., 2010; Khanra et al., 2021), as well as on the underlying business models' innovation and the challenges a firm faces (Opresnik &

Taisch, 2015; Rabetino et al., 2017). In addition to the above, the impact of servitization on a firm's performance comes into research focus (Benedettini et al., 2015; Kohtamäkiet al., 2019). However, even though servitization strategy and its relationship with the performance of manufacturing companies are undoubtedly significant research questions, the number of quantitative studies is not large. On the contrary, the majority of studies are qualitative and exploratory case studies (Vandermerwe & Rada, 1988; Eisenhardt, 1989; Khanra et al., 2021). The minority of quantitative studies that investigate the relationship between a firm's performance and servitization, do not offer unique results that allow unambiguous conclusions.

With the main purpose of contributing to filling the perceived gap, this paper aims to identify the relationship between the servitization strategy and the performance of manufacturing companies in the Republic of Serbia. To achieve this goal, the paper is structured as follows. The first part presents the results of the literature analysis based on which the expected relationships between the servitization strategy and the financial performance of manufacturing companies are hypothesized. Methodological aspects of the study design are described in the second part of the paper, after which the results of the conducted research are presented and discussed in the third part of the paper. The paper ends with some concluding remarks.

1. Literature review and hypotheses development

Services affect the functionality of the base product and they create additional value for customers. Nevertheless, their effects on producers' performance are not clear. The relationship between a servitizer's performance and the servitization strategy is probably the most complex aspect of research in this domain. Ambiguous results, methodological differences with an unclear effect of these differences on the results, as well as partial studies that do not include all factors that can influence the relationship (Kastalli & Van Looy, 2013; Feng et al., 2021), are some of the factors that make this research question complex.

Adequate implementation of the servitization strategy can increase revenues and profits, which then becomes the basis of sustainable growth (Martinez et al., 2010; Kastalli & Van Looy, 2013; Raddats et al., 2016; Kowalkowski et al., 2017; Mastrogiacomo et al., 2017; Garcia Martin et al., 2019; Adrodegari & Saccani, 2020; Kharlamov & Parry, 2021). The positive impact of the servitization strategy on the sales and revenues of manufacturing companies can be a result of a more complete satisfaction of consumer needs, a wider coverage of the market, a higher level of satisfaction, and customer loyalty. Thus, for example, servitization as a strategic option enables manufacturers to continuously monitor the state of the product during its use by the customer and to act proactively to prevent failures and/or maintain the product efficiency (Heskett et al., 2008; Kowalkowski et al., 2017). By actively monitoring the condition of a product and regularly replacing components, the product lifecycle can be extended (Kastalli & Van Looy, 2013; Benedettini et al., 2015). All of the previous means that consumers receive better quality products, which then increase their level of satisfaction and loyalty, leading to repeated purchases and increased sales revenue (Heskett et al., 2008). In addition, when a customer's needs and the product itself are better understood, a firm can improve the product design and reduce the costs of its use, which further encourages the sale of a new generation of products (Oliva & Kallenberg, 2003). By enriching its offer with services, the manufacturer may gain new information about customer needs, which can lead to increased sales of related and complementary products (Kastalli & Van Looy, 2013).

Despite the described positive impact on revenues, the implementation of the servitization strategy requires investments and changes in operating the business (Gebauer et al., 2005; Lenka, Parida & Wincent, 2016). In this way, the servitization strategy confronts manufacturers with greater internal and external risks, some of which are completely new and arise precisely because of the implementation of this strategy (Benedetini et al., 2015). Some of these challenges concern the change in organizational structure and culture, the need for a new set of resources and capabilities, as well as changes in supply chain relationships, both downstream and upstream (Kindström & Kowalkowski, 2014; Cao et al., 2015; Díaz-Garrido et al., 2018; Makkonen et al., 2022).

Lack of knowledge to manage services, but also different characteristics of services that are not aligned with the usual values and goals of production, all can increase the cost of servitization (Kastalli & Van Looy, 2013). Moreover, a manufacturing firm may be confronted with high market barriers in introducing services in its offer. For example, customers may expect that the additional service from its manufacturing supplier should be free of charge, or they may resist connecting more closely with the manufacturer to provide additional services because they fear the outflow of internal information (Coreynen et al., 2017). In a word, the research results on the relationship between servitization strategy and profit are not unambiguous. Some authors find that the servitization strategy increases the firm's profitability and that this relationship is linear (Neely, 2008; Kastalli & Van Looy, 2013), that is, positive and non-linear (Kohtamäki et al., 2013; Khanra et al., 2021), others identify a non-linear, U-shaped relationship (Kastalli & Van Looy, 2013; Kohtamäki et al., 2020). Moreover, it is indicated that the model of maturity is valid in the case of servitization (Martinez et al., 2010; Mastrogiacomo et al., 2017; Adrodegari & Saccani, 2020; Feng et al., 2021). This maturity is reflected by the firm's experience in implementing the strategy, as well as the level of its application, where a higher level of servitization implies greater importance of the services within the firm's offer (Gomes et al., 2021).

Based on the literature review, the following relationships are expected between the servitization strategy and the company's financial performance:

H1: *A higher level of servitization strategy is positively correlated with the company's operating income*.

H2: *A higher level of servitization strategy is positively correlated with the company's operating costs*.

H3: *The firm's profit is positively correlated with the level of servitization and experience of the company in implementing the servitization strategy*.

2. Methodology

2.1. Data and sample

The research was conducted on a sample of 10 large and medium-sized companies located in the area of the city of Niš. After the initial contact with company representatives, respondents were sent a link to an online questionnaire (Google Forms) through which data for the research was collected. The research was conducted in the period from December 2023 to February 2024. Available evidence suggests that the servitization strategy is more often a practice of large and medium-sized enterprises (Eloranta et al., 2021; Kharlamov & Parry, 2021), and this was the argument for sample units' selection. Data on the sample's features are shown in Table 1.

Table 1. Data on the sample's features

Sample's characteristics	
Firm size (%)	
Large	30
Medium	70
Production processes (%)	
Production to order	60
Serial production	30
Line production	10
Average financial performance (RSD)	
Operating income	6,955,393.37
Operating costs	11,118,285.43
Net result (profit)	674,040.00
Note. RSD-Dinar of the Republic of Serbia	

Source: Authors

2.2. Variables and methods

A firm's financial performance is measured by operating income, operating costs, and net results. Data on these variables were collected for each respondent from their financial reports which are available in the database of the Serbian Business Registers Agency. The search for financial reports is conducted based on the respondent's registration number, which is data collected through the online questionnaire. The firm's experience in implementing the servitization strategy is measured by the number of years of strategy implementation. Similar to Adrodegari & Saccani (2020), Dmitrijeva et al. (2019), and Martín-Peña et al. (2023), the level of servitization strategy is assessed by the relative share of services in the firm's sales, where higher relative importance of services implies a higher level of servitization strategy. Because the observed variables are not linearly related (indicated by scatterplot), the Spearman correlation coefficient is used to measure the strength, and direction of the association between the variables. The analysis was carried out in SPSS v.29.

3. Results and Discussion

Correlation analysis results (Table 2) indicate that the correlations between the observed variables have the hypothesized direction. Namely, the level of the implemented servitization strategy is positively correlated with all financial performance of the company, that is, with operating income (H1), operating costs (H2), and net profit (H3). Also, a positive correlation is identified between the company's profit and the experience it has in implementing the servitization strategy (H3).

Table 2. Correlation analysis results, Spearman correlation coefficient

Variables		Operating income	Operating costs	Net result	Level of servitization strategy	Experience in implementing servitization strategy
Operating income						
	Correlation coefficient	1.00	0.806**	0.636*	0.413	0.110
	Sig.		0.005	0.048	0.235	0.778
Operating costs						
	Correlation coefficient	0.806**	1.000	0.345	0.070	-0.358
	Sig.	0.005		0.328	0.848	0.344
Net result						
	Correlation coefficient	0.636*	0.345	1.000	0.394	0.376
	Sig.	0.048	0.328		0.260	0.318
Level of servitization strategy						
	Correlation coefficient	0.413	0.070	0.394	1.000	0.937**
	Sig.	0.235	0.848	0.260		<0.001
Experience in implementing servitization strategy						
	Correlation coefficient	0.110	-0.358	0.376	0.937**	1.000
	Sig.	0.778	0.344	0.318	<0.001	

Source: Authors

Similar to the results of Neely (2008), Martinez et al. (2010), Baines & Lightfoot (2013), Kastalli & Van Looy (2013), Benedettini et al. (2015), our results indicate that an increase in the level of implemented servitization strategy is positively correlated with an increase in operating revenue, operating costs and net results of the manufacturing companies. The increase in the share of services in the sales is accompanied by an increase in sales revenue, and this may be the result of different effects, including: wider market coverage attained by introducing services into the offer (Kastalli & Van Looy, 2013; Benedettini et al., 2015; Bustinza et al., 2015; Abou-Foul et al., 2021), the possibility to define a higher price based on the expanded offer (Wise & Baumgartner, 1999; Ulaga & Reinartz, 2011; Kohtamäki et al., 2013; Vendrell-Herrero et al., 2017), as well as increased satisfaction and loyalty of the customers which lead to their repeated purchases (Yeo et al., 2021).

By providing services, manufacturing companies can develop stronger connections with their consumers. Consumer loyalty is based on the greater satisfaction they get from consuming innovative products, i.e. integrated product-service offerings (Bustinza et al., 2015). Services generate more stable revenues, have a longer life span, and are less subject to commoditization, which is why they allow maintaining a competitive advantage in mature industries (Benedettini et al., 2015). Bustinza et al. (2015) argue that the servitization strategy contributes to the differentiation of the offer. By innovating and differentiating their offer, manufacturing companies can respond more effectively to the changing demands and expectations of consumers (Leković, 2018). Innovating the offer by enriching it with services is seen as an innovation practice that is more difficult to imitate and, thus, as an effective tool for manufacturing companies to achieve a sustainable competitive advantage (Kindström & Kowalkowski, 2014).

At the same time, the higher the share of services in the sales of manufacturing companies, the higher the operating costs, which implies that this strategy is resource-demanding and requires additional effort from the company, which increases with the increase in the level of its implementation (Neely, 2008; Martinez et al., 2010; Bressanelli et al., 2018; Kohtamäki et al., 2020). Existing evidence suggests that in some cases the costs of servitization can be so high that they force the company to abandon this strategic direction (Coreynen et al., 2017).

Finally, more intensive implementation of the servitization strategy is related to higher profitability of the company, which leads to the conclusion that the benefits of this strategy exceed the investments that its implementation requires (Kastalli & Van Looy, 2013; Martinez et al., 2010) and that this effect is reinforced the more experienced the company is in implementing the strategy (Adrodegari & Saccani, 2020; Suarez et al., 2013). The value of the correlation coefficients indicates that the positive relationship is more pronounced between the level of servitization strategy and operating income and profit, compared to the strength of the positive correlation between the level of servitization strategy and the company's operating costs.

However, although the relationships between the analyzed variables are identified following those set by the hypotheses, the results are not statistically significant. The small size of the sample, as well as its geographic focus on the area of the city of Niš, are recognized as the key reasons for the results not being statistically significant. The absence of statistical significance limits the generalization of the results and conclusions. Nevertheless, the fact that in all cases the relations that are in line with the expected ones are identified, is an argument that justifies the study and opens the potential for further research in this direction. All of the above makes this research a preliminary, pilot study.

The results indicate certain interesting relationships that are not hypothesized, and which are worth further research. Thus, for example, a positive and statistically significant relationship is identified between the length of servitization implementation and the operating income. Also, the results indicate that longer implementation of the servitization is accompanied by a reduction in operating costs. Longer implementation of the servitization strategy results in learning, establishing, and mastering routines in its implementation, which positively affects revenues and reduces investments in strategy implementation (Abou-Foul et al., 2021; Coreynen et al., 2017). After the successful completion of the initial phase, servitization's further application can affect the reduction of expenditures (Benedettini et al., 2015). For example, by proactively monitoring the functionality and condition of products (which can be an element of the manufacturer's enriched offer), the number of product failures, repairs, and overhauls is reduced (Neely, 2008; Baines et al., 2009; Tao & Qi, 2019). Investing in technology and digital servitization ensures more efficient collection and processing of the required data (Lenka et al., 2016; Kohtamäki et al., 2020), while increasing the efficiency of resource use, as well as investing in relationships with supply chain members and developing closer relationships, lead to a reduction in operating costs and an increase in company effectiveness (Ulaga & Reinartz, 2011; Benedettini et al., 2015; Bressanelli et al., 2018).

Conclusion

The results of the research that is conducted on a sample of 10 medium and large manufacturing companies that operate in the territory of the city of Niš indicate the existence of a correlation between the level of servitization and the firm's financial performance. As expected by the hypotheses, a higher level in the implementation of the servitization strategy, i.e. higher relative importance of services in the sale of manufacturing companies, is accompanied by higher values of operating income, operating costs, as well as the net result (profit). Also, a longer implementation of the servitization strategy is related to the higher profitability of a company. However, although the direction of the correlation relationships is identified as expected, the results are not statistically significant. The primary reasons for this can be seen in the small size of the sample and its narrow geographical focus, which are also considered as key limitations of the conducted study. Therefore, this research should be understood as a preliminary, pilot study whose intention is to encourage a research effort towards identifying and understanding the relationship between the servitization strategy and the performance of manufacturing companies in the Republic of Serbia. Bearing in mind the fact that the number of quantitative studies in the domain of servitization strategy is relatively small and that there are no unique results on servitization importance for the financial performance of manufacturing companies, the presented research primarily contributes to filling the existing gap and enriching the knowledge base in this research field, especially in contexts which are less researched, such as the economic system of the Republic of Serbia. Also, the paper has the potential to raise awareness and initiate the interest of practitioners in the strategy of servitization. As this is a pilot study of the relationship between a firm's financial performance and servitization, its function is to trigger academic interest, to argue the justification, and to recommend further research of the mentioned phenomena. Further research can pursue the following avenues: inclusion of additional variables that would provide a more comprehensive overview of the focal relationship, application of more complex statistical methods that would include a wider set of variables, as well as increase in sample size and geographic dispersion. Also, although they are not hypothesized, the results of the presented research indicate the existence of a correlation between the company's experience in implementing the servitization strategy, on the one hand, and operating income (positive link) and operating costs (negative link) on the other hand. The obtained results can be interpreted as a confirmation of the concept of maturity in the implementation of the servitization, which is also one of the possible directions for future research.

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ECONOMICS OF SUSTAINABLE DEVELOPMENT
Vol. 9, January-June 2025, № 1
UDK 33+502/504
ISSN 2560-421X

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P. 51-74
ORIGINAL SCIENTIFIC ARTICLE
10.5937/ESD2501051K
Received: September 1, 2024
Accepted: January 22, 2025

KEY ASPECTS AND DETERMINANTS OF BUSINESS PERFORMANCE MANAGEMENT PROCESS IN REGENERATIVE ENTERPRISES

Abstract

Business performance management within regenerative enterprises enables tracking and evaluating the impact of their activities on ecological systems, communities, and economic structures. Unlike traditional business performance management, which primarily emphasizes financial performance, regenerative business performance management includes metrics that assess environmental restoration, resource efficiency, and social well-being. Understanding how to manage business performance in a regenerative context is crucial for enterprises striving to contribute meaningfully to sustainable development and the circular economy. This paper seeks to explore the business performance management processes that facilitate the transition to regenerative business models, focusing on how businesses can plan, measure, analyze, and improve their regenerative business performance. By synthesizing insights from recent literature and empirical studies, this paper proposes a comprehensive framework for regenerative business performance, offering actionable strategies and practices for businesses seeking to align their operations with regenerative principles.

Keywords: *regenerative enterprise, regenerative business, regenerative business model, regenerative principles, business performance management*

JEL classification: *M21, Q56*

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КЉУЧНИ АСПЕКТИ И ДЕТЕРМИНАНТЕ ПРОЦЕСА УПРАВЉАЊА ПОСЛОВНИМ ПЕРФОРМАНСАМА У РЕГЕНЕРАТИВНИМ ПРЕДУЗЕЋИМА

Апстракт

Управљање пословним перформансама у регенеративним предузећима омогућава им да прате и процене утицај својих активности на еколошке системе, заједнице и економске структуре. За разлику од традиционалног приступа управљању перформансама, које првенствено наглашава финансијске перформансе, управљање регенеративним перформансама укључује индикаторе на основу којих се процењује допринос обнови животне средине, ефикасности употребе ресурса и друштвеном благостању. Разумевање начина управљања перформансама у регенеративном контексту је кључно за предузећа која настоје да значајно допринесу одрживом развоју и циркуларној економији. Рад настоји да истражи процесе управљања перформансама који олакшавају прелазак на регенеративне пословне моделе, фокусирајући се на то како предузећа могу планирати, мерити, анализирати и побољшати своје регенеративне перформансе. Свеобухватном анализом новије литературе из ове области и емпиријских студија, рад предлаже концептуални оквир за регенеративне пословне перформансе, нудећи стратегије и праксе које се могу применити за предузећа која желе да ускладе своје пословање са регенеративним принципима.

Кључне речи: *регенеративно предузеће, регенеративни бизнис, регенеративни пословни модел, регенеративни принципи, управљање пословним перформансама*

Introduction

In recent years, the traditional approach to business has been challenged by the need for greater environmental and social responsibility. The emergence of the regenerative economy marks a transformative change in the way businesses understand their relationship with the environment and society. Unlike traditional sustainability, which primarily focuses on minimizing harm, a regenerative economy advocates for the restoration and enhancement of natural systems, community well-being, and economic resilience (Antikainen & Valkokari, 2016; Andreucci et al., 2021). This shift has become particularly significant in light of escalating environmental degradation, social inequalities, and the need to build resilience against climate change (Chhabra, 2023). The regenerative economy provides a compelling vision for how businesses can thrive while fostering broader societal and ecological health, yet achieving such outcomes requires a sophisticated and adaptive performance management system (East, 2020; Konietzko et al., 2023).

Regenerative enterprises represent a shift towards a business model that actively contributes to the restoration of ecosystems, the promotion of social equity, and the creation of positive, long-term impacts for society (Aoustin, 2023; Buckley, 2022; Jovanović Vujatović et al., 2024). This business model is rooted in principles that go beyond sustainability, with an emphasis on regeneration - actively improving environmental and societal conditions through business practices (Andreucci et al., 2021).

Performance management in regenerative enterprises goes beyond traditional financial performance metrics (Tàbara, 2023; Gervais et al., 2024). It incorporates a holistic view that integrates Triple Bottom Line – environmental, social, and economic factors – while prioritizing regeneration over sustainability (Bojović, 2011). In this context, performance management in regenerative enterprises is not solely about monitoring profits and other financial performances, but about assessing an enterprise's capacity to contribute to long-term ecological restoration, social equity, and economic resilience (Hahn & Tampe, 2021).

1. Sustainable vs. regenerative business

The distinction between sustainable and regenerative businesses is important, especially in the context of evolving economic and environmental challenges. Key differences of those businesses are the following (Lyle, 1996; Du Plessis, 2012; Rhodes, 2015; Wahl, 2019; Gibbons, 2020; Marković et al., 2020; Ibrahim & Ahmed, 2022; Haar, 2024):

1. Fundamental goals and mindset. - The primary goal of a sustainable business is to neutralize negative impacts on the environment and society. In other words, it seeks to function in a way that meets the needs of the present generations without limiting the ability of future ones to meet their own needs. The emphasis is on stability and maintaining balance within the system. In contrast, a regenerative business goes beyond just minimizing harm; its goal is to restore, renew, and regenerate ecosystems, societies, and economies. A regenerative approach focuses on positive impact - not just sustaining the status quo, but improving it. Regenerative businesses seek to revitalize natural systems, increase biodiversity, rebuild communities, and support the well-being of both people and the planet. It is about creating a net positive impact that actively contributes to the long-term flourishing of ecosystems and societies.

2. Environmental approach: avoiding harm vs. restoring health. - In a sustainable business, the focus is on eco-efficiency. It means using resources wisely, reducing waste, and minimizing environmental damage. The aim is to ensure the business does not exceed the planet's carrying capacity. For example, companies may adopt energy-efficient technologies, minimize waste, or shift to renewable energy sources, but the ultimate focus is on not contributing to environmental degradation. Instead of focusing on minimizing damage, a regenerative business strives to improve ecological systems - for example, restoring degraded landscapes, enhancing soil health, or fostering biodiversity through its operations.

3. Profit and value creation. - In a sustainable business model, value creation is typically focused on long-term financial performance while considering environmental and social impact. While profit is important, the sustainable business primarily focuses on balancing environmental and social performance with financial profitability. A regenerative business model views value creation as a much broader concept that includes environmental, social, and economic prosperity. The emphasis is on co-creating value for all stakeholders, including nature and future generations. Profit in a regenerative business is still important, but it is understood as part of a broader system where financial success is directly tied to positive environmental impact, social equity, and community well-being.

4. Business strategy and operations. - Sustainable business practices often follow - reduce, reuse, recycle idea. Businesses focus on improving the efficiency of their operations to reduce carbon footprint, waste, and resource consumption. These businesses are often more reactive, responding to environmental challenges through compliance, innovation for efficiency, and meeting sustainability criteria set by certifications or regulations. Regenerative business models take a more proactive approach, innovating to transform systems and create positive feedback loops that restore and regenerate the environment, economy, and society. Instead of merely reducing harm, regenerative enterprises aim to create ecosystems where their activities actively improve conditions over time.

5. Human and social impact. - Social sustainability in sustainable business focuses on ensuring that human rights, fair labor practices, and community development are prioritized. Sustainable businesses often aim to reduce inequality and ensure fair treatment for workers and stakeholders. However, the scope is often limited to mitigating negative social impacts (e.g., improving working conditions or supporting local communities). Regenerative business goes a step further by seeking to revitalize communities and build resilience at the local and global levels. It actively works to restore social systems, promote equity, and empower people. This approach embraces the idea that businesses can play an integral role in healing social structures, fostering collaboration, and increasing community well-being through initiatives like fair trade, local empowerment, and educational initiatives.

6. Longevity and resilience. - Sustainability is about maintaining balance over time, ensuring that the enterprise can thrive while minimizing its negative impacts. It is about reducing risks (e.g., climate risks, supply chain disruptions) and securing long-term viability by adhering to environmentally responsible practices. Regenerative businesses focus on building resilience in the face of complex, systemic challenges. Their approach to longevity is based on creating adaptable, flexible systems that can thrive in ever-changing conditions. Instead of just surviving, they aim to flourish within regenerative economic cycles.

Summarized key differences between sustainable business and regenerative business are presented in Table 1.

Table 1. Sustainable business vs. regenerative business

Aspect	***Sustainable business***	***Regenerative business***
Primary goal	Minimize harm and maintain balance	Restore, renew, and regenerate ecosystems, economies, and societies
Environmental focus	Eco-efficiency, reducing resource consumption, and waste	Creating closed-loop systems and revitalizing ecosystems
Profit model	Profit with consideration for environmental and social impact	Profit integrated with regeneration and societal impact
Approach to systems	Reactive, focused on reducing harm	Proactive, focused on systemic transformation and positive feedback loops

Aspect	***Sustainable business***	***Regenerative business***
Social impact	Reduce inequality, support fair labor practices	Revitalize communities, co-create value with stakeholders
Business strategy	Efficiency improvements, compliance with sustainability standards	Holistic redesign of business practices for restorative impact

Source: Authors

2. Principles of regenerative enterprises

The key principles on which the operation of a regenerative enterprise is based can be systematized as follows (Fath et al., 2019; Caldera et al., 2022; Konietzko et al., 2023; Vilar & Perelló, 2023; Drupsteen & Wakkee, 2024; Gervais et al., 2024; Seefeld, 2024):

1) Systems thinking

- Holistic perspective - Regenerative enterprises view business as an interconnected part of a larger ecological and social system. Instead of isolating individual elements, they consider the entire value chain and ecosystem in which they operate.
- Interconnectedness - They understand that all parts of a system influence one another. By considering feedback loops (both positive and negative), regenerative businesses can design operations that strengthen rather than deplete ecosystems and communities.
- Long-term vision - It discourages short-term decision-making focused solely on profits and instead encourages investments in regenerative practices that will pay off over time.

2) Regenerative design and innovation

- Closed-loop systems - Regenerative enterprises focus on creating circular systems that eliminate waste. They design products and services to be reused, repurposed, or composted. This contrasts with traditional linear models, where products are made, used, and discarded.
- Cradle-to-cradle design - Building on the cradle-to-cradle philosophy, regenerative businesses ensure that materials used in their products can be safely reintegrated into natural systems or remade into new products at the end of their life cycle.
- Innovative solutions - Regenerative businesses continuously innovate not just for profit, but for restoration.

3) Ecosystem restoration

- Restoring natural capital - This principle focuses on natural regeneration through processes such as regenerative agriculture, reforestation, and soil revitalization.
- Positive ecological impact - Rather than just reducing harm (as in traditional sustainability), regenerative enterprises aim to improve the health of the environment.
- Sustainability in production and supply chains - Regenerative enterprises invest in supply chains that support environmental health, using sustainably sourced

materials, energy-efficient production methods, and low-impact logistics that contribute positively to ecological restoration.

4) Social regeneration and equity

- Creating social value - Regenerative businesses seek to create not just financial value but also social value. This might involve empowering local economies, addressing income inequality, and investing in education and workforce development.
- Equity and justice - A core principle of regenerative enterprises is the belief in social equity. They are committed to addressing systemic inequalities such as poverty, gender disparity, and discrimination. This often means adopting policies that promote fair wages, diversity and inclusion, and ethical labor practices.
- Community engagement - This may include supporting local initiatives, fostering local entrepreneurship, or providing access to services and resources that empower people.

5) Economic regeneration

- Value beyond profit - Regenerative businesses redefine value by measuring success using metrics that consider social, environmental, and economic outcomes.
- Building resilient economies - They work to build resilient local and global economies by encouraging business models that distribute wealth more equitably, promote cooperation over competition, and create shared prosperity. This can mean investing in local economies, supporting small and medium-sized enterprises, and fostering cooperative business models.
- Long-term viability - Regenerative enterprises focus on long-term economic stability and health, ensuring that their business models are adaptable, future-proof, and resilient to environmental and societal changes.

6) Adaptive and resilient leadership

- Adaptability - Regenerative enterprises are not rigid in their approaches. They embrace flexibility, innovation, and adaptive problem-solving to meet changing circumstances.
- Leadership with purpose - Regenerative leaders are those who guide their enterprises with a long-term vision, focusing on purpose and impact rather than just financial returns. They inspire collective action and collaboration among employees, customers, and communities, all while maintaining a commitment to social and ecological justice.
- Collaborative decision-making - Instead of top-down management, regenerative businesses encourage collaborative decision-making that includes diverse perspectives.

7) Transparency and accountability

- Open communication - Regenerative businesses are transparent in their operations, sharing information about their environmental and social impacts, financial performance, and the challenges they face. This openness helps build trust with all stakeholders.
- Third-party certifications - To ensure accountability, regenerative enterprises

often seek certifications that verify their commitment to ethical, social, and environmental principles.
- Continuous improvement - Regenerative enterprises are committed to continuous improvement in all aspects, learning from both their successes and shortcomings.

8) Purpose-driven mission
- Holistic impact - Regenerative businesses are driven by a sense of purpose that transcends just making profits. Their mission is to make a positive difference—to contribute to the health of the environment, society, and future generations.
- Stakeholder capitalism - Rather than focusing solely on shareholder value, regenerative enterprises embrace stakeholder capitalism, where value is created for all stakeholders.

9) Circular and restorative economy
- Circular business models - Regenerative enterprises often adopt circular economy principles, which emphasize the continual reuse of resources, reducing waste, and ensuring that products and materials are reintegrated into the economy through recycling, repurposing, or remanufacturing.
- Restorative practices - Regenerative businesses prioritize restoring depleted resources, such as soil, water, and biodiversity. They actively seek to reverse the damage caused by past industrial practices and engage in activities that restore ecological systems and bring life back to degraded environments.

3. Key aspects of performance management of regenerative enterprises

Managing the performance of regenerative enterprises requires a dynamic, adaptive approach that aligns with the core principles of regeneration: restoration, renewal, and resilience. It is not just about managing financial performance but also ensuring that ecological, social, and economic goals are met in an integrated, sustainable way. A comprehensive approach to managing the performance of regenerative enterprises includes the following steps (Mason, 2017; Coleman et al., 2018; Yankovskaya et. al, 2022; Pavez et al., 2022; Krstić, 2022; Oyefusi et al., 2024): 1) Establish clear regenerative goals and objectives, 2) Measuring performance of regenerative enterprises in the aim of their managing and directing, 3) Foster continuous monitoring and feedback loops, 4) Establish integrated management systems, 5) Engage and empower employees, and 6) Align partnerships and supply chains.

Before establishing the system for regenerative performance management, it is essential to define what regeneration means for the enterprise. It means setting ambitious but measurable regenerative goals. It includes steps to establish regenerative goals based on the following:

a) *Long-term and short-term goals.* - Long-term regeneration targets could include carbon neutrality by a certain year, restoring biodiversity to specific areas, or achieving zero waste across the value chain. Short-term goals may focus on specific project milestones (e.g., planting a certain number of trees, reducing carbon emissions by a percentage in one year);

b) *SMART goals.* – It includes specific, measurable, achievable, relevant, and time-bound criteria (Lawlor, 2012) for both ecological and social targets. This ensures that goals are actionable and progress can be tracked;
c) *Stakeholder alignment.* – It is essential that goals are aligned with stakeholder interests, whether they are employees, customers, suppliers, or local communities. Regenerative enterprises often seek broad buy-in for their mission and involve stakeholders in co-creating objectives.

The second step highlights a performance dashboard that covers multiple dimensions of its impact - economic (financial), environmental (ecological), social, and governance (Krstić, 2022, p. 78). The dashboard allows managers to track progress and make informed decisions. Key components could include: a) Economic performance metrics - Traditional financial metrics alongside regenerative economic metrics like local sourcing ratios, job creation in local communities, and financial resilience against environmental risks; b) Environmental (ecological) performance metrics - Track environmental impacts such as carbon footprint, water usage, waste reduction, and biodiversity restoration; c) Social impact metrics - Measure social outcomes such as community well-being, fair wages, employee satisfaction, and stakeholder engagement; d) Governance metrics - Measure transparency, stakeholder involvement, ethical business practices, and governance structures (e.g., board diversity, decision-making processes, adherence to regenerative principles).

Regenerative enterprises should continuously monitor and assess their progress toward regeneration goals (Krstić, 2022, p. 78-80). This involves (Xu et al., 2018): a) Regular impact assessments - Conduct periodic reviews of ecological, social, and financial performance. These could be quarterly or bi-annually, depending on the size and complexity of the organization; b) Employee and stakeholder feedback - Regular feedback from employees, customers, and communities is essential for understanding how well the business is living up to its regenerative claims. It includes surveys, focus groups, and community meetings as a way to gather feedback and adjust strategy accordingly; c) Adaptation and agile management - Given the long-term, complex nature of regeneration, regenerative enterprises need the ability to adapt quickly to changing circumstances. This could include adopting an agile approach to project management, where goals are adjusted based on real-time data and feedback; d) Real-time data tracking - technologies like Internet of Things sensors, blockchain, and data analytics can provide real-time data on things like energy use, emissions, and waste. This allows for more informed decision-making and quicker adjustments.

The core operations of regenerative enterprises often span multiple sectors/industries - agriculture, manufacturing, technology, finance, etc. An integrated management system ensures all aspects of the business are aligned with regenerative values. This could involve: a) Sustainability management systems - Establish clear frameworks for environmental and social management. This could include formal certifications such as ISO 14001 (environmental management) or ISO 26000 (social responsibility), which provide guidelines for managing sustainability impacts (Esquer-Peralta et al., 2018, Krstić, 2022); b) Circular economy models - Implementing a circular economy model within the business ensures that products and materials are reused, recycled, and regenerated. A closed-loop system can help manage waste and reduce environmental impact. Tools like the Cradle to Cradle framework or Life Cycle Assessment are useful to assess circularity (Bjørn & Hauschild, 2018); c) Integrated financial and impact reporting - Frameworks like Integrated Reporting or Sustainability Accounting

Standards Board guidelines to combine financial performance with environmental, social, and governance factors (Shoaf et al., 2018). This allows businesses to have a unified view of their financial and impact performance.

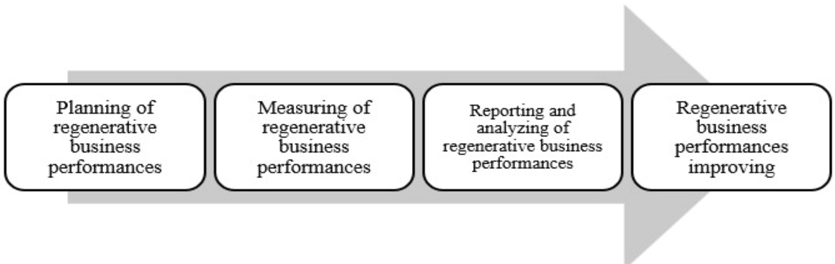
Regenerative enterprises rely on a culture of empowerment, collaboration, and shared vision. To manage performance effectively, it is important to provide the following: a) Inclusive decision-making - Involve employees at all levels in the decision-making process. This fosters ownership and commitment to regenerative goals; b) Employee training and capacity building - Regularly invest in training programs that equip employees with the knowledge and tools to contribute to the enterprise's regenerative objectives. This could involve sustainability education, leadership training, or even personal well-being initiatives; c) Recognition and incentives - Align incentives with regenerative goals. For example, bonus structures or rewards could be tied to both financial and sustainability performance targets, such as energy savings, social impact achievements, or meeting regenerative milestones (Krstić, 2022, p. 127).

One of the defining characteristics of regenerative enterprises is their interconnectedness with external stakeholders. Managing performance must include collaboration with partners who share regenerative values. To align partnerships and supply chains it is important the following: a) Supply chain auditing and certification - Regularly assess the environmental and social practices of suppliers. Encourage or require sustainability certifications (e.g., Fair Trade, B Corp, or ISO 14001) to ensure that suppliers align with the company's regenerative principles (Initiative et al., 2010); b) Collaborative networks - Participate in industry groups, consortiums, or multi-stakeholder initiatives focused on sustainability or regeneration. Collaborative efforts often lead to shared resources, knowledge, and best practices that can improve overall performance; c) Community engagement - Work closely with local communities, NGOs, and other organizations to ensure your business is contributing to regional regeneration efforts. This might include joint projects for ecosystem restoration, community development, or climate adaptation (Howard et al., 2019).

4. Main phases of business performance management in regenerative enterprises

In general, the process of performance management in regenerative enterprises can be divided into four main phases (Figure 1).

Figure 1. Four main phases of regenerative business performance management



Source: According to Krstić (2022, p. 47)

4.1. *Regenerative business performance planning*

Effective planning is at the heart of regenerative business performance management. The planning phase involves setting clear, long-term goals that align with the principles of regeneration (Krstić, 2022, p. 53). Unlike traditional business models that focus primarily on profit maximization, regenerative enterprises aim to create value that extends beyond financial returns, fostering positive environmental and social outcomes. Goal-setting for regeneration should reflect not only ecological and social priorities but also a company's core values and mission. Regenerative businesses adopt triple-bottom-line goals (economic, environmental, and social), ensuring that their strategies create positive impacts across all domains. For instance, an enterprise may set specific targets for carbon sequestration, biodiversity restoration, and community empowerment, while also maintaining financial profitability (Hahn & Tampe, 2021; Gervais et al., 2024).

A key part of this planning process is the development of regenerative business models that promote closed-loop systems, reduce dependency on finite resources, and prioritize ecosystem health (Antikainen & Valkokari, 2016). For example, businesses can adopt Cradle-to-Cradle design principles, ensuring that every product or service is designed for end-of-life disassembly and reuse, rather than disposal (Braungart & McDonough, 2009). The goal is to design business processes that regenerate rather than deplete resources.

Moreover, stakeholder engagement is critical during the planning phase. Regenerative businesses must ensure that their objectives align with the needs and expectations of local communities, employees, customers, and other stakeholders. This requires ongoing dialogue and collaboration to co-create value that benefits all parties (Chhabra, 2023). By involving stakeholders early in the process, regenerative enterprises can ensure that their business models reflect the principles of equity and justice, ensuring that the benefits of regeneration are shared equitably (Hope & Laasch, 2024).

A comprehensive planning process also includes risk management strategies. Since regenerative enterprises often operate in complex, uncertain environments, businesses must account for environmental and social risks, as well as potential economic shocks. Adaptive management approaches are critical here, enabling businesses to adjust their strategies based on real-time feedback from their operations and the broader environment (Tàbara, 2023). This adaptive approach ensures that regenerative businesses remain resilient in the face of changing market conditions and environmental uncertainties.

Planning the strategic and operational performance of a regenerative enterprise involves creating a roadmap that aligns the enterprise's long-term vision with actionable, short and medium-term goals. This requires integrating sustainability, regeneration, and profitability into a cohesive strategy and operational framework. Below is a step-by-step guide on how to plan and optimize both the strategic and operational performance of a regenerative enterprise (Hardman, 2010; Wahl, 2016; Kamrowska-Zaluska & Obracht-Prondzyńska, 2018; Hahn & Tampe, 2021; Allen, 2021; Krstić, 2022; Caldera et al., 2022; Candelarie, 2023; Das & Bocken, 2024; Wexler et al., 2024; Gervais et al., 2024):

1) *Develop a clear and compelling vision.* - The first step in planning both strategic and operational performance is to define a compelling regenerative vision (Krstić, 2022). This vision should serve as the foundation for all future decisions and actions. Purpose-driven mission should be formulated. Mission statement should focus on the business's core purpose beyond profit, outlining

its commitment to regenerating ecosystems, communities, and local economies. Regenerative framework should be a base for a vision. Vision should also provide a roadmap for regeneration. Alignment regenerative mission with stakeholders shoud ensure that regenerative mission of an enterprise aligns with the needs and aspirations of employees, customers, investors, suppliers, and communities.

2) *Conduct a deep strategic assessment.* - Before building your strategy, perform a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) that includes regenerative dimensions of business. This will provide insights into the current state of business and help prioritize areas of improvement. For the purpose of strategic assessment should be used: a) Environmental audit - Assess how the enterprise currently impacts the environment. b) Social and economic audit - Review current impact on local communities, workers, and broader society. c) Financial health - Review current financial performance.
3) *Set long-term strategic goals (5-10 years).* - Strategic goals should reflect long-term regenerative vision and should be aligned with environmental, social, and economic regeneration. The goals should be divided into key focus areas: a) Environmental regeneration - Long-term environmental targets such as reducing carbon emissions by a certain percentage, restoring ecosystems, or achieving zero waste; b) Social impact - Social outcomes the enterprise wants to achieve, such as creating a certain number of local jobs, increasing employee satisfaction, or enhancing community resilience; d) Economic performance - Economic goals like revenue growth, profitability, and financial sustainability, but with a long-term perspective that balances profit with regeneration.
4) *Assess and adjust strategy*. - Performance management requires a proactive strategy that evolves (Krstić, 2022). It includes steps for strategic management: a) Scenario planning - Assess potential risks and opportunities related to climate change, market shifts, regulatory changes, and societal needs; b) Benchmarking and adoption of best practices - Regularly benchmark the enterprise’s performance against industry standards or competitors; c) Strategic pivoting - For instance, if carbon offsetting becomes less viable, businesses may shift toward regenerative practices like carbon sequestration in soils or forests, or scale new solutions such as bio-based materials.
5) *Define key strategic initiatives*. - To achieve long-term goals, enterprises should identify strategic initiatives that will drive success (Krstić, 2022). These initiatives should be regenerative and transformational, pushing the business to both grow and regenerate, and include the following: a) Sustainable business model innovation; b) Partnerships and collaborations; c) Technology Integration; and d) Impact Investment Strategy.
6) *Establish operational goals and metrics (1–3 years).* - Once strategic goals are set, break them down into operational goals. These are shorter-term, more tactical goals that will help the enterprise to achieve the overarching strategic objectives (Krstić, 2022). Key operational areas to focus on are the following: a) Resource efficiency - Implement processes to reduce resource use (water,

energy, raw materials), minimize waste, and improve energy efficiency; b) Supply chain regeneration - Create a regenerative supply chain that focuses on sourcing sustainable raw materials, working with ethical suppliers, and promoting regenerative agricultural or forest management practices; c) Employee engagement and well-being: Develop operational plans for employee engagement, mental and physical well-being, and fair labor practices; d) Product and service innovation - Develop new products or services that are regenerative, such as products with minimal environmental footprints or services that actively restore ecosystems. Operational key performance indicators (KPIs) could be the following: carbon footprint (reductions in emissions, energy efficiency improvements, and other carbon-related metrics); waste and resource metrics (reductions in water, materials, and energy consumption, as well as waste diversion and recycling); social impact key performance indicators (worker satisfaction, community investment, and inclusivity); Financial metrics (revenue growth, profitability, and cost reductions from sustainability efforts).

7) *Build a regenerative culture*. - The performance of a regenerative enterprise depends not just on systems and processes but also on a culture that embraces regeneration. This culture should be built into, both strategic and operational planning (Krstić, 2022), as well as: a) Regenerative leadership - Develop leaders who understand and embody the regenerative principles. They should be role models in promoting sustainability, social justice, and regeneration in their decision-making; b) Employee involvement - to participate in regenerative initiatives, whether it is through innovation hubs, idea generation workshops, or volunteer opportunities; c) Regenerative mindset training - Train all levels of the organization on regenerative practices and sustainable business models. Below are key values integral to a regenerative organizational culture (Table 2).
8) *Continuous improvement and adaptation*. - A regenerative enterprise must be agile, responsive, and open to evolution. The performance of regenerative business should be continually assessed against changing market conditions, new technologies, and emerging sustainability trends. Staying ahead of technological and ecological trends is critical to long-term success.

Table 2. Key values of regenerative organizational culture

Systems thinking
• ***Value*** *of regenerative organizational culture*: Embraces interconnectedness and complexity within ecological, social, and economic systems. • ***Explanation:*** A regenerative culture sees the organization as a living system that is interdependent with its surroundings. Decisions are made with an understanding of their ripple effects across multiple systems, promoting systemic health and long-term benefits. • ***Application:*** Businesses integrate their operations with larger ecological and community networks, ensuring their activities contribute to the regeneration of the environment and society.
Purpose-driven mission
• ***Value*** *of regenerative organizational culture*: Centers around a collective commitment to regeneration. • ***Explanation:*** The enterprise's mission transcends profit-making to encompass ecological restoration, social equity, and economic resilience. • ***Application:*** Employees and stakeholders align their efforts with the organization's regenerative goals, fostering a shared sense of purpose.

Collaboration and inclusivity
• ***Value** of regenerative organizational culture*: Promotes co-creation and shared ownership. • ***Explanation:*** Regenerative enterprises value input from diverse stakeholders, including employees, communities, and partners. This inclusivity ensures that the organization benefits all stakeholders equitably. • ***Application:*** Practices like participatory decision-making and stakeholder engagement sessions reflect this value, ensuring the needs and voices of all parties are respected.
Adaptability and continuous learning
• ***Value** of regenerative organizational culture*: Encourages resilience and agility in the face of change. • ***Explanation:*** A regenerative culture recognizes that the environment, markets, and communities are dynamic. Continuous learning, feedback integration, and adaptive strategies are prioritized. • ***Application:*** Regular reviews of performance metrics and feedback loops enable the organization to refine its practices, innovate, and respond effectively to new challenges.
Environmental stewardship
• ***Value** of regenerative organizational culture*: Embodies a responsibility to regenerate natural systems. • ***Explanation:*** Protecting and enhancing the environment is central to decision-making. Regenerative enterprises prioritize reducing harm and actively contribute to ecosystem restoration. • ***Application:*** Examples include adopting circular economy principles, implementing zero-waste policies, and engaging in reforestation or soil regeneration initiatives.
Social equity and justice
• ***Value** of regenerative organizational culture*: Focuses on creating fair and inclusive opportunities for all. • ***Explanation:*** Regenerative organizations aim to uplift communities, address systemic inequalities, and ensure equitable distribution of benefits. • ***Application:*** Initiatives like fair labor practices, living wages, community investment programs, and partnerships with marginalized groups exemplify this value.
Transparency and accountability
• ***Value** of regenerative organizational culture*: Builds trust through openness and ethical practices. • ***Explanation:*** Regenerative enterprises operate with honesty and provide clear reporting on their social, environmental, and economic impacts. • ***Application:*** Regular publication of impact reports, third-party audits, and certifications (e.g., B Corp, Fair Trade) uphold this value.
Long-term thinking
• ***Value** of regenerative organizational culture*: Balances immediate needs with future generations' well-being. • ***Explanation:*** Decisions are guided by their potential to contribute to long-term resilience and systemic health, rather than short-term gains. • ***Application:*** Investments in renewable energy, biodiversity, and community development programs are planned with decades-long horizons.
Empowerment and employee engagement
• ***Value** of regenerative organizational culture*: Nurtures a sense of ownership and agency among employees. • ***Explanation:*** Employees are encouraged to participate actively in regenerative initiatives and are provided with the resources and autonomy to innovate. • ***Application:*** Training programs on regenerative principles, collaborative leadership models, and recognition for contributions to regeneration foster this value.
Ethical leadership
• ***Value** of regenerative organizational culture*: Demonstrates responsibility and vision at all organizational levels. • ***Explanation:*** Leaders embody regenerative principles, inspiring and guiding the organization toward systemic impact. • ***Application:*** Ethical leadership is reflected in transparent governance structures, diversity on boards, and decision-making that prioritizes regenerative goals over profits.

Source: According to Wahl (2016)

4.2. *Regenerative business performance measuring*

The measurement of regenerative business performance goes far beyond traditional financial metrics. To assess an enterprise's regenerative impact, it is essential to evaluate multiple dimensions of performance: ecological, social, and economic (Dake, 2018). These dimensions require a diverse set of indicators and measurement tools that can capture the complexity of regenerative outcomes.

Ecological metrics are perhaps the most straightforward in the context of regenerative performance, as they directly measure the influence of business operation on the environment (Krstić, 2022, p. 122). These indicators might include carbon footprint, water use efficiency, waste reduction, and energy consumption (Hope & Laasch, 2024). However, regenerative businesses need to go further by measuring their contributions to ecosystem restoration and biodiversity conservation (Fath et al., 2019). For example, businesses can track the restoration of degraded ecosystems, the creation of wildlife corridors, or the implementation of regenerative agricultural practices on company-owned land (Ryan et al., 2023). Social metrics focus on the impact of business activities on communities and social systems. This might include measuring Social Return on Investment (Then et al., 2017), which quantifies the social value created through community engagement, job creation, education, and health improvements (Caldera et al., 2022). Regenerative businesses should also measure the equity and inclusivity of their operations, ensuring that marginalized communities have access to the benefits created by the enterprise (Chhabra, 2023). Economic performance in regenerative businesses can be assessed using traditional metrics like profit, profit margins, and profitability rates. However, the emphasis in regenerative business models is on long-term resilience rather than short-term profit maximization. Thus, businesses should also track financial sustainability through metrics that assess their capacity to weather economic fluctuations and continue to contribute positively to environmental and social regeneration (Brozovic, 2020). Tools such as Life Cycle Assessment (Curran, 2013), Environmental Impact Assessments (Morris & Therivel, 2001), and Material Flow Analysis (Bringezu & Moriguchi, 2018) are essential in evaluating the environmental and social impacts of regenerative business models (Emanuelsson et al., 2021). These tools provide quantitative data that allow businesses to track their progress toward regenerative goals, identify areas for improvement, and communicate their impacts to stakeholders (Hope & Laasch, 2024).

Measuring the performance of regenerative enterprises - businesses that aim to restore, renew, and regenerate natural, social, and economic systems - can be challenging due to the complexity and interconnectedness of the goals they pursue. However, it is not only possible but essential to evaluate regenerative enterprises' impact across a variety of dimensions. Namely, regenerative performance can be assessed through the following dimensions and indicators:

- *Ecological (environmental) regenerative performance* - 1. Carbon footprint that measures reductions in greenhouse gas emissions, energy consumption, and carbon sequestration; 2. Biodiversity indices assess the health of ecosystems through indicators like species diversity, the presence of endangered species, or habitat restoration (e.g., restored wetlands, reforestation efforts); 3. Soil health and water quality that monitor soil regeneration (e.g., soil carbon, soil organic matter, or water retention) and the quality of water resources (e.g., reduction of runoff, cleaner water); 4. Waste and circular economy metrics that track waste reduction, material circularity, and closed-loop systems, including the use of renewable materials, repurposing, and zero waste initiatives; 5. Natural capital accounting determines the value of natural resources and ecosystems restored or preserved, including methodologies like the Natural Capital Protocol, which helps to measure, value, and account for natural capital impacts and dependencies (Coleman et al., 2018; Hein et al., 2020).

- *Social regenerative performance* - 1. Fair wages and labor practices monitor how well the business supports its employees, including living wages, fair working conditions, diversity, inclusion, and worker well-being; 2. Community engagement and development assess how the business engages with local communities and supports long-term development, such as providing education, healthcare, or infrastructure, and building resilience in the face of climate change; 3. Stakeholder equity measures the extent to which the business distributes its benefits across stakeholders - employees, suppliers, communities, customers, and shareholders; 4. Health and well-being metrics track improvements in health, education, and other social determinants of well-being in communities that the business impacts (Oyefusi, 2024).
- *Economic (financial and non-financial) regenerative performance* - 1. Profitability and financial health as traditional business metrics like revenue, profit margins, cost reductions, and cash flow, but assessed in the context of regenerative goals; 2. Local economic impact assessing the economic contribution to local economies, such as job creation, local sourcing of materials, and fostering economic resilience through decentralized economic models (e.g., cooperatives, local production); 3. Impact on business ecosystem measuring how the enterprise's business model supports the broader business ecosystem, including suppliers, customers, and partners, in regenerative practices; 4. Sustainable innovation tracks investments in sustainable technologies, business model innovations, and R&D that contribute to regeneration (Krstić, 2022, p. 80).
- *Cultural and organizational regeneration performance* - 1. Leadership and governance measure the effectiveness of leadership in fostering regenerative values, transparency, and participatory governance; 2. Employee empowerment and culture assess how much employees are empowered to take initiative, make decisions, and contribute to the regeneration mission; 3. Circular business model adoption examines how well the enterprise has adopted circularity in its operations, from supply chain to design processes; 4. Purpose alignment assesses how closely business strategies align with the regenerative purpose of the enterprise (Mahadevan, 2017).
- *Holistic performance measurement frameworks* - 1. Global Reporting Initiative (GRI) and GRI standards offer detailed reporting criteria for sustainability and regenerative practices (Krstić, 2022; Miao & Nduneseokwu, 2025), helping businesses measure and report on environmental, social, and governance (ESG) issues (Hedberg & Von Malmborg, 2003; Hope & Laasch, 2024); 2. Integrated reporting framework combines financial and non-financial reporting, integrating environmental, social, and governance factors with financial performance into a single narrative (De Villiers & Hsiao, 2017; Rezaee, 2025). This is particularly useful for regenerative enterprises that aim to show their value beyond financial outcomes.

Regenerative enterprises can use specialized tools to evaluate their impact in a structured way. Several frameworks can help in analyzing the regenerative performance of a business. Triple Bottom Line (TBL) provides a rigorous assessment of social and environmental impact. This certification provides a clear standard for regenerative business practices and can serve as a guide to measure performance in a regenerative context. TBL focuses on three pillars of sustainability: People (How does the business positively impact society - employees, customers, communities?), Planet (What is the business's environmental footprint, and how is it regenerating ecosystems?), and Profit (Is the business financially sustainable while achieving positive social and environmental outcomes?). When evaluating a regenerative business, enterprise looks at the ecological and social impacts alongside financial performance (Lee & Yoon, 2024). SROI (Social Return on Investment) is a framework used to assess and quantify the social and environmental impact of business activities in monetary terms. By comparing the social value generated with the resources invested, the enterprise can assess how effectively the business is creating social good and restoring ecosystems (Krstić, 2022). SROI is especially helpful for measuring non-financial outcomes, like health, well-being, and environmental regeneration (Then et al., 2017, Krstić, 2022). Life Cycle Assessment (LCA) evaluates the environmental impact of a product or service across its entire life cycle - from raw material extraction through production, use, and disposal. By using LCA, enterprises can identify key stages to reduce their environmental impact, helping to track regeneration efforts more precisely (Curran, 2013).

Measuring the performance of regenerative enterprises requires a multi-dimensional approach that goes beyond financial returns. It involves tracking ecological restoration, social and economic benefits, and ensuring that the business's internal practices align with regenerative principles. Tools like Triple Bottom Line, SROI, and LCA help integrate these metrics into a coherent system, enabling businesses to assess their holistic impact and make data-driven decisions that foster long-term sustainability.

4.3. *Regenerative business performance reporting and analyzing*

Once performance data is collected, the next step is to analyze and interpret the results to gain actionable insights. Regenerative businesses use systems thinking to interpret data in ways that acknowledge the interdependencies between ecological, social, and economic factors (Fath et al., 2019). By adopting a holistic analysis approach, businesses can uncover the impact of their actions on broader systems and identify opportunities for improvement (Gervais et al., 2024). Analyzing the performance of a regenerative enterprise involves measuring its success across multiple dimensions: environmental, social, and economic, alongside traditional business performance metrics. It involves several steps.

The first step refers to *gathering qualitative and quantitative data*. Quantitative data can be obtained by: a) Environmental metrics including data on emissions reductions, waste diversion, energy use, and carbon sequestration (LCA and Carbon Footprint Analysis can quantify the environmental impact); b) Social metrics including data on employee retention, community investment, health and safety, fair wages, and diversity can be gathered through employee surveys, community reports, and third-party audits; c) Economic metrics including financial performance data (revenue, profit margins, ROI) and economic resilience indicators (local job creation, revenue generated for local suppliers) which can be analyzed using standard accounting methods and financial analysis. On the other side, qualitative data are obtained by: a) Stakeholder feedback, engaging stakeholders (e.g., employees, suppliers, community members) through surveys, interviews, or focus groups; b) Case studies and success stories as qualitative assessments of successful regenerative projects or initiatives within the enterprise can provide insight into the broader; c) Employee and community sentiment through qualitative measures such as storytelling, interviews, and testimonials can provide deep insights into the social and cultural impact of the enterprise (Emanuelsson et al., 2021).

The second step requires *impact assessment tools*, such as SROI, LCA, and Impact Management Project (IMP). IMP provides a framework to assess and manage impact performance. It is designed to help businesses understand their impact on people and the planet, using key metrics and standards to analyze outcomes (Curran, 2013; Then et al., 2017; Lee & Yoon, 2024).

The third step includes *benchmarking and comparative analysis*. Benchmarking involves comparing a regenerative enterprise's performance with that of other similar organizations, industry standards, or even best-in-class examples. This can help you assess how your enterprise is performing relative to its peers in terms of environmental sustainability (e.g., carbon footprint, waste management), social impact (e.g., community well-being, employee satisfaction), and economic resilience (e.g., financial performance, local sourcing). Industry reports, sustainability rankings, and certifications can be used for these purposes (Orsato et al., 2015).

After benchmarking, the enterprise should *evaluate the alignment with regenerative principles.* A regenerative enterprise must consistently assess whether its activities and operations align with regenerative principles. This means evaluating restorative practices (e.g., through reforestation, soil regeneration, or water restoration), social equity and justice: (such as fair wages, employee empowerment, and community development), and economic resilience (e.g., local suppliers, communities). This alignment can be assessed by conducting regular internal reviews, external audits, and stakeholder assessments. Additionally, engaging with thought leaders or experts in regenerative practices can provide valuable insights into alignment and progress.

Once performance is analyzed, it is important to *communicate the results* clearly and effectively to stakeholders. Integrated Reporting (IR) combines both financial and non-financial performance into a cohesive narrative, showing how business strategy leads to sustainable value creation over time. An IR report might cover (Miao & Nduneseokwu, 2025):

- Financial performance: revenue, costs, profit, profit margin and return on investment;
- Non-financial performance: environmental impact (e.g., carbon emissions, resource usage), social impact (e.g., community well-being, worker satisfaction), and governance (e.g., ethical sourcing, transparency);
- Forward-looking strategy: future goals for improving regenerative practices and strategies for resilience in the face of climate change or market disruptions.

Lastly, transparency is crucial for regenerative enterprises. Reporting not only builds trust with stakeholders but also ensures accountability for the progress of regeneration.

4.4. *Regenerative business performance improving*

Continuous performance improvement is a core principle in regenerative enterprises, as they aim not only to minimize negative impacts but also to enhance ecological and social outcomes over time (Hahn & Tampe, 2021). Regenerative businesses apply various approaches, such as lean management, design thinking, and adaptive management, to refine their operations and performance continually (Konietzko et al., 2023). These approaches are centered around the idea that businesses must remain flexible, learning from both successes and setbacks to improve their regenerative impact.

Regenerative enterprises embrace a culture of innovation and adaptation, using feedback from performance data to refine their strategies, products, and services (Tàbara, 2023). The principle of circular innovation plays a key role, where businesses not only optimize their existing processes but also explore novel ways of closing resource loops, reducing waste, and restoring ecosystems (Zucchella & Previtali, 2019).

Adaptive management is an iterative approach that emphasizes the importance of flexibility and responsiveness in decision-making (Ryan et al., 2023). This approach allows businesses to continuously adjust their strategies based on new data and evolving conditions, ensuring that regenerative goals remain relevant and achievable as circumstances change. By fostering a culture of innovation and responsiveness, regenerative enterprises are better positioned to navigate the complexities of the modern business landscape while contributing to the long-term health of the society.

Approaches such as lean management and design thinking are particularly effective in driving improvements. Lean principles reduce waste in all forms - whether material, energy, or time - while design thinking fosters innovation through empathy and stakeholder engagement (Siahaan et al., 2023). Lean management, in particular, encourages businesses to eliminate waste, improve efficiency, and reduce their resource consumption. By focusing on minimizing the use of non-renewable resources and improving resource recovery, businesses can significantly reduce their ecological footprint (Brozovic, 2020). Design thinking, on the other hand, promotes innovative problem-solving by focusing on human-centered design and addressing sustainability challenges creatively (Hardman, 2013).

Improving the performance of a regenerative enterprise involves taking strategic, operational, and cultural actions that enhance both short-term impact and long-term sustainability. Since regenerative businesses aim to restore and renew ecosystems, societies, and economies, improving performance requires innovation, continuous learning, and alignment across all areas of the business.

A comprehensive approach to improving the performance of a regenerative enterprise comprises the following (Roland & Landua, 2013; Gonzalez-Perez & Piedrahita-Carvajal, 2022):

1) *Set and refine clear, ambitious goals.* - Clear, measurable, and impactful goals will help guide efforts and provide motivation for continuous progress. SMART goals ensure that goals for environmental, social, and economic regeneration are Specific, Measurable, Achievable, Relevant, and Time-bound. In addition, it is important to prioritize the areas where the enterprise can make the most difference. Besides, a regenerative enterprise should align goals with stakeholders. This alignment will ensure greater buy-in and collective action.
2) *Improve resource efficiency and circularity*. - A key feature of regenerative

enterprises is reducing resource depletion while fostering regenerative processes. Moving towards circularity and increasing resource efficiency can enhance both environmental and financial performance. It is possible through adopting circular business models, optimizing energy and water use, and waste reduction and management.

3) *Innovate with regenerative products and services*. - Regenerative enterprises are often defined by their ability to offer products or services that restore, renew, and regenerate. Innovating in this area can significantly improve performance by increasing customer demand, expanding market reach, and contributing to ecological and social regeneration (e.g. sustainable product design, exploring new business models, collaborative innovation).
4) *Strengthen social impact and community engagement*. - Regenerative enterprises don't just restore the environment; they also strengthen communities and promote social equity. Improving social performance will help build stronger, more resilient relationships with stakeholders. It includes investing in local communities, fair labor practices, fostering stakeholder collaboration, and increasing social transparency.
5) *Enhance financial resilience and diversification*. - A regenerative enterprise must be financially sustainable to continue its work in restoration and regeneration. Improving financial resilience involves aligning profitability with regenerative objectives and diversifying income streams. It suggests the following: 1. Align profit with purpose (prioritizing long-term value over short-term profits, adopting pricing models that reflect the true environmental and social cost of goods and services, and reinvesting profits into regeneration initiatives), 2. Diversify revenue streams, 3. Access regenerative financing (regenerative finance options like impact investing, green bonds, or social impact bonds), 4. Measure Return on Regeneration Investment (RRI) (tracking the financial performance of regeneration projects).
6) *Leverage technology and innovation*. - Technology can play a critical role in driving regenerative change. By adopting new technologies and tools, the enterprise can increase efficiency, enhance regeneration efforts, and better track its progress. It means using digital tools for monitoring and reporting, adopting regenerative technologies, and automation for efficiency.
7) *Foster a regenerative corporate culture*. - The internal culture of a regenerative enterprise plays a key role in its success. By nurturing a culture of collaboration, innovation, and commitment to sustainability, employees will be more motivated to contribute to regenerative goals.
8) *Adopt a continuous improvement mindset*. - Regenerative enterprises are always evolving and improving. To stay ahead and keep improving, establish feedback loops and mechanisms for continuous learning. It includes regular impact reviews, engaging in peer learning, and iterative strategies.

Improving the performance of a regenerative enterprise requires a balanced focus on innovation, operational efficiency, social impact, and financial resilience. By setting clear goals, improving resource efficiency, fostering community engagement, leveraging technology, and maintaining a culture of continuous improvement, regenerative enterprises can grow while staying true to their mission of regeneration. Strategic leadership, employee engagement, and adaptive practices will ensure that the enterprise remains on track to meet both its regenerative and business goals.

Conclusion

At the core of regenerative performance management lies regenerative economics - a framework that seeks to define business success in ways that promote the health of ecosystems and communities. Unlike traditional economics, which measures value largely in terms of financial profit, regenerative economics incorporates social and environmental returns, fostering the idea that real business success is realized when ecosystems and societies thrive. This paradigm integrates environmental performance, social impact, and financial health into a holistic model that seeks to balance all three dimensions.

The performance management process within regenerative enterprises is vital for ensuring that business practices contribute to the restoration and regeneration of ecosystems, communities, and economies. By effectively planning, measuring, analyzing, and improving performance, regenerative businesses can drive long-term, positive systemic change. This process requires the integration of multi-dimensional metrics that go beyond financial profit. As regenerative business models continue to evolve, it will be essential to develop and refine performance management frameworks that support continuous improvement and the emergence of positive tipping points in sustainability. Future research could explore new methodologies for integrating regenerative principles into traditional performance management systems, while also considering how technology and innovation can accelerate the transition toward a regenerative economy. Moreover, performance management in regenerative enterprises requires the integration of new metrics that capture non-financial outcomes. These metrics include measures of ecological health, such as biodiversity restoration, carbon sequestration, and resource regeneration, as well as social metrics such as community well-being, labor practices, and stakeholder engagement. These metrics allow businesses to assess the broader, long-term impact of their activities, while also promoting continuous learning and adaptation.

The regenerative business paradigm is still evolving, but it holds the potential to reshape entire industries by encouraging restorative practices at every level of business operations. As more enterprises adopt regenerative principles, they will not only create value for themselves but they also play a key role in solving some of the most difficult challenges facing humanity, such as resource depletion, social inequality and biodiversity loss. By embracing regeneration, businesses can redefine their purpose/missions, improve the health of the planet, and ensure that future generations inherit a world that is not only sustainable but also abundant, thriving, and just.

Acknowledgement:

This work is the result of research based on the obligations under the Agreement in 2024 (No. 451-03-65/2024-03), concluded between Ministry of Science, Technological Development and Innovation of the Republic of Serbia and Faculty of Economics, University of Niš. This work was supported by the European Union’s Horizon Europe research and innovation programme under Grant number 101136834.

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ECONOMICS OF SUSTAINABLE DEVELOPMENT

Vol. 9, January-June 2025, № 1
UDK 33+502/504
ISSN 2560-421X

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P. 75-85
ORIGINAL SCIENTIFIC ARTICLE
10.5937/ESD2501075N
Received: June 22, 2024
Accepted: September 27, 2024

FINANCIAL EFFECTS OF THE CIRCULAR ECONOMY: HOW CIRCULAR ECONOMY PRACTICES BOOST PERFORMANCE OF SMALL AND MEDIUM ENTERPRISES IN SELECTED EUROPEAN SOUTHEAST COUNTRIES

Abstract

This paper examines the effects of circular economy (CE) practices on the financial performance of small and medium enterprises (SMEs) in selected European Southeast countries (namely, Serbia, Bulgaria, and Romania). It emphasizes the impact of different kinds of SMEs, like those focused on products, services, or both, and their benefits due to CE practices. Results of Logistic regression shows that Bulgaria is leading all kinds of SMEs in CE adaptation. However, there is a lot of potential in Serbia because there is a positive correlation between turnover increase and selling or reusing leftover materials or designing products that are easier to maintain, repair, or reuse.

Key words: *Circular Economy, Small and Medium Enterprises, SMEs' Turnover, Multinomial Logistic Regression, Sustainable Development*

JEL classification: *Q01, Q56, Q57.*

ФИНАНСИЈСКИ ЕФЕКТИ ЦИРКУЛАРНЕ ЕКОНОМИЈЕ: КАКО ПРАКСА ЦИРКУЛАРНЕ ЕКОНОМИЈЕ ПОБОЉШАВА УЧИНАК МАЛИХ И СРЕДЊИХ ПРЕДУЗЕЋА У ОДАБРАНИМ ЗЕМЉАМА ЈУГОИСТОЧНЕ ЕВРОПЕ

Апстракт

Овај рад испитује утицај пракси циркуларне економије на финансијски учинак малих и средњих предузећа у изабраним земљама југоисточне Европе (прецизније

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- Србији, Бугарској и Румунији). Рад истиче утицај различитих врста малих и средњих предузећа, попут оних која су фокусирана на производе, услуге, или оба, и њихове предности због пракси циркуларне економије. Резултати логистичке регресије показују да Бугарска предњачи у прилагођавању свих врста малих и средњих предузећа циркуларне економије. Међутим, у Србији постоји велики потенцијал, јер постоји позитивна корелација између повећања промета и продаје или поновне употребе одпалог материјала или дизајнирања производа који се лакше одржавају, поправљају или поново користе.

Кључне речи: *циркуларна економија, мала и средња предузећа, промет малих и средњих предузећа, мултиноминална логистичка регресија, одрживи развој*

Introduction

Numerous challenges related to climate change and environmental degradation, which have been present for decades all over the world, lead to a reconsideration of the business philosophies of economic actors in order to make important changes in the way of treating the natural and social community. It is spread by new approaches to business, which are adopted not only by large companies, but by all economic actors, regardless of their size.

The circular economy (CE) concept emerged as an approach to changing the way human activities relate to nature (Geissdoerfer et. al., 2017). The circular model represents changes in the way resources are regulated, produced and consumed. According to this concept, it is essential to update the traditional linear business model with a circular model, using the principles of reduction, reuse and recycling (Prieto-Sandoval et al., 2018). Despite the prevailing opinion that socially responsible practices are the responsibility of large companies, awareness of the need to involve SMEs in solving environmental problems is increasingly present. Although, viewed individually, they have a smaller impact on the environment than larger companies, SMEs represent 90% of all companies in the world (World Bank, 2019) and more than 99% in Europe, so their cumulative impact is large. As the dominant form of business, which also employs the largest number of people, but also has a large environmental impact, the SME sector can play a crucial role in managing limited social and environmental resources (Moore & Manring, 2009; Zhu et al., 2019).

In addition, there are other reasons why SMEs decide to transition to circular business models. For example, taking advantage of new opportunities due to the development of green markets (OECD, 2021), better access to environmentally responsible companies, knowledge flows and the wider market. There is an opinion that companies could profit from the adoption of circular practices, through cost savings due to the reduced use of resources, and the development of new markets (Ciravegna & Micheilova, 2022). These are the reasons why an increasing number of SMEs invest in transformation processes and start their journey towards the CE. A survey by the European Commission (2022) showed that more than half of SMEs in EU countries have already invested or plan to invest in dealing with problems caused by climate change, while two-thirds of SMEs have implemented resource efficiency activities, mainly through minimizing waste or energy saving (European Commission, 2022).

According to data from the European Union, only 7.2% of the global economy is circular, which means that a linear economy, characterized by unsustainable production and consumption, is still dominant (EU, 2023). In order to overcome environmental challenges, a set of documents and recommendations was created at the level of the European Union. One of the most important is the Circular Economy Action Plan, which covers the entire value chain from production to consumption, as well as repair and remanufacturing, but also waste management and secondary raw materials (EC, Directorate-General for Communication, 2020). Also, the European Green Deal, which aims to turn the EU into a "modern, resource-efficient and competitive economy" (COM, 2019). In the area of small and medium enterprises, the European SME Strategy (COM, 2020) was adopted in order to contribute to the goals of sustainable development and support the digital and green transition (European Commission, 2022). Although this set of policies and recommendations applies to all EU countries, the characteristics of national policies, financing systems, institutional contexts and incentives may differ between countries, which affects circular practices in SMEs (Zamfir et al., 2017). Also, factors such as geographical, ecological, economic and social influence the implementation of CE (Bačova et al., 2016).

The goal of the research is to investigate the impact of implementing CE practices on the financial performance of SMEs, analyze the effectiveness of existing policies and initiatives in promoting CE adoption among SMEs and to identify possible challenges and chances faced by SMEs in implementing circular practices. The research sample includes Serbia, Bulgaria and Romania because they are neighboring countries that share some common demographic characteristics, but two of which belong to the EU (Bulgaria and Romania), in which the circular transition process is at a higher level, since there are strategic documents and action plans in the field of CE, while in Serbia this process, both in terms of legislation and in terms of practice, is still at the beginning.

In order to reach the objective of the paper, the following hypotheses are developed:

Hoa: Did the circular economy adaptation increase the turnover of SMEs in Serbia, Bulgaria and Romania in the last two years (2019-2021)?

Hob: Is there any significant difference between types of SMSs for adaptation of circular economy, which can result in promotion of circular economy?

1. Literature review

Circular economy is a concept that promotes the use of resources in such a way as to increase the value of products or services through life cycle extension, while at the same time reducing waste or material that cannot be reused. By practicing the 3Rs practices (Reduce, Reuse, and Recycle), companies adopt innovative waste management practices, reduce generated waste and use recycled materials in the production process (Marković et al., 2023). The goal is to maximize the use of the product during its life cycle, and to return it to the production after the end of its useful life in order to create new value (Geissdoerfer et. al., 2017). CE changes the traditional way of using resources by extending their life cycle, and the results of this are visible not only through environmental and social performance, through reduced resource consumption and waste treatment, reduced harmful emissions, but also in a positive effect on the financial performance of the businesses (Rodríguez-Espındola et al., 2022).

In the literature, the prevailing opinion is that the transition to CE may have positive effects on company performance (Morić et al., 2020; Geissdoerfer et. al., 2017; Demirel & Danisman, 2019; Kirchherr et al., 2017). Numerous papers indicate that cost reduction based on optimization of resource use, seen from a long-term perspective, leads to certain benefits, such as increasing profits and a better position in the market, better competitive position (Morić et al., 2020). That is, it is considered that companies can potentially benefit from CE implementation through cost savings due to reduced needs for natural resources, as well as the development of new markets (Wijkman & Skånberg, 2015; Rizos et al., 2016; Taranic et al., 2016). The adoption of circular economy activities, through the development of new model of business, extends the product's useful life and encourages the use of resources in multiple cycles, which, along with minimizing waste, can have benefits that will be shown through financial indicators (Aboulamer, 2018; Lüdeke& Freund et al., 2019). In summary, earlier research has indicated that the adoption of a circular economy may have a positive effect, in terms of financial benefits for firms, suggesting that a link between the implementation of CE activities and financial performance exists (Rosa & Paula, 2023; Kurapatskie & Darnall, 2013).

However, there are still some questions about the effects of a circular economy on a company's economic performance. Companies that strive to work in accordance with CE principles should improve recycling capacities, enable systems to collect waste in order to reuse it as a resource and reduce the amount of production material (Wang et al., 2014; Ghisellini et al., 2016). That is, companies have to bear certain costs of implementing circular economy practices. However, it should be taken into account that some environmental innovations based on the application of CE require large costs and a long period to produce an impact on company performance (Soltmann et al., 2015).

SMEs are increasingly motivated to switch to circular models not only due to legislative pressures, but also because of potential cost savings in the long term, access to new markets, a good reputation on the market, etc. (OECD, 2011). The number of studies examining the adoption of CE in SMEs is relatively small, especially when it comes to comparative analysis in different geographical locations to discover best practices in SMEs. For SMEs, it is difficult to predict financial benefits because the adoption of circular economy practices generally implies additional investments, which can be unprofitable and excessive for SMEs (Dalhammar, 2016). Therefore, the implementation of the CE concept in the business model of companies, and especially SMEs, is not an easy process, considering that it can cause large costs that directly affect financial performance. As the resources of SMEs are generally limited, adapting to the CE can be a big challenge for them.

2. Methodology

In order to perform statistical research, the following dependent and independent variables were considered in developing the model:

Dependent Variable:

Company's annual turnover. The value of the dependent variable is obtained based on the answer to the research question (European Commission, 2022):

"Over the past two years, has your company's annual turnover increased, decreased or remained unchanged?"

Independent Variables:

(i) Selling your residues and waste to another company (SRW)
(ii) Recycling, by reusing material or waste within the company (RMW)
(iii) Designing products that are easier to maintain, repair or reuse. (DP)

The multinomial logistic regression model estimates the probability of observing each category of the dependent variable, given the independent variables. It uses a separate logistic regression equation for each category compared to a baseline category. Here is the general form for the kth category (k = 1, 2):

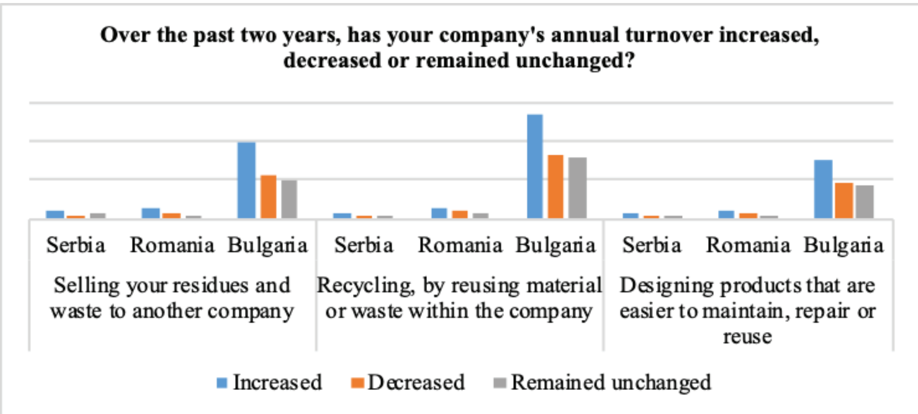
$$Ln\ (P(SCR13 = k) / P(SCR13 = Baseline)) = \beta_0\_k + \beta_1\_k * SRW + \beta_2\_k * RMW + \beta_3\_k * DP$$

We can interpret the results as the coefficients (β) representing the change in the log odds of belonging to a specific category compared to the baseline for a one-unit increase in the corresponding independent variable. Negative coefficients indicate that a higher value of the independent variable increases the odds of being in that category.

3. Results and discussion

The Flash Eurobarometer 498 survey released their report for November-December 2021, *SMEs, green markets and resource efficiency* on the basic bilingual questionnaire by Ipsos European Public Affairs and we have taken data for Serbia, Romania, and Bulgaria to show different levels of reported changes in specific practices concerning SMEs and resource efficiency.

Figure 1: The change in companies' turnover during the period 2019-2021



Source: The Flash Eurobarometer 498 survey, November-December 2021

From Figure 1, we can say that Bulgaria had the largest recorded rise in selling residues and garbage to another company, followed by Romania and then Serbia. Nevertheless, all three countries have a significant number of SMEs, indicating growth in this behavior.

Bulgaria is dominating in all green initiatives, as their number of firms is 10 times higher than that of Romania and Serbia, which recycle through the reuse of materials or garbage within the company as well as selling residues to other companies or designing products that can be repaired or reused.

Figure 2: Companies' turnover in 2020

Source: The Flash Eurobarometer 498 survey, November-December 2021

From the figure 2 companies' total turnover in 2020, the data provides insights into how businesses in Serbia, Romania, and Bulgaria are implementing sustainable practices. The majority of larger businesses with annual revenue above two million euros sell garbage and residues to other businesses, mostly in Bulgaria and less in Romania and Serbia. Larger SMEs are more likely to recycle, particularly by reusing trash or resources inside the company. Out of all turnover categories, Bulgaria has the highest recycling rate. Larger SMEs are more involved in producing "products that are easier to maintain, repair, or reuse" (European Commission, 2022); Bulgaria leads all turnover categories. These findings show that the commitment to implementing sustainable practices increases with business turnover, with Bulgaria continuously leading the way in this regard.

Table 1: Differences in CE practices according to what companies sell

What does your company sell?	Selling your residues and waste to another company			Recycling, by reusing material or waste within the company			Designing products that are easier to maintain, repair or reuse		
	Serbia	Romania	Bulgaria	Serbia	Romania	Bulgaria	Serbia	Romania	Bulgaria
Products	64	88	745	56	71	993	33	57	516
Services	45	75	543	47	11	1021	20	84	461
Both products and services	95	113	840	57	85	1111	47	77	739

Source: The Flash Eurobarometer 498 survey, November-December 2021

The information supplied sheds light on the operations of businesses in Serbia, Romania, and Bulgaria, with a focus on waste and surplus inventory sales, recycling, and product creation.

Companies in Bulgaria, Romania, and Serbia sell leftovers and trash to other businesses; Bulgaria leads in quantity, followed by Romania, and Serbia in the lowest place. In Bulgaria, recycling activities are quite common, especially the repurposing of resources or garbage inside the company. Furthermore, enterprises in all three of the countries routinely claim to have a higher percentage of products designed with ease of maintenance, repair, or recycling. Businesses are realizing more and more how important it is to adopt sustainable practices because of legal pressure and customer demand for environmentally friendly goods and services. Encouraging and promoting sustainable business practices is crucial for enhancing resource efficiency and environmental reform in the region's small and medium-sized firm sector.

5. Determinants of the implementation of circular economy activities in SMEs

We used multi-logistic regression for the analysis as our dependent variable have more than two responses.

The data shown in Table 2 says that in the last two years, turnover for Serbian SMEs selling their residues and waste to another company has increased more as compared to Romania and Bulgaria, but the Bulgarian SMEs have a lower standard error and their coefficient is significant at the 1% level as well. It means that in Serbia an increase in selling SMEs' residues and waste to another company will increase their turnover by 41 percent. SMEs in Serbia are providing products instead of services, as they can sell their residues and waste. Romania is ahead of Bulgaria and Serbia in this. However, if the SMEs are working with the products and services, they are getting more benefits by selling their residues and waste to other companies.

Table 2: Selling residues and waste to another company (M)

Variables	Coefficients			Standard Error		
	Serbia	Romania	Bulgaria	Serbia	Romania	Bulgaria
Increased in turnover as base outcome Decreased	-.41*	-.398**	-.263***	.227	.190	.065
Providing services as base outcome Products	.657*	1.03***	.692***	.243	.211	.068
Providing services as base outcome Products and services	1.15***	1.352***	.687	.234	.212	.067

Source: authors' own calculations-using STATA

According to Table 3, we cannot interpret the results for Serbia and Romania as they are insignificant, but for Bulgaria, we can say that turnover of SMEs that are recycling their waste at their own company has increased in the last two years. Bulgarian SMEs producing products or both (products and services) have been recycling within their company as compared to only service-provider SME's.

Table 3: Recycling, by reusing material or waste within the company

Variables	Coefficients			Standard Error		
	Serbia	Romania	Bulgaria	Serbia	Romania	Bulgaria
Increased in turnover as base outcome Decreased	-.391	.082	-.209***	.245	.192	.065
Providing services as base outcome Products	.302	-.237	.222***	.247	.210	.063
Providing services as base outcome Products and services	-.023	-.184	.193**	.249	.208	.063

Source: authors' own calculations-using STATA

From Table 4, we can see that Serbian SMEs, which are "designing products that are easier to maintain, repair or reuse" (European Commission, 2022), increased their turnover in the last two years by 94%, as compared to only 15% for Bulgarian SMEs. However, Bulgarian SMEs producing products get more benefit if they are designing products easier to maintain, repair, or reuse by 28.5%. When it comes to both products and services, Serbian SMEs are 21% better than Bulgarian SMEs, but we cannot say anything about Romanian SMEs due to the insignificance of the results.

Table 4: Designing products easier to maintain, repair or reuse

Variables	Coefficients			Standard Error		
	Serbia	Romania	Bulgaria	Serbia	Romania	Bulgaria
Increased in turnover as base outcome Decreased	-.94**	-.279	-.149**	.315	.200	.071
Providing services as base outcome Products	.615	-.025	.285***	.316	.219	.075
Providing services as base outcome Products and services	.877**	.262	.670**	.303	.212	.071

Source: authors' own calculations-using STATA

Conclusion

The findings showed a significant positive relationship between selling leftover materials and waste and higher revenue for Bulgarian SMEs. This discovery is consistent with the ideas of the circular economy, which focus on optimizing resource usage and reducing waste, potentially resulting in economic advantages. Serbian and Romanian SMEs show room for improvement. The results of the second hypothesis showed varied findings about the advantages of various CE procedures for different types of SMEs. Product-providing SMEs in Serbia showed some advantages, like making products easier to maintain. However, there was no definitive proof of these benefits being consistent across two other countries and industries. Furthermore, due to data constraints and inconclusive findings for Romania, further research is required in these areas. This research emphasizes the capacity of circular economy activities, namely the sale of residues and garbage, to increase small and medium-sized enterprises' revenue. Country-specific characteristics and variances across different types of SMEs significantly influence the success of these approaches.

Acknowledgements:
This research was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-65/2024-03 and Contract No. 451-03-66/2024-03/200371).

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Zoran Simonović. - Vol. 5, br. 1 (2021)- . - Niš :
Society of Economists "Ekonomika", 2020 - (Niš :
"Medivest"). 68 стр. - 24 cm

Dva puta godišnje.
ISSN 2560-421X = Economics of Sustainable
Development