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- *The Scientific Bulletin of Politehnica University of Timisoara, Transaction on Management. Economics Engineering. Transportation Engineering (ranked according to CNCSIS classification in Romania: C class).*



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## CONTENT


| | | |
|---|---|---|
| | **Editorial ……………………………………………………………………...** | 5 |
| 1 | **Regional Automotive Markets and Global Risk: An Empirical Assessment** Oana PANAZAN, Nicoleta STELEA and Cătălin GHEORGHE | 7 |
| 2 | **State of the Art: Social Implications of AI Systems Integration in Civil Aviation,** Serban MERTOL and Cella BUCIUMAN | 20 |
| 3 | **Human-Centered AI Integration in Air Traffic Control: Operational, Ethical and Social Implications,** Serban MERTOL, Cella BUCIUMAN and Caius LUMINOSU | 26 |
| 4 | **Developing Competencies and Training Skills Through Erasmus+ Programme,** Ileana-Virginia TOFAN, Andra DIACONESCU, Daniela MARGAN, Zenovia FURNEA | 31 |
| 5 | **Using ML.NET To Educate High School Students on Machine Learning for A Smoother Transition into Higher Education in Computer Science,** Andra DIACONESCU, Jadranka Ogrizović MILOJKOVIĆ and Velimir RADLOVAČKI | 35 |
| 6 | **Applying Lean Principles to the Manufacturing of Air Intake Manifolds in the Automotive Industry: Improving Process Efficiency** Oana-Andreea BALANEAN and Matei TAMASILA | 39 |
| 7 | **Digital and Sustainability Solutions in Higher Education for Circular Economy Awareness. A Theoretical Approach with Case Study Debate** Anca DRAGHICI, Maria-Elena BOATCA, Ionel LUNGU, Roxana DAMASCHIN-TECU, Ioana-Gabriela CIOATA and Cristina Camelia CIOFU | 44 |
| 8 | **Circular Economy Principles Applied to the Recycling of Used Cooking Oil: The OilRight Case Study,** Roxana DAMASCHIN-TECU, Livia-Maria CIOLAC, Ioana-Gabriela CIOATA and Cristina Camelia CIOFU | 60 |

**Scientific Bulletin**
**of Politehnica University of Timisoara, Romania**

**Transactions on ENGINEERING AND MANAGEMENT**

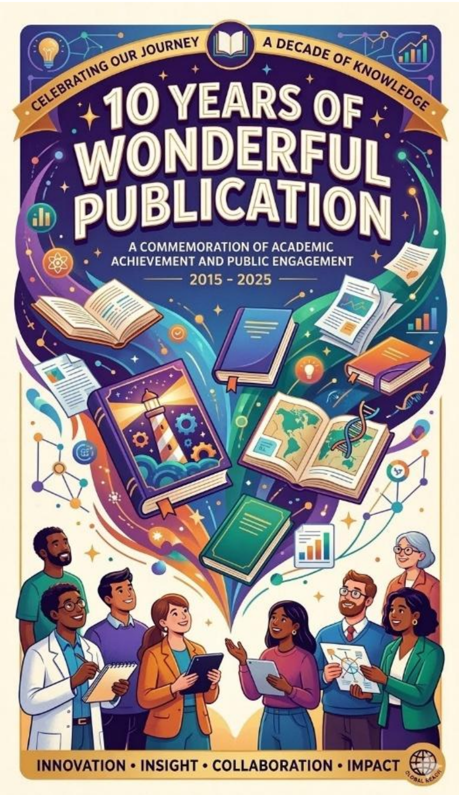
**Vol. 11, Issue 2, 2026**

# Editorial

Anca DRAGHICI[1] and Larisa IVASCU[2]

The volume 2, from 2025 of the "***Scientific Bulletin of Politehnica University of Timisoara – Transaction on Engineering and Management***" (ISSN 2392-7364) continue to surprise having an increase visibility due to the journal index in CrossRef (https://www.crossref.org/), CEEOL (https://www.ceeol.com/) and index Copernicus (https://journals.indexcopernicus.com/) databases. In addition, the Editorial Board announced the compliance of the articles published with the Open Science movement and this only thanks to the excellent collaboration and constant support offer by the UPT Library and the Politehnica Publishing House.

All articles of the ***Scientific Bulletin*** of this number have been reviewed by the members of the *Associated Editors and of the Scientific Committee;* their professional and volunteer review work impact the quality content of the papers included in this volume. Furthermore, the ***Scientific Bulletin*** benefits from the constant support of the R&D staff of the ***Research Center in Engineering and Management (RCEM)***[3] (of the Faculty of Management in Production and Transportation, Politehnica University of Timisoara, FMPT/UPT, Romania); RCEM provide a productive and positive network, and a scientific community through which we support knowledge sharing, buddy schema and trainings (formal or informal).




In 2025, the "***Scientific Bulletin of Politehnica University of Timisoara – Transaction on Engineering and Management***" (ISSN 2392-7364) celebrate 10 years of regular and continuous appearance of our journal. That is why the Editorial Board has decided to have 2 separate numbers of volume 11 and to promote young generations of researchers together with their recent achievements, but also to demonstrate the power of our community by considering valuable contributions of the senior researchers.

The main research topics discussed in the current issue of the Scientific Bulletin of Politehnica University of Timisoara are:

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The first paper, "***Regional Automotive Markets and Global Risk: An Empirical Assessment***" (developed by a group of colleagues from Transilvania University of Brasov, Romania), analyzes the regional interdependencies and transmission of financial and geopolitical risks in the global automotive industry using wavelet coherence analysis.

The second paper, ***State of the Art: Social Implications of AI Systems Integration in Civil Aviation*** (developed by authors from Politehnica University of Timisoara, Romania), provides a comprehensive review of the integration of Artificial Intelligence (AI) in civil aviation, emphasizing social, ethical, operational, and human factors. Similar, the third paper (***Human-Centered AI***

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***Integration in Air Traffic Control: Operational, Ethical, and Social Implications***), developed by the same authors as the previous paper, explores the social implications, opportunities, and challenges of integrating Artificial Intelligence (AI) into air traffic control and management systems.

The fourth paper entitled ***Developing Competencies and Training Skills Through Erasmus+ Programme*** (developed by a group of authors from Politehnica University of Timisoara and colleagues from the pre-university system) examines the significant impact of the Erasmus+ programme on students' educational, professional, and personal development, focusing on experiences from a Romanian high school's participation in an exchange with Lisbon. It highlights how Erasmus+ fosters key competencies such as communication in English, practical job skills, and adaptability through real-world training and cultural immersion.

Fifth paper, ***Using ML.NET To Educate High School Students on Machine Learning for A Smoother Transition into Higher Education in Computer Science*** (developed by group of authors from Politehnica University of Timisoara, Romania and colleagues from the School Center "Nikola Tesla" Varsec, Serbia) explores how ML.NET, a machine learning framework by Microsoft, can be effectively used to introduce machine learning concepts to high school students, particularly in vocational education settings. The authors highlight the challenges of teaching machine learning at this level, such as complexity, computational requirements, and the need for advanced mathematics and demonstrate how ML.NET addresses these by offering an accessible, hands-on approach that integrates seamlessly with existing C#/.NET curricula.

Th sixth paper (***Applying Lean Principles to the Manufacturing of Air Intake Manifolds in the Automotive Industry: Improving Process Efficiency***) was proposed by a group of authors from Politehnica University of Timisoara, Romania and presents a case study on applying Lean manufacturing principles to optimize the semi-automated production of air intake manifolds in the automotive industry. By systematically analyzing the production line, identifying and eliminating non-value-added activities, and implementing Lean tools such as line balancing, chaku-chaku principles, and optimized material flow, the study achieved measurable improvements: cycle time was reduced from 69 to 65 seconds, the number of operators decreased from four to three, labor productivity increased by 46%, and the line balance rate improved from 83% to 90%.

Further, the next paper (***Digital and Sustainability Solutions in Higher Education for Circular Economy Awareness. A Theoretical Approach with Case Study Debate***) has been proposed by a group of authors from Politehnica University of Timisoara, Romania and explores the role of higher education institutions (HEIs) in fostering the transition to a circular economy (CE) by integrating digital and sustainability solutions into curricula, campus operations, and research. It highlights the necessity of shifting from the traditional linear economic model to a circular approach to minimize resource depletion and environ-mental degradation. The study introduces a holistic framework designed to guide universities in implementing digital and sustainable practices that enhance awareness of CE principles.

The last paper (***Circular Economy Principles Applied to the Recycling of Used Cooking Oil: The OilRight Case Study***) has been developed by colleagues from Politehnica University of Timisoara, Romania and the research approach explores how circular economy principles can be applied to the collection and recycling of used cooking oil, focusing on a local initiative in Timisoara, Romania, to promote sustainable waste management, resource recovery, and community engagement.

We hope that this anniversary volume of the Scientific Bulletin will give you not only the joy of being part of the Research Center in Engineering and Management (RCEM) celebration, but also the satisfaction of a pleasant reading that will stimulate creativity, new ideas and ... new article proposals.

Scientific Bulletin
of the Politehnica University of Timisoara, Romania

TRANSACTIONS on ENGINEERING AND MANAGEMENT

Volume 11, Number 2, 2025

# Regional Automotive Markets and Global Risk: An Empirical Assessment

Oana PANAZAN[1], Nicoleta STELEA [2], Cătălin GHEORGHE[3]

**Abstract** –The automotive industry plays a central role in the global economy, with its dynamics closely tied to financial and geopolitical stability. This study investigates the connection between regional automotive markets in the United States, Europe, China, and Japan and two established indicators of global uncertainty: the CBOE Volatility Index (VIX) and the Geopolitical Risk Index (GPR). Using continuous wavelet transform and wavelet coherence analysis on daily data, the research uncovers time–frequency patterns in the transmission of financial and geopolitical shocks. The findings show that the U.S. and China act as epicenters of instability, the former closely linked to financial volatility, and the latter highly sensitive to geopolitical and trade tensions. Europe and Japan, while deeply embedded in global supply chains, primarily appear as receivers of shocks, reacting most strongly during systemic crises such as the COVID-19 pandemic or the 2022 energy crisis, which was triggered by Russia's invasion of Ukraine and the subsequent surge in global energy prices. The paper contributes by highlighting the heterogeneity of regional interdependencies and the asymmetric roles of automotive markets in shaping global risk dynamics. These insights provide a valuable framework for investors and policymakers, underscoring the importance of region-specific risk monitoring in anticipating global instability.

**Keywords:** automotive industry; stock indices; volatility; geopolitical risk; regional markets.

## I. INTRODUCTION

The automotive sector is one of the most dynamic and interconnected industries of the global economy, contributing significantly to GDP, international trade, technological innovation, and employment. The globalization of production and the integration of supply chains have created unprecedented interdependencies among regional automotive markets, such that local shocks are rapidly transmitted worldwide.

Prior research shows that disruptions in automotive supply chains generate contagion effects even for competitors, with impacts varying across business cycles and regions (Filbeck et al., 2016), while resilience strategies such as multiple sourcing or emergency stockpiles can mitigate these risks and sustain competitiveness (Rezapour et al., 2017). More recently, volatility originating from semiconductor shortages was directly transmitted to the automotive sector during the COVID-19 outbreak, underscoring the vulnerability of highly integrated supply chains (Marobhe & Dickson, 2023).

From a macroeconomic perspective, sectoral returns provide valuable information for forecasting economic growth, with the automotive industry standing out for its strong ability to anticipate macroeconomic stability (Marfatia, 2023). In Europe, studies confirm the role of exports and economic complexity, particularly in post-communist economies integrated into global value chains, emphasizing the importance of the automotive sector in the digital and green transition (Rusnák et al., 2024).

At the same time, financial markets have become increasingly sensitive to external risk factors. The CBOE Volatility Index (VIX), often described as the "fear gauge" of financial markets, reflects investors' expectations of short-term risk, while the Geopolitical Risk Index (GPR) has gained prominence in a context shaped by international tensions, regional conflicts, and unpredictable trade policies.

Rising economic and geopolitical uncertainty directly influences investment decisions, capital flows, and highly globalized industries such as the automotive sector. Evidence from China shows that the COVID-19 pandemic triggered strong contagion effects within supply chains, adversely affecting both directly impacted firms and their upstream and downstream partners, confirming the central role of logistical disruptions in amplifying stock market volatility (Wang et al., 2022). China's transition from traditional

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vehicles to electric ones has also been marked by instability and erratic dynamics, driven by dual-credit policies and rapid production adjustments, highlighting the sector's structural vulnerabilities (Tang & Wu, 2024).

Nevertheless, the existing literature remains fragmented and does not fully capture the nexus between the automotive industry and global risk. Most contributions focus on a single region, most notably the U.S. market (Caiado & Lúcio, 2023), or on individual firms, as shown by research on investor responses to firm-specific information and idiosyncratic shocks (Geiger et al., 2022), limiting the comparative understanding of major automotive hubs.

In addition, financial volatility and geopolitical risk are often studied separately: while VIX is widely acknowledged as a barometer of financial uncertainty (Bollerslev et al., 2009), research on the GPR highlights the effects of international tensions on investment flows and stock market volatility (Caldara & Iacoviello, 2022).

Yet recent episodes demonstrate that these dimensions frequently overlap and reinforce one another, as during the COVID-19 pandemic, when macro-financial stocks were simultaneously transmitted through geopolitical and trade channels (Shahbaz et al., 2024). Finally, dynamic multi-scale approaches that can capture how relationships between automotive markets and global risk indicators evolve over time and across frequencies remain scarce, even though wavelet-based methods have proven effective in identifying such linkages in other cyclical industries (Akorsu et al., 2025).

This paper seeks to fill these gaps by offering a comparative and integrated analysis of the automotive markets in the United States, Europe, China, and Japan, in relation to two established global uncertainty indicators, the VIX and GPR. By employing the continuous wavelet transform (CWT) and wavelet coherence (WTC), the study provides a dynamic perspective on the transmission of financial and geopolitical shocks, highlighting regional asymmetries in the role of automotive markets in shaping global risk.

The main contribution of this paper is twofold: on the theoretical side, it advances the literature by documenting the heterogeneous and multi-scale nature of sectoral interdependencies in a key global industry that has so far received limited comparative attention; on the practical side, it offers actionable insights for investors and policymakers by showing how risk transmission differs across regions and why differentiated monitoring of automotive markets is essential for anticipating global instability.

The paper proceeds as follows. Section 2 synthesizes the existing literature. Section 3 outlines the dataset and methodological framework. Section 4 reports and interprets the empirical findings. Section 5 examines both theoretical contributions and practical implications. Finally, Section 6 offers concluding insights and highlights directions for future research.

## II. LITERATURE REVIEW

### *II.I Financial market volatility, the VIX, and implications for the automotive sector*

Elevated levels of the VIX reflect a deterioration in investor sentiment and are associated with declines in stock returns, effects that are particularly strong in cyclical sectors such as the automotive industry. These impacts intensify during crisis periods, when markets become more vulnerable to external shocks and rapid changes in liquidity conditions.

Recent studies confirm that energy-dependent sectors, such as the automotive industry, are affected not only by financial volatility but also by oil market fluctuations, with shocks from these two sources amplifying perceived risk and generating persistent volatility during episodes of major instability (Balcilar et al., 2018; Jain et al. 2023). Moreover, the influence of the VIX extends beyond returns, shaping firms' financing decisions: an increase in the index leads U.S.-listed companies to rely more heavily on market leverage, particularly in the long term, highlighting its structural impact on capital markets (Vuong, Nguyen & Wong, 2022).

At the international level, stock price volatility in the automotive sector is correlated with macroeconomic factors such as capital market development, GDP, or unemployment rates (Vychytilová et al., 2019). More recent evidence shows that the VIX has substantial predictive power for stock market volatility in emerging economies, especially in China, where the influence is more pronounced in the near future and in the case of downside volatility (Xiao et al., 2021).

This study extends these perspectives by simultaneously incorporating financial and geopolitical uncertainty, measured through the VIX and the GPR, to provide a more comprehensive understanding of how regional automotive markets are linked to global risk.

### *II.II Geopolitical risk and transmission to automotive markets*

Beyond the financial uncertainty captured by the VIX, the literature during the previous 20 years has increasingly emphasized the role of geopolitical risk, typically measured by the GPR. This index measures the economic and financial consequences of political events, international tensions, and armed conflicts. Prior research consistently shows that elevated GPR values reduce investor confidence, discourage capital formation, and heighten stock market volatility.

The automotive sector is particularly vulnerable to such shocks because of its globalized production structure and reliance on complex supply chains. Empirical studies demonstrate that supply chain disruptions, trade tariffs, and economic sanctions are rapidly transmitted to automotive firms' performance. Importantly, these effects are heterogeneous across regions: emerging markets and economies directly exposed to geopolitical tensions tend to react more strongly than advanced economies, where policy buffers partially mitigate the shocks. This underscores the relevance of the automotive industry as a key case for examining the interaction between geopolitical risk and financial markets.

In addition to these global risks, the automotive sector is also sensitive to firm-specific and informational shocks. For example, research documents that company-level announcements such as recalls or customer complaints induce significant adjustments in institutional investors' trading strategies (Geiger et al., 2022). Moreover, recent studies emphasize the role of investor sentiment, showing that alternative proxies such as Google Trends influence trading activity and returns, particularly in more vulnerable firms (Qureshi, 2025). Taken together, these findings suggest that the automotive sector is simultaneously exposed to macroeconomic, geopolitical, and industry-specific shocks, which makes it a particularly suitable domain for investigating the links between uncertainty and global risk.

### *II.III Regional interdependencies and shock spillovers in the automotive industry*

While the literature on VIX and GPR emphasizes the role of financial and political uncertainty, a parallel stream of research highlights the importance of regional interdependencies. Evidence from conditional volatility models and multi-scale approaches demonstrates that relationships across financial markets are inherently dynamic, evolving with economic cycles and major global events. The transmission of international shocks has been extensively documented; for example, Antonakakis et al. (2014) show dynamic spillovers amid oil prices and economic policy uncertainty. Within the automotive industry, empirical studies confirm that supply chain disruptions propagate contagion effects even to competitors, with stronger impacts during recessions and greater vulnerability for U.S. firms compared to Japanese firms (Filbeck et al., 2016). More recent findings for China suggest that logistics bottlenecks and elevated transportation costs amplify stock crash risk, particularly for firms with intensive international exposure or monopolistic structures (Chen et al., 2025).

In this context, the United States and China emerge as main transmitters of shocks, while Europe and Japan generally act as receivers, despite their deep integration in global supply chains. Structural factors such as globalization, the energy transition, and reliance on critical raw materials intensify these interdependencies, producing stronger synchronization of volatility during crisis episodes. Research on supply chain resilience further demonstrates that buffering strategies, including safety stocks, supplier diversification, and backup capacity, enhance firms' adaptability, though their effectiveness depends critically on positioning within the supply chain, differentiating upstream from downstream actors (Qamar et al., 2025).

The methodological literature also supports the notion that cyclical sectors, particularly the automotive industry, exhibit heightened sensitivity to external shocks. Wavelet coherence studies reveal strong reactions to market uncertainty (Patel et al., 2025), while dynamic specifications such as DCC-GARCH capture the propagation of systemic risk associated with energy volatility (Naeem et al., 2020). The COVID-19 outbreak provided a natural experiment, as it disrupted stock performance and volatility in heterogeneous ways across industries, confirming the fragility of cyclical sectors (Najaf et al., 2022). Moreover, recent wavelet-based evidence indicates that oil market shocks exert a negative effect on automotive equities, more pronounced in China than in the United States (Akorsu et al., 2025).

Taken together, these findings indicate that shock transmission in the automotive sector is regionally heterogeneous and conditioned by the global environment. This reinforces the need for a comparative and dynamic analysis of regional automotive markets. Building on these considerations, the following research hypotheses are proposed:

H1. Fluctuations in regional automotive markets exert a significant impact on global volatility, as measured by the VIX index, with varying intensity across regions.

H2. Increases in geopolitical risk, captured by the GPR index, have negative effects on the performance of regional automotive indices, with stronger reactions in China and the United States compared to Europe and Japan.

## III. DATA AND METHODOLOGY

### *III.I Dataset*

The empirical analysis relies on financial time series that capture both the evolution of regional automotive markets and the dynamics of global uncertainty. To represent the automotive sector, four specialized stock indices corresponding to the main economic regions were selected: the Dow Jones Automobiles & Parts Titans 30 (United States, DJTATO), the STOXX Europe 600 Automobiles & Parts (Europe, SXAR), the FTXIN4401010 Automobile Index (China), and the Nikkei Automobiles & Auto Parts (Japan, NAUT). These indices were chosen because the four regions account for a substantial share of global automobile production and consumption and play central roles in international supply chains.

In the case of Europe, the SXAR is widely regarded as a systemic benchmark. Prior studies document bidirectional causal relationships between this index and both the broader equity market and other key sectors (Badea et al., 2019). It also reflects the sensitivity of the European automotive sector to exchange rate shocks, as research has shown that appreciation of the EUR/USD exchange rate significantly affects German, French, and British exports (Leuwer & Süssmuth, 2017).

Global uncertainty is measured using two well-established indicators. The VIX serves as a proxy for investor expectations regarding short-term market volatility, while the GPR constructed by Caldara and Iacoviello (2022) quantifies the intensity of international events with economic and political implications. These indicators capture complementary dimensions of uncertainty: a financial dimension, with direct effects on asset pricing, and a geopolitical dimension, associated with political and security tensions.

The dataset was collected from reputable international sources: Bloomberg and Refinitiv for the stock indices and the VIX, and the Caldara and Iacoviello database for the GPR. The sample period spans January 1, 2014, to August 15, 2025, encompassing both phases of economic expansion and major crisis episodes, thus enabling a robust analysis of dynamic interrelationships. All series were converted into logarithmic returns to ensure comparability and mitigate issues related to scale heterogeneity.

*III.II Methodology*

To capture the interdependencies among the indices, we employed the CWT and WTC, which allow for the simultaneous examination of relationships across both time and frequency domains (Torrence & Compo, 1998). This approach has been increasingly applied in recent literature to evaluate multi-scale correlations between risk indicators, such as VIX and SKEW, and sectoral returns, highlighting the heterogeneous sensitivity of cyclical versus defensive sectors to financial shocks (Bouri et al., 2024).

The main method applied is the CWT, which is used to decompose return series into a time–frequency domain. For a time series x(t), the CWT is described as:

$$W_x(\tau,s)=\int_{-\infty}^{\infty} x(t)\,\frac{1}{\sqrt{|s|}}\,\Psi^*\left(\frac{t-\tau}{s}\right)dt, \quad (1)$$

where τ stands for the translation parameter (time position), s is the scaling factor (associated with frequency), and $\psi^*$ indicates the complex conjugate of the mother wavelet function. This formulation allows for the identification of periods in which the signal contains high- or low-frequency components and thus provides a detailed representation of how fluctuations in automotive markets relate to financial and geopolitical uncertainty.

To assess the robustness of the outcomes obtained through CWT, the analysis was complemented with WTC, which measures the local coherence between two time series. If x(t) and y(t) are two series, the wavelet coherence is defined as:

$$R^2(s,\tau)=\frac{\left|S\left(s^{-1}W_{x,y}(\tau,s)\right)\right|^2}{S(s^{-1}|W_x(\tau,s)|^2)\cdot S\left(s^{-1}\left|W_y(\tau,s)\right|^2\right)} \quad (2)$$

where $W_x(s,\tau)$ and $W_y(s,\tau)$ are the wavelet transforms of the series x and y, $W_{x,y}(s,\tau) = W_x(s,\tau)W_y^*(s,\tau)$ stands for the cross-wavelet transform of time series, s represents the scale (inversely related to frequency). The operator S(·) indicates a local smoothing function applied in both time and scale. This measure ranges between 0 and 1, where values close to 1 indicate a high degree of local correlation between the two series at a given time and frequency, while values close to 0 suggest weak or no correlation. WTC is particularly suited for detecting dynamic linkages that vary over time and across different frequency bands, making it highly relevant for assessing the interaction between automotive indices and global risk indicators.

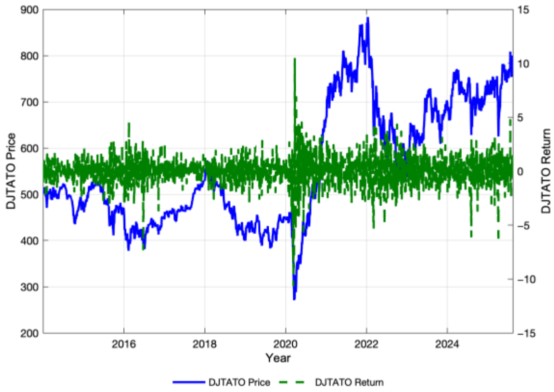
The combination of the two methods provides a robust methodological framework. While CWT enables a detailed exploration of the dynamic structure of the series, WTC validates the stability and significance of the relationships identified between regional automotive markets and global risk indicators. Together, these approaches allow the results to more accurately capture the complex reality of financial and geopolitical interdependencies.

*III.III Descriptive statistics and stationarity*

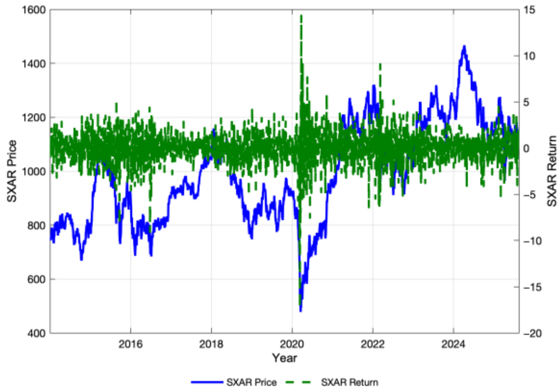
Figure 1 depicts the dynamics of prices and returns for the selected indices. The series exhibit the typical behavior of financial assets: prices follow a long-term upward trajectory, punctuated by episodes of elevated volatility, particularly around 2020 and 2022, when sharp fluctuations occurred. Returns are markedly more volatile and fluctuate around zero, which is consistent with stationarity.

For DJTATO and SXAR, volatility intensifies during crisis periods, followed by recoveries and the re-establishment in the long run trend. By contrast, the FTXIN4401010 index displays a steeper upward trajectory and more extreme volatility episodes, reflected in returns through high-amplitude spikes that highlight its greater sensitivity to external shocks. The NAUT index follows a pattern similar to SXAR, though with wider variations in returns.

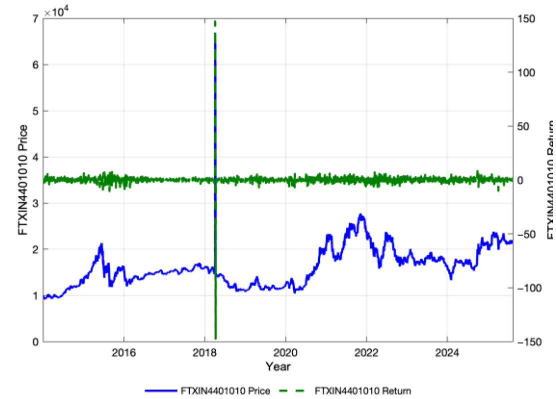
Taken together, these dynamics confirm that while prices maintain a long-term growth trend, returns remain highly volatile and characterized by extreme values. This has direct implications for risk assessment, underscoring the need for models capable of capturing fat-tailed distributions and extreme events in the automotive sector.



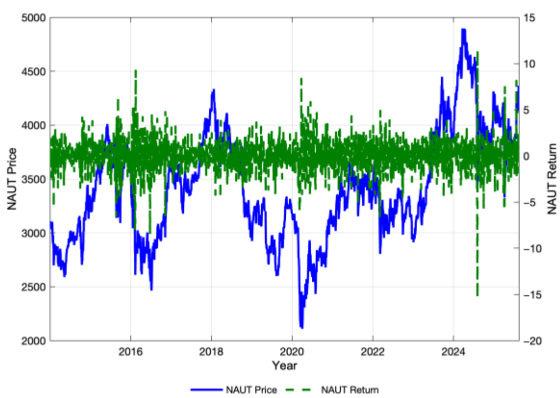

DJTATO




SXAR




FTXIN4401010




NAUT

*Fig. 1. Evolution of prices and returns for the analyzed stock market indices*

Statistical analysis (Table 1) and the boxplots (Figure 2) highlight the main distributional characteristics, emphasizing both measures of central tendency and the presence of extreme values and deviations from normality.

For DJTATO, the proximity of the mean and median (0.02) suggests relative symmetry. However, the negative skewness (−0.42) and high kurtosis (11.12) indicate a leptokurtic distribution, with fat tails and frequent outliers, a pattern also evident in the boxplot. SXAR displays a comparable profile: although the mean (0.01) and median (0.05) are close, the negative skewness (−0.50) and elevated kurtosis (12.10) point to substantial departures from normality and a higher frequency of extreme values.

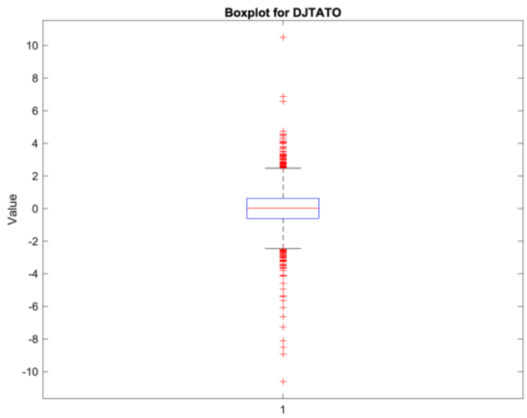
The case of FTXIN4401010 is more pronounced. While the mean (0.03) and median (0.00) are close to zero, the large standard deviation (4.27) and extreme values (±147) confirm its exceptionally high volatility. The distribution appears nearly symmetric (skewness = −0.08), yet the extremely elevated kurtosis (980.07) reveals a strong concentration around the mean and extremely long tails. This is also reflected in the boxplot, where the relatively narrow IQR (1.64) contrasts sharply with the magnitude of extreme observations.

For NAUT, the mean and median close to zero and the modest skewness (−0.29) suggest near symmetry. Nevertheless, the high kurtosis (9.84) again signals fat tails and frequent outliers, a feature corroborated by the boxplot.

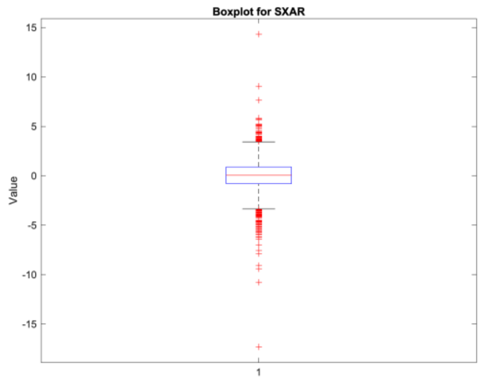
The Jarque–Bera test decisively denies normality for all series (p = 0.000), confirming that returns exhibit leptokurtosis and frequent extreme values. Although the IQR is relatively similar across indices (1.24–1.70), indicating moderate dispersion at the center, it fails to capture the underlying tail risk.

*Table 1 Descriptive statistics*

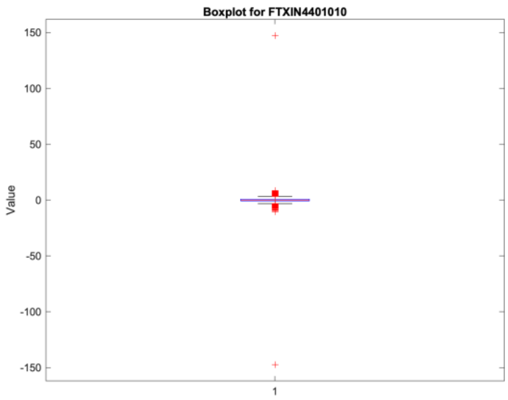
| Indicator | DJTATO | SXAR | FTXIN4401010 | NAUT |
|---|---|---|---|---|
| Mean | 0.02 | 0.01 | 0.03 | 0.01 |
| Median | 0.02 | 0.05 | 0.00 | 0.00 |
| Maximum | 10.49 | 14.33 | 147.19 | 11.43 |
| Minimum | -10.60 | -17.30 | -147.31 | -15.37 |
| Standard deviation | 1.23 | 1.64 | 4.27 | 1.56 |
| Skewness | -0.42 | -0.50 | -0.08 | -0.29 |
| Kurtosis | 11.12 | 12.10 | 980.07 | 9.84 |
| Jarque-Bera | 8,042.21 | 10,114.14 | 115,000,000.00 | 5,691.71 |
| Probability | 0.000 | 0.000 | 0.000 | 0.000 |
| IQR | 1.24 | 1.70 | 1.64 | 1.55 |



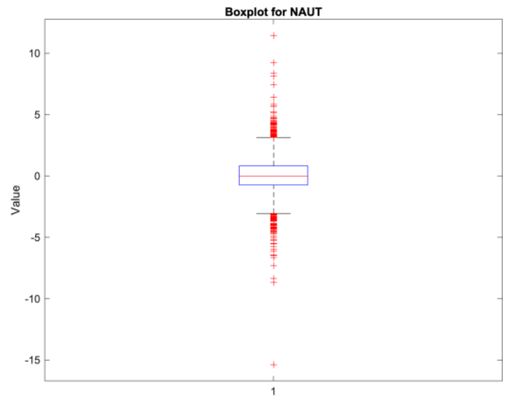

DJTATO




SXAR




FTXIN4401010




NAUT

*Fig. 2 Boxplot representation of return distributions*

The results of the Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) unit root tests (Table 2) indicate that all analyzed series are stationary. Both the ADF and PP tests yield strongly negative t-statistics with associated p-values of 0.000 for all indices (DJTATO, SXAR, FTXIN4401010, and NAUT), which allows for a decisive rejection of the null hypothesis of a unit root. This outcome confirms that the series do not follow a random walk and can be treated as stationary in levels. Complementarily, the KPSS test reports LM statistics below the critical thresholds with low significance levels, further corroborating the absence of a systematic trend and supporting the conclusion of stationarity.

For robustness, first-order differences were also examined and found to be significant; however, their relevance is secondary since the series are already stationary at level. Overall, the joint evidence from all three tests consistently supports the stationarity of the stock market return series under consideration.

*Table 2. Results of unit root tests*

| Unit Root Tests | | Index | DJTATO | SXAR | FTXIN4401010 | NAUT |
|---|---|---|---|---|---|---|
| ADF | level | t-Stat. | -44.445 | -52.474 | -30.391 | -54.571 |
| | | Prob.* | 0.000 | 0.000 | 0.000 | 0.000 |
| | 1st diff | t-Stat. | -24.346 | -22.039 | -22.579 | -19.533 |
| | | Prob.* | 0.000 | 0.000 | 0.000 | 0.000 |
| PP | level | Adj. t-Stat | -44.449 | -52.490 | -75.322 | -54.574 |
| | | Prob.* | 0.000 | 0.000 | 0.000 | 0.000 |
| | 1st diff | Adj. t-Stat | -672.363 | -893.411 | -713.726 | -1044.410 |
| | | Prob.* | 0.000 | 0.000 | 0.000 | 1.000 |
| KPSS | level | LM-Stat. | 0.121 | 0.026 | 0.050 | 0.038 |
| | 1st diff | LM-Stat. | 0.032 | 0.027 | 0.047 | 0.043 |

# IV. RESULTS

## *IV.I CWT results*

The application of the CWT to regional automotive indices reveals pronounced heterogeneity across markets in both the frequency and intensity of fluctuations. For the United States and China, the CWT spectra highlight extended high-energy zones during episodes of financial crises and trade tensions, indicating a heightened sensitivity of these markets to external shocks. By contrast, the European and Japanese indices exhibit more stable dynamics, with marked intensifications only during periods of severe global turbulence. These findings support the view of the United States and China as primary shock transmitters in the global automotive industry, while Europe and Japan act mainly as recipients.

Figure 3 presents the wavelet coherence between each regional index (DJTATO, SXAR, FTXIN4401010, and NAUT) and the global uncertainty indicators VIX and GPR. For the U.S. automotive index (DJTATO), strong and persistent coherence with VIX is observed in several critical episodes. In 2016, the coherence peaks around the U.S. presidential election and the associated monetary policy uncertainty, reflecting how the political transition under the Trump administration amplified financial volatility. In 2020, the COVID-19 outbreak generated simultaneous demand and supply impacts, while in 2022 the Russia–Ukraine war and the global energy crisis again produced strong co-movements with volatility. The relationship with GPR is less persistent but becomes significant after 2018, particularly during 2022–2023, a period of heightened geopolitical instability. These episodes coincide with the intensification of U.S.–China trade tensions and tariff policies introduced under the Trump administration, which directly affected the automotive supply chain.

In Europe (SXAR), coherence with VIX is sustained from 2015 to 2020, intensifying during the pandemic, when supply chains were severely disrupted and demand collapsed. Episodes of coherence with GPR are weaker but emerge in 2017–2019, coinciding with the Brexit negotiations and the migration crisis, and reappear in 2022 with the outbreak of the Russia–Ukraine war and the associated energy shock. These results indicate that the European automotive industry is more sensitive to geopolitical events of a regional nature, while financial volatility dominates during global crises.

For China (FTXIN4401010), coherence with VIX is weaker and episodic. Strong linkages appear in 2015–2017, during the domestic stock market crash and yuan devaluation, and again in 2018–2019, corresponding to with the escalation of the U.S.–China trade war. By contrast, coherence with GPR strengthens considerably after 2020, reflecting the impact of technological sanctions, trade restrictions, and the reconfiguration of global supply chains. This pattern underscores that geopolitical tensions, rather than financial volatility alone, are the dominant drivers of uncertainty in the Chinese automotive sector.

In Japan (NAUT), strong and persistent coherence with VIX is observed in 2015–2018, when the Japanese economy was highly dependent on external demand, and again during 2020–2022, when the pandemic and the collapse of global logistics severely disrupted automobile production. The relationship with GPR becomes more visible between 2018 and 2022, a period marked by Asia–Pacific tensions and the global semiconductor shortage, underscoring the exposure of Japan's automotive industry to both geopolitical shocks and supply chain vulnerabilities.

Taken together, the results confirm that the United States and China are the most exposed and reactive to global financial and geopolitical shocks. The United States shows a strong alignment with financial volatility, especially during episodes of political transition and crisis, while China exhibits greater sensitivity to geopolitical risk, particularly in the post-2018 period of escalating trade tensions with the U.S. and subsequent sanctions. Europe and Japan, although less frequently at the epicenter of shocks, display heightened vulnerability during episodes of global turbulence such as the COVID-19 outbreak and the 2022 energy crisis.

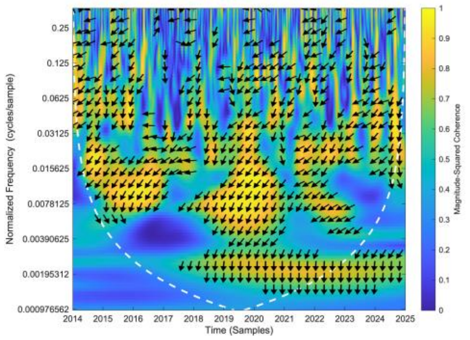
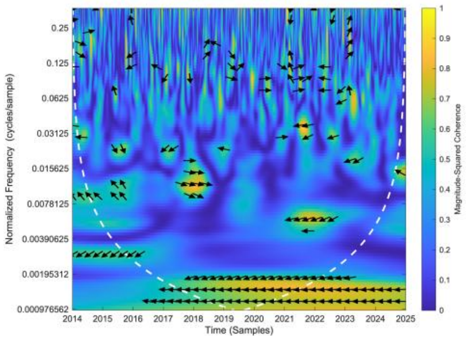
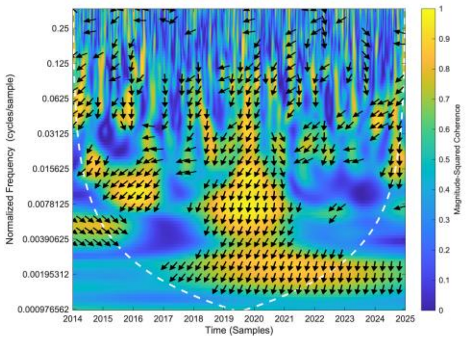
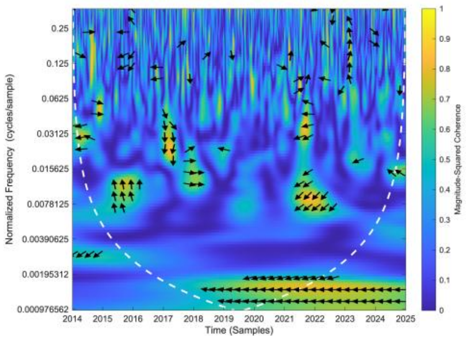
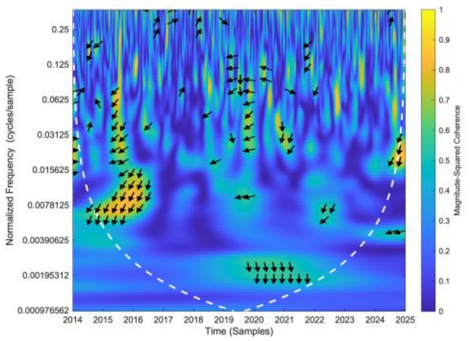
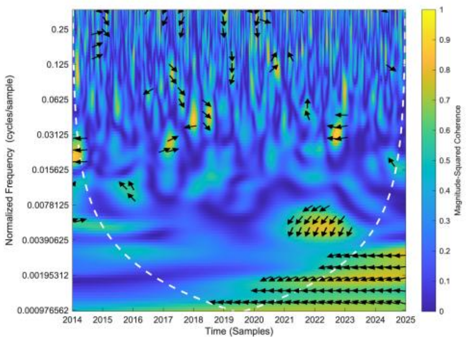
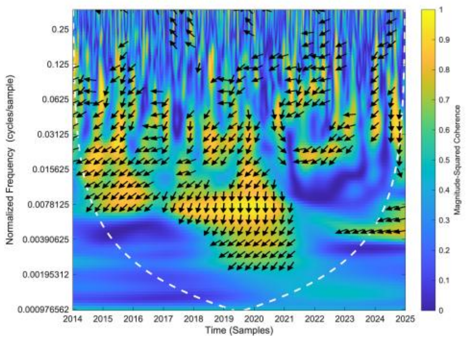
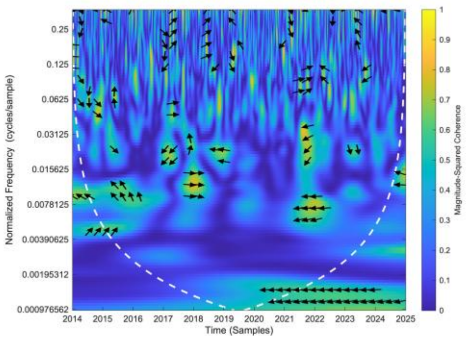
| Index | VIX | GPRD |
|---|---|---|
| **DJTATO** |  |  |
| **SXAR** |  |  |
| **FTXIN4401010** |  |  |
| **NAUT** |  |  |

*Fig. 3. Wavelet coherence analysis between automobile indices, VIX and GPR*

*IV.II Robustness test - wavelet coherence (WTC)*

To validate the empirical consistency of the findings, the analysis was extended using WTC between regional automotive indices and the global risk indicators, VIX and GPR. The results indicate that periods of financial crises and major geopolitical tensions are associated with elevated coherence, particularly at short time horizons, reflecting the rapid transmission of international shocks to the automotive sector.

In the United States, the coherence between DJTATO and VIX is both persistent and intense. It strengthens around the 2016 presidential election, when markets were unsettled by uncertainties regarding the new administration and Federal Reserve policy, in 2020, when the pandemic triggered a sharp contraction in demand and widespread production disruptions, and in 2022, with the Russia–Ukraine conflict and the ensuing global energy crisis. The association with GPR is more fragmented but becomes visible after 2018, corresponding to the escalation of the U.S.–China trade conflict, and intensifies during the geopolitical turmoil of 2022–2023.

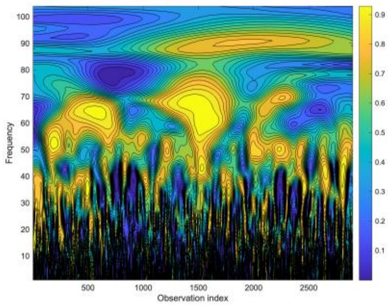
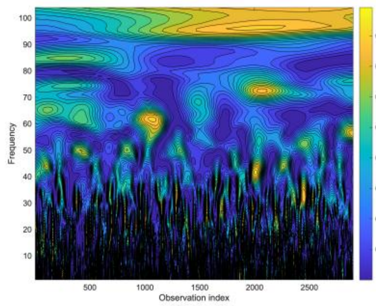
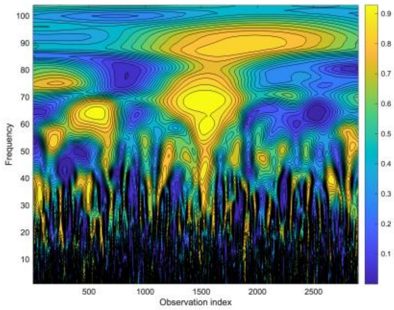
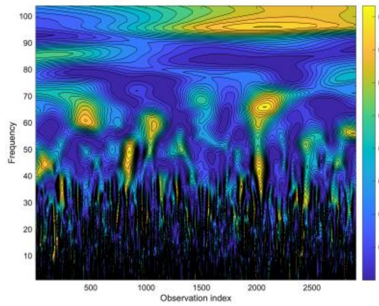
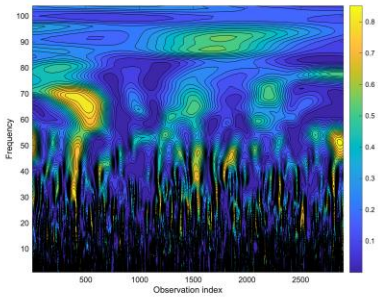
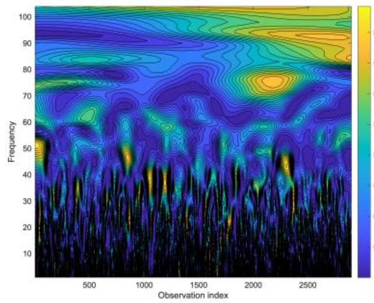
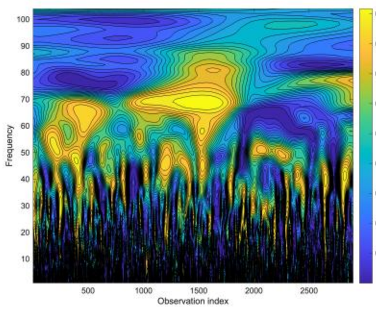
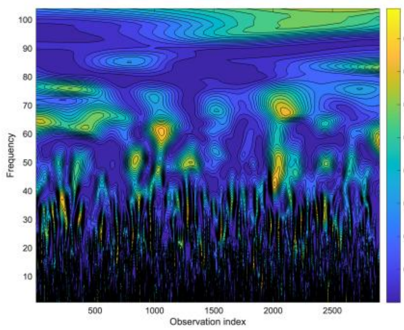
| **Index** | **VIX** | **GPRD** |
|---|---|---|
| **DJTATO** |  |  |
| **SXAR** |  |  |
| **FTXIN4401010** |  |  |
| **NAUT** |  |  |

*Fig. 4 Wavelet Transform Coherence (WTC) between automotive indices, VIX, and GPRD*

Europe, represented by the SXAR index, displays robust yet more intermittent coherence with VIX. Strong co-movements are evident in 2019–2020, when the COVID-19 pandemic severely disrupted supply chains and German exports, and again in 2022, when the Ukraine war drove an energy price shock. Coherence with GPR is weaker but emerges during 2017–2019, amid Brexit negotiations and the migration crisis, and strengthens after 2022 as geopolitical tensions in Eastern Europe intensified.

For China, the FTXIN4401010 index exhibits weaker and more episodic coherence with VIX. Significant linkages appear in 2015–2016, during the stock market crash and yuan devaluation, and again in 2018–2019, amid escalating trade frictions with the United States. By contrast, coherence with GPR increases markedly after 2020, reflecting the impact of technological sanctions, restrictions on critical raw materials, and the restructuring of global supply chains, which heightened the vulnerability of the Chinese automotive sector to geopolitical shocks.

In Japan, the NAUT index shows strong and persistent coherence with VIX, particularly between 2015 and 2018, and again in 2020–2022, when the pandemic and global logistical bottlenecks severely disrupted the automotive sector. This link underscores the high dependence of Japan's economy on global financial volatility and external demand. Coherence with GPR is weaker but becomes evident between 2018 and 2022, a period marked by Asia-Pacific tensions, the energy crisis, and disruptions in the semiconductor supply chain.

Taken together, the results reinforce the role of the United States and Japan as automotive markets closely tied to global financial volatility, while China emerges as more vulnerable to geopolitical and trade-related risks. Europe occupies an intermediate position, reacting strongly to both financial and geopolitical shocks but in a more intermittent manner, often conditioned by major crises such as the pandemic and the 2022 energy shock. These findings are consistent with prior evidence indicating that the U.S. functions as a primary transmitter of shocks to global markets, while China and Japan tend to act predominantly as receivers under regimes of extreme volatility, and Europe reflects selective exposure dependent on geopolitical and energy contexts (Mensi et al., 2023).

## V. DISCUSSIONS AND IMPLICATIONS

The combination of CWT and WTC provides a robust framework for assessing the role of regional automotive markets in the transmission and reception of financial and geopolitical shocks. The results consistently indicate that the United States and China function as epicenters of global volatility, exerting direct influence on financial dynamics and geopolitical risk perceptions. By contrast, Europe and Japan emerge primarily as recipients of shocks, reacting to external disturbances but rarely generating systemic instability themselves. This conclusion is in line with the literature on dynamic spillovers and asymmetric shock transmission across markets (Naeem et al., 2020), while adding a sectoral dimension specific to the automotive industry.

For the United States, our findings reveal strong and persistent coherence between the automotive index (DJTATO) and VIX, particularly during periods of political and economic stress. The political transition following the 2016 election, the COVID-19 outbreak in 2020, and the Ukraine conflict in 2022 all coincide with heightened volatility spillovers into the U.S. auto sector. This pattern underscores Bloom's (2009) argument that cyclical industries are highly responsive to uncertainty shocks and corroborates recent findings on extreme volatility in the U.S. automotive industry during the pandemic (Caiado & Lúcio, 2023). On the geopolitical side, the link with GPR becomes more evident after 2018, reflecting the increase of U.S.–China trade tensions and technology sanctions. This supports the validity of GPR as a proxy for political risk (Caldara & Iacoviello, 2022) and highlights the dual channels, financial and geopolitical, through which the U.S. automotive sector internalizes global shocks.

In Europe, the relationship with VIX is less persistent but intensifies during global crises. The COVID-19 shock (2019–2020) and the 2022 energy crisis, triggered by the war in Ukraine, both amplified volatility spillovers to the SXAR index. This evidence aligns with Rusnák et al. (2024), who emphasize the dependence of the European auto industry on exports and economic complexity, making it structurally vulnerable to external disruptions. Coherence with GPR is weaker overall but appears in region-specific episodes, such as Brexit negotiations and the migration crisis (2017–2019), and resurges in 2022 amid Eastern European geopolitical tensions. These findings confirm Bossman et al. (2023) observation that policy uncertainty and geopolitical risk asymmetrically affect EU equity sectors, amplifying volatility during crises. Furthermore, Szczygielski et al. (2025) demonstrate that the global energy crisis reinforced such vulnerabilities, with industry resilience to uncertainty varying widely across European economies and firms.

China presents a distinct trajectory. Coherence with VIX is episodic, evident during the 2015–2016 stock market crash and yuan devaluation and again during the 2018–2019 escalation of the U.S.–China trade war. However, coherence with GPR rises sharply after 2020, reflecting the increasing role of geopolitical and trade-related risks, technology sanctions, restrictions on critical raw materials, and supply chain reorganization. The Shanghai lockdown of 2022 further highlighted the asymmetric impact of shocks, with limited effects on global automotive giants but significant losses for Tier-1 suppliers (Song et al., 2025). This confirms Tang & Wu's (2024) assessment of the structural instability of the Chinese auto industry in its energy transition and echoes Ouyang et al. (2024), who find heightened sensitivity of sectoral responses at high frequencies. The divergence from Chen & Sun

(2022), who report strong VIX spillovers into Chinese financial markets, suggests that, in the automotive sector, geopolitical and trade risks overshadow purely financial channels of volatility. While aggregate volatility in China is indeed shaped by rare U.S.-origin shocks, as shown by Wu & Li (2025), these effects are less persistent in the automotive sector, where they are effectively overshadowed by geopolitical uncertainty and trade disruptions.

Japan, in contrast, exhibits strong and long-lasting coherence with VIX, confirming its high exposure to global financial volatility and external demand. The pandemic, logistics bottlenecks, and the semiconductor shortage amplified these spillovers, corroborating the evidence of Marobhe & Dickson (2023) on the propagation of shocks from the microchip sector to automotive production. The link with GPR becomes visible between 2018 and 2022, driven by regional tensions in the Asia–Pacific and global energy and semiconductor crises. These findings are consistent with Nishikawa & Sato (2025), who emphasize the sensitivity of Japanese automakers to external uncertainty and exchange rate risk.

From a theoretical perspective, the results substantiate the hypothesis that regional interdependencies are heterogeneous and shaped by domestic structural factors such as industrial policies, regulatory frameworks, and degrees of global integration. This resonates with recent studies by Shahbaz et al. (2024) and Marfatia (2023), which document the transmission of uncertainty shocks across policy, sectoral, and macroeconomic domains, and with evidence on the suitability of wavelet-based methods for capturing dynamic dependencies in cyclical sectors (Patel et al., 2025). By incorporating a time–frequency dimension, this study extends prior literature, offering a more granular understanding of the dynamics of uncertainty transmission in the automotive industry.

Beyond the theoretical contribution, the findings carry important practical implications. First, they suggest that investors and policymakers should adopt a differentiated monitoring strategy: developments in the United States and China warrant particular scrutiny, as these markets act as major sources of global instability. Europe and Japan, while less likely to generate systemic shocks, can still amplify volatility through trade dependencies, energy vulnerabilities, and supply chain fragility. Second, the evidence highlights that sectoral resilience cannot be decoupled from sustainability and governance issues. As Lin et al. (2025) note, ESG-related supply chain incidents can significantly reduce shareholder value, reinforcing the importance of integrating risk management with sustainability practices across the automotive value chain.

## VI. CONCLUSIONS

This study investigated the connection between regional automotive markets in the United States, Europe, China, and Japan and two global risk indicators: financial volatility, captured by the VIX index, and geopolitical risk, measured by the GPR index. By applying the CWT and complementing it with WTC as a robustness test, the analysis uncovered complex, time–frequency patterns of interdependence, highlighting the heterogeneous sensitivity of regional markets to international shocks.

The empirical evidence indicates that the United States and China act as key transmitters of shocks within the global automotive industry. In the U.S., the connection with financial volatility is strong and persistent, intensifying during episodes such as the 2016 political transition, the COVID-19 epidemic in 2020, and the outbreak of the Russia–Ukraine conflict in 2022. In China, coherence with VIX is more episodic, while the influence of geopolitical risk has grown substantially since 2020, reflecting escalating trade frictions with the U.S., technology sanctions, and pressures surrounding critical raw materials. By contrast, Europe and Japan emerge primarily as receivers of shocks: Europe is especially vulnerable to energy and supply chain disruptions, while Japan’s automotive sector reflects global financial volatility and semiconductor-related bottlenecks.

These results corroborate the hypothesis that regional interdependencies are asymmetric and shaped by structural factors such as industrial policies, market openness, and the degree of global integration. While the U.S. and China serve as emitters of volatility, Europe and Japan, despite being deeply embedded in global value chains, play a more reactive role, absorbing shocks generated elsewhere.

The key contribution of this research lies in offering a comparative and sector-specific perspective on how regional automotive markets connect to the dynamics of global uncertainty. Theoretically, the findings enrich the literature on volatility transmission and geopolitical risk by introducing evidence from one of the world’s most cyclical and strategically important industries. Practically, the study underscores the need for risk management and investment strategies that take into for regional asymmetries, placing particular emphasis on the monitoring of U.S. and Chinese markets as primary sources of global instability.

At the same time, the analysis has certain limitations. It focuses on a restricted set of automotive indices and only two global uncertainty measures, which narrows the range of explanatory factors. Furthermore, the relationships identified are primarily statistical and do not fully capture the institutional or political mechanisms through which shocks are transmitted. Future research should broaden the scope by integrating additional sectors that are heavily dependent on global supply chains, such as electronics or energy, and by applying complementary approaches, including time-varying parameter VAR models, regime-switching techniques, or complex network analyses. Such extensions would allow for a deeper understanding of how systemic risk propagates across industries and regions.

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# State of the Art: Social Implications of AI Systems Integration in Civil Aviation

Serban MERTOL[1] and Cella BUCIUMAN[2]

**Abstract -** The integration of Artificial Intelligence (AI) systems in civil aviation is transforming operational processes, safety management, and human-machine interactions. This paper reviews the state of the art in AI deployment in aviation, emphasizing social implications, ethical considerations, and work- force adaptation. Key challenges include accountability, safety assurance, cultural perception, and regulatory alignment. Specific attention is given to human factors, ethics, and the evolving professional roles required to manage AI-enabled systems.

**Keywords:** Artificial Intelligence, Civil Aviation, Human- Machine Interaction, Ethics, Safety Culture

## I. INTRODUCTION

Artificial Intelligence (AI) is increasingly embedded in civil aviation, influencing air traffic management, aircraft operations, predictive maintenance, and safety management systems (ICAO, 2025; FAA, 2024). The rapid adoption of AI is not only transforming technical processes but also reshaping social and organizational dynamics within aviation (EASA, 2025). While technological advancements promise efficiency gains and enhanced safety, they also introduce challenges in workforce adaptation, ethical oversight, and accountability. For instance, pilots and air traffic controllers are required to work with complex AI systems that may change their decision-making processes and operational responsibilities (Kabashkin et al., 2023).

The integration of AI systems raises questions about trust, transparency, and social acceptance. Social perception of AI varies across regions, affecting adoption rates and regulatory policies (Zhang and Zhu, 2025). Furthermore, aviation is a safety-critical domain, where errors can have catastrophic consequences. This amplifies the social stakes of AI deployment. As AI tools take on more decision-making functions, understanding the interaction between humans and machines becomes essential (Cummings, 2014). This paper systematically reviews the current state of AI in aviation, focusing on social implications, ethical frameworks, human- machine collaboration, and workforce transformation.

## II. AI INTEGRATION IN AVIATION SYSTEMS

### *2.1 Applications and Benefits*

AI applications in civil aviation are increasingly diverse, covering multiple operational domains. Predictive maintenance algorithms analyze large volumes of sensor data from aircraft systems to identify potential component failures before they occur, reducing unplanned downtime and optimizing maintenance schedules (FAA,2024). Autonomous flight management systems assist pilots in monitoring complex flight dynamics, automating routine tasks such as autopilot adjustments, altitude management, and fuel efficiency optimization (Lopes et al., 2025). AI-assisted air traffic management enhances routing, congestion prediction, and emergency response, improving overall airspace efficiency and reducing delays.

AI is transforming passenger services through chatbots, automated scheduling, and baggage handling optimization. These applications improve operational efficiency and enhance the overall passenger experience by minimizing delays and service disruptions. Table 1 summarizes common AI applications and their operational benefits.

### *2.2 Human-Machine Collaboration*

Despite the technical advantages of AI, human oversight remains essential for operational safety. Over-reliance on AI can lead to the" automation paradox", where humans become less skilled in critical decision-making during unexpected situations. Conversely, under-utilization of AI can prevent organizations from realizing potential efficiency gains. The most effective deployment of AI in aviation is therefore within a hybrid human-machine framework, where responsibilities are clearly defined and decision-making is shared between AI systems and human operators (Cummings, 2014; Dekker, 2017).

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*Table 1: AI applications in civil aviation and operational benefits*

| AI Application | Function | Benefit |
|---|---|---|
| Predictive Maintenance | Monitors aircraft systems and predicts component failures | Reduces unplanned downtime, lowers maintenance costs |
| Autonomous Flight Management | Assists pilots in navigation and monitoring | Enhances safety and situational awareness |
| Air Traffic Management Optimization | AI-assisted routing and traffic prediction | Increases airspace capacity and reduces delays |
| Safety Monitoring | Detects anomalies in operational procedures | Improves incident prevention and early warning |
| Passenger Experience | AI chatbots and assistance systems | Enhances customer satisfaction and operational efficiency |

*Table 2: Examples of Human-Machine Collaboration in Aviation*

| Task | Human Role | AI Role |
|---|---|---|
| Flight Navigation | Decision-making and contingency management | Monitoring systems, suggesting optimal routes |
| Aircraft Maintenance | Performing repairs | Predicting failures and recommending interventions |
| Air Traffic Control | Approving flight paths, ensuring safety | Analyzing traffic patterns, forecasting con- gestion |
| Incident Investigation | Root cause analysis | Data aggregation and anomaly detection |

Table 2 illustrates examples of collaborative tasks between human operators and AI systems. These collaborations ensure that AI supports operational decisions without replacing human expertise, maintaining high levels of safety and accountability.

*2.3 Operational Challenges and Considerations*

While AI provides significant operational advantages, its integration is not without challenges. Reliability and robustness of AI systems must be continuously monitored to prevent unexpected failures. AI models require high-quality, representative datasets; biased or incomplete data can lead to erroneous predictions that may compromise safety (Hagerty and Rubinov, 2019). AI decision-making processes must be transparent and explainable to ensure trust among human operators and regulatory compliance (EASA, 2025).

The adoption of AI also impacts workflow and professional roles. Pilots, air traffic controllers and maintenance personnel are required to acquire new skills, including AI system interpretation, oversight, and ethical decision-making. Organizations must develop training programs to bridge knowledge gaps and facilitate smooth human-machine collaboration (Kabashkin et al., 2023).

*2.4 Emerging Trends in Aviation AI*

Recent research indicates a shift towards adaptive AI systems, which are continuously learning from operational data and improve performance over time. These systems can anticipate operational disruptions, optimize fuel consumption, and improve safety outcomes. Other trends include multi-agents. AI frameworks for collaborative decision-making in complex airspace environments and digital twins for predictive simulation of aircraft and air traffic scenarios (Lopes et al., 2025; FACSNET, 2023).

Integrating AI with cybersecurity frameworks is another critical trend, as AI systems are vulnerable to adversarial attacks that could compromise aviation safety. Organizations are investing in AI monitoring, anomaly detection, and secure design protocols to mitigate these risks.

Overall, the integration of AI in aviation systems represents a transformational shift, enhancing efficiency, safety, and passenger experience, while requiring careful management of human, ethical, and operational factors.

## III. CASE STUDIES AND BEST PRACTICES

*3.1 Case Study 1: AI in Predictive Maintenance*

Predictive maintenance using AI has been widely adopted by commercial airlines to enhance reliability and reduce downtime. Airlines such as Lufthansa and Delta have implemented AI algorithms to analyze sensor data from aircraft engines and key systems. These systems detect anomalies and predict component failures before they occur (FAA,2024; Lopes et al., 2025).

Key outcomes from these implementations include:

- Reduced unscheduled maintenance events by up to 20– 30%.
- Lowered operational costs through optimized spare parts inventory.
- Improved safety through early detection of potential failures.

*3.2 Case Study 2: AI-Assisted Air Traffic Management*

Air Traffic Management (ATM) is another area where AI has demonstrated significant operational benefits. For example, EUROCONTROL and NASA have trialed AI-based routing systems to optimize airspace utilization and minimize delays (Lopes et al., 2025). The AI systems analyze traffic patterns, weather, and congestion in real time to suggest optimal flight paths to controllers.

Lessons learned from these deployments include:

- Human oversight remains critical for handling unexpected or extreme situations.
- Transparent AI recommendations improve controller trust and adoption.
- Continuous data validation is essential to prevent erroneous predictions.

### 3.3 *Case Study 3: AI in Passenger Experience and Operations*

Airlines are also leveraging AI to enhance passenger ser- vices, including automated check-in, personalized travel recommendations, and baggage handling optimization. For in- stance, Singapore Airlines and KLM have integrated AI chat- bots and operational prediction systems to improve passenger satisfaction and reduce delays. Key takeaways:

- AI can improve customer satisfaction while reducing operational workload.
- Ethical considerations must guide AI personalization to protect passenger privacy.
- Integration with legacy IT systems can be challenging but necessary for full benefits.

### *3.4 Best Practices for AI Integration in Aviation*

Based on these case studies, several best practices emerge for organizations integrating AI in aviation, as presented in Table 3. By following these best practices, aviation organizations can maximize the benefits of AI while mitigating risks, maintaining safety, and ensuring regulatory and ethical compliance

*Table 3: Best Practices for Ai Integration in Aviation*

| Practice | Description | Benefit |
|---|---|---|
| Human-in-the-Loop Design | Ensure humans can override AI decisions when necessary | Maintains safety and operator trust |
| Continuous Data Validation | Regularly check data quality and model predictions | Reduces errors and improves AI reliability |
| Transparency and Explainability | Make AI reasoning understandable to operators | Enhances trust and accountability |
| Ethical Guidelines | Incorporate privacy, fairness, and bias mitigation measures | Supports regulatory compliance and social acceptance |
| Phased Implementation | Gradually deploy AI with monitoring and feedback loops | Allows adjustment and reduces operational risk |

*Table 4: AI-Influenced Accountability Considerations*

| Domain | Consideration | Impact |
|---|---|---|
| Human Operators | Training, situational awareness and decision-making authority | Ensures effective oversight and reduces human error |
| AI Systems | Transparency, explainability and reliability | Enables traceable decision-making and operational trust |
| Regulatory Bodies | Standards, certification and compliance monitoring | Aligns AI deployment with international safety policies |
| Organizations | Safety culture adaptation, reporting, and accountability structures | Promotes proactive risk management and ethical operations |

## IV. SOCIAL AND ETHICAL IMPLICATIONS

### *4.1 Safety Culture and Accountability*

The integration of AI in aviation fundamentally transforms safety culture and accountability structures. Traditional safety management relies on clear hierarchical responsibility, but AI systems introduce a shared responsibility model where both human operators and AI algorithms influence operational outcomes (Silva and Martens, 2023).

Understanding and managing accountability in this context is crucial to prevent ambiguity in case of incidents. AI systems may autonomously flag anomalies, suggest corrective actions, or even override human decisions in critical scenarios. This necessitates a transparent chain of decision- making, where operators can trace the rationale behind AI recommendations. Organizations must implement protocols that define the boundaries of AI authority and human intervention. Regulatory agencies like ICAO and EASA emphasize the importance of safety assurance frameworks that encompass both technological reliability and human oversight (ICAO, 2025; EASA, 2025; FAA,2024). Table 4 illustrates the key domains of accountability affected by AI integration.

### *4.2 Ethical Considerations*

Ethical challenges arise from AI's capacity to make or influence critical operational decisions. Bias in AI algorithms, stemming from unrepresentative training data, can lead to unequal outcomes or unintended risks (Hagerty and Rubinov, 2019). Transparency is another core concern: operators and regulators must understand why an AI system makes specific recommendations or actions. Lack of explainability can undermine trust and impede accountability.

Operational ethics also involve ensuring AI does not com- promise passenger safety or crew welfare. For example, AI algorithms used in scheduling or predictive maintenance must balance efficiency gains with human-centered safety priorities. Organizations are increasingly implementing ethics boards and algorithmic audits to monitor AI behavior and mitigate potential harm (EASA, 2025).

### *4.3 Cultural and Social Considerations*

Perceptions of AI vary across cultures, affecting both acceptance and adoption in aviation operations (Zhang and Zhu, 2025). Operators in regions with high trust in automation may rely heavily on AI, while others may prefer manual oversight. These cultural differences must be considered in global aviation operations, training programs, and policy development.

AI systems also interact with social factors such as environmental sustainability and public safety perception. For instance, AI-enabled flight routing optimizations can reduce fuel consumption and emissions but may alter flight paths over populated areas, potentially raising public concerns (WSJ, 2023). Engaging stakeholders, including pilots, air traffic controllers, passengers, and regulators, is critical to ensure ethical and socially responsible AI integration.

Table 5 summarizes the key ethical and cultural considerations for aviation AI.

*4.4 Human Factors and Workforce Implications*

AI deployment reshapes the skills and responsibilities required of aviation professionals. Pilots, air traffic controllers, and maintenance personnel must learn to interpret AI outputs, manage exceptions, and maintain situational awareness in increasingly automated environments (Kabashkin et al., 2023). Overreliance on AI may lead to skill degradation, while underutilization may reduce operational efficiency. Effective training programs are critical to ensure that personnel remain proficient and can interact safely with AI systems.

Additionally, AI can improve workforce safety by predicting potential hazards, scheduling rest periods, and monitoring human performance. However, careful design is required to prevent AI from introducing stress or cognitive overload. A balanced approach emphasizes AI as a support tool rather than a replacement, enhancing human capability while preserving accountability and safety culture.

The social and ethical implications of AI in aviation are multifaceted, involving accountability, ethics, human factors, cultural perceptions, and social impact. Organizations, regulators, and operators must collaborate to implement transparent, ethical, and culturally sensitive AI practices. By combining robust technical design with human-centered operational policies, aviation can harness AI's benefits while maintaining trust, safety, and social acceptance.

*Table 5: Ethical And Cultural Considerations in AI Aviation Deployment*

| Ethical/Cultural Issue | Description | Mitigation |
|---|---|---|
| Bias in AI Decisions | Risk of inequitable outcomes due to in- complete or biased training data | Use diverse datasets, regular audits, and bias detection protocols |
| Transparency | Difficulty in explaining AI reasoning and recommendations | Implement explainable AI techniques and operator training |
| Accountability | Determining responsibility for AI- influenced decisions or errors | Develop clear operational protocols, shared responsibility frameworks |
| Environmental Impact | AI route optimization may affect emissions and communities | Conduct sustainability assessments and public engagement |
| Social Acceptance | Public trust in AI systems affects adoption and safety perception | Communication campaigns, stakeholder consultations, and participatory design |

## V. CHALLENGES AND PROSPECTS

*5.1 Regulatory and Certification Challenges*

One of the primary challenges in integrating AI into civil aviation is ensuring regulatory compliance and certification of AI systems. Traditional aviation regulations were designed for human-operated systems and conventional automation, not adaptive, data-driven AI. Regulatory bodies such as the FAA, EASA, and ICAO are developing frameworks for AI safety assurance, but gaps remain in standardization, harmonization, and verification of AI performance across different operational contexts (ICAO, 2025) (EASA, 2025; FAA, 2024).

Certification processes must address the dynamic nature of AI systems, which continuously learn and evolve. Unlike conventional software, AI can change behavior based on new operational data, posing challenges for static certification methods. Organizations are exploring" continuous certification frameworks", real-time monitoring, and AI auditing to ensure that AI operations remain within safe boundaries.

*5.2 Technical Challenges*

AI systems in aviation face technical limitations, including robustness, reliability, and vulnerability to adversarial conditions. Data quality is critical: biased, incomplete, or unrepresentative datasets can lead to erroneous predictions and unsafe operational decisions (Hagerty and Rubinov, 2019). Additionally, AI models must operate reliably under rare or extreme scenarios, which are difficult to simulate or anticipate in training datasets.

Integration of multiple AI modules, such as predictive maintenance, flight management, and air traffic optimization, raises interoperability and system compatibility issues. Ensuring seamless coordination between AI components and human operators is crucial to avoid conflicting recommendations or unanticipated system behaviors (Lopes et al., 2025).

*5.3 Workforce and Human Factors Challenges*

The rapid adoption of AI is transforming professional roles in aviation. Pilots, air traffic controllers, and maintenance personnel must acquire new competencies, including interpreting AI outputs, managing exceptions, and understanding ethical considerations (Kabashkin et al., 2023). Organizations must develop training programs that balance automation benefits with skill retention to prevent the automation paradox, where operators become over-reliant on AI and lose critical manual decision-making skills.

Moreover, human factors such as cognitive workload, situational awareness, and trust in AI significantly impact safety and performance. Designing human-machine interfaces that support clear communication, transparency, and intuitive control is essential to reduce error and maintain operational reliability (Cummings, 2014; Dekker, 2017).

*5.4 Ethical and Social Governance Challenges*

Ethical governance of AI systems is a persistent challenge. Ensuring fairness, transparency, accountability, and social acceptance require proactive policies and monitoring. AI decisions may inadvertently introduce bias or unequal treatment, especially if training data does not represent diverse populations (Hagerty and Rubinov, 2019). Cultural differences in trust and AI acceptance further complicate implementation in global aviation operations (Zhang and Zhu, 2025).

Organizations are beginning to implement ethics committees, audits, and monitoring mechanisms to evaluate AI decisions and align them with social norms. Effective governance requires collaboration between regulators, operators, AI developers, and human factors experts.

*5.5 Operational and Environmental Challenges*

Operationally, AI must remain robust in dynamic, unpredictable environments. Weather variability, traffic congestion, and emergency situations can challenge AI decision-making and coordination with human operators. Environmental considerations, such as emissions and contrail effects, must be incorporated into AI flight optimization algorithms to balance efficiency with sustainability (WSJ, 2023).

*5.6 Future Research Directions and Prospects*

Future research in aviation AI focuses on hybrid human- AI decision-making, resilient socio-technical systems, and explainable AI. Hybrid decision-making approaches aim to optimize the strengths of human judgment and AI computational capabilities while mitigating the weaknesses of each. Resilient socio-technical systems account for both technological and human factors, ensuring safe operation even under unexpected disruptions.

Emerging technologies such as digital twins allow operators to simulate real-time flight scenarios and test AI interventions safely. Multi-agent AI frameworks enable collaborative decision-making in complex airspace environments, enhancing efficiency and reducing risk (Lopes et al., 2025; FACSNET, 2023). Research on AI monitoring, cybersecurity, and continuous learning certification is critical to maintaining safety and trust in adaptive AI systems.

Table 6 summarizes the main challenges in aviation AI and potential strategies to address them.

While AI integration offers transformative benefits in civil aviation, it also presents multifaceted challenges. Addressing regulatory, technical, human, ethical, operational, environmental, and cybersecurity considerations is essential to ensure safe and socially responsible adoption. Future research and development must focus on hybrid decision-making, resilient socio-technical systems, explainable AI, and continuous monitoring to maximize AI's potential while maintaining trust, safety, and operational excellence.

*Table 6: Key Challenges and Prospects in Aviation AI*

| **Challenge** | **Description** | **Potential Solution** |
|---|---|---|
| Regulatory Compliance | Aligning AI deployment with safety standards and certification frameworks | Develop continuous certification, monitoring, and harmonized regulations |
| Workforce Skills | Adapting human operators to AI-assisted roles while maintaining critical manual skills | Implement specialized training, simulation programs, and cognitive workload management |
| Ethical Oversight | Ensuring fairness, transparency, accountability, and social acceptance | Establish ethics committees, audits, explainable AI methods, and stakeholder engagement |
| Operational Reliability | AI robustness in dynamic, unpredictable environments | Multi-agent coordination, real-time monitoring, and scenario testing |
| Data Quality | Incomplete or biased datasets can compromise AI predictions | Use diverse, high-quality datasets, regular validation, and bias detection mechanisms |
| Environmental Impact | AI-enabled optimization may affect emissions and public perception | Integrate sustainability assessment and environmental considerations into AI algorithms |
| Cybersecurity | AI systems may be vulnerable to adversarial attacks or malicious manipulation | Develop secure design protocols, anomaly detection, and continuous monitoring |

## VI. CONCLUSION

AI integration in civil aviation offers substantial benefits in efficiency, safety, and operational flexibility. However, it introduces significant social and ethical implications that must be proactively managed. Multidisciplinary approaches, encompassing technical, regulatory, and human factors perspectives, are essential for sustainable adoption. Clear accountability, workforce adaptation, and transparent governance frameworks are critical to ensuring that AI support rather than undermines aviation safety. Future work should emphasize hybrid human- AI collaboration, ethical design, and resilient socio-technical systems capable of adapting to emerging challenges.

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# Human-Centered AI Integration in Air Traffic Control: Operational, Ethical and Social Implications

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**Abstract -** The integration of Artificial Intelligence (AI) in Air Traffic Control (ATC) and Air Traffic Management (ATM) is reshaping aviation operations worldwide. Beyond efficiency gains, AI introduces profound implications for safety, accountability, ethics, and human factors. This paper reviews the state of the art by analyzing five representative case studies: predictive traffic flow management in EUROCONTROL's Network Manager, AI-enabled remote tower operations, speech recognition for controller–pilot communications, AI-assisted flight plan processing, and unmanned aircraft systems (UAS) integration. These cases illustrate both the opportunities of AI (such as enhanced situational awareness, workload reduction, and environmental benefits) and the challenges, including automation bias, data privacy, fairness, and cultural acceptance. Building on regulatory perspectives from ICAO, EASA, FAA, NATS, and leading technology providers, the paper identifies best practices and base principles for responsible AI deployment in ATC. Findings highlight that AI must remain human-centered, with transparency, explainability, and accountability embedded into system design and training. The conclusion emphasizes that while AI offers transformative potential, its success depends on balancing innovation with ethical responsibility and social trust.

**Keywords:** Artificial Intelligence, Air Traffic Control, Remote Towers, Voice Recognition, Flight Planning, Unmanned Aircraft Systems, Safety, Human Factors, Ethics, Social Implications

## I. INTRODUCTION

Artificial Intelligence (AI) is rapidly emerging as a trans- formative force in Air Traffic Control (ATC) and Air Traffic Management (ATM). Driven by increasing traffic demand, environmental pressures, and the need for resilient operations, AI is being explored to enhance efficiency, safety, and decision-making across the aviation ecosystem. International and national organizations—including ICAO, EASA, FAA, NATS, EUROCONTROL—and technology providers such as Saab and Indra have initiated strategies and pilot projects to integrate AI into core ATM functions (ICAO, 2025; Indra, 2022).

The potential benefits of AI include predictive traffic flow management, automation of routine tasks, improved situational awareness, and enhanced support for human decision-making. At the same time, challenges such as automation bias, ac- countability, transparency, and cultural acceptance must be addressed to ensure responsible adoption. AI directly reshapes the roles, skills, and trust relationships of controllers, pilots, and other aviation professionals, raising important human and social implications (Zhang et al., 2020).

This paper examines five representative case studies to illustrate AI's operational and social impacts. The analysis builds on guidance from these organizations and emphasizes best practices for human-centered AI integration, explainability, and accountability.

## II. LITERATURE REVIEW

The integration of AI in ATC and ATM has been increasingly explored by both academic research and operational organizations. This review synthesizes key findings from recent literature, regulatory guidance, and industry initiatives, highlighting technological, human, ethical, and operational dimensions.

### *2.1 AI Integration in ATC and ATM*

AI applications in ATC range from predictive traffic flow management to automation in remote towers, voice recognition, flight plan processing, and UAS integration. ICAO and EASA emphasize AI's potential to enhance operational safety, efficiency, and environmental sustainability while maintaining human oversight and ethical considerations (ICAO, 2025; EASA, 2025). FAA initiatives, particularly the UAS Traffic Management (UTM) program, illustrate AI's role in safe drone integration (FAA, 2024).

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Operational organizations such as EUROCONTROL and NATS have conducted pilots using AI for congestion prediction, slot optimization, and controller support, demonstrating tangible benefits (NATS, 2023; EUROCONTROL, 2023). Technology providers like Saab and Indra have contributed AI solutions for remote tower operations, voice recognition, and flight plan validation, high- lighting practical implementation challenges and human–AI collaboration requirements (Saab, 2022; Indra, 2022).

### *2.2 Technological Considerations*

AI in ATC relies on high-quality, domain-specific datasets from radar, ADS-B, weather systems, flight plans, and communications. Predictive analytics, voice recognition, and UAS detect-and-avoid systems all require diverse and representative training data for reliability (FAA, 2024; EUROCONTROL, 2023; Indra, 2022).

Key technological factors include system reliability, redundancy, real-time integration with legacy ATM systems, explainability of AI outputs, and scalability to handle high traffic volumes. Remote tower operations highlight the importance of robust sensor infrastructure, flight plan processing emphasizes seamless integration with operational databases, and UAS integration requires real-time monitoring and autonomous conflict resolution (ICAO, 2025; Saab, 2022).

### *2.3 Human Factors and Social Implications*

AI reshapes controller workflows, workload distribution, and decision-making. Trust in AI outputs is crucial: over- reliance can cause automation bias, while under-reliance may underutilize system capabilities. Voice recognition and flight plan validation can reduce repetitive tasks but require careful human oversight (Kabashkin, et al., 2023; Dekker, 2017).

Skill transformation is essential; controllers must supervise AI, interpret alerts, and manage mixed manned–unmanned environments. Cultural and social acceptance, particularly for remote towers and UAS, ensures operational changes are embraced (Silva and Martens, 2023).

### *2.4 Ethical, Safety, and Accountability Dimensions*

Ethical considerations include fairness, transparency, privacy, and equitable treatment. AI systems must account for accents, language diversity, and avoid biased prioritization, while maintaining human oversight (EASA, 2025; Crawford and Paglen, 2019). Safety relies on redundancy, error detection, and continuous validation. Clear accountability frameworks are necessary for trust and regulatory compliance (ICAO, 2025; FAA, 2024; Indra, 2022).

### *2.5 Environmental and Operational Impacts*

AI in traffic flow management, flight plan optimization, and UAS operations can reduce fuel consumption and emissions (EUROCONTROL, 2023; Kabashkin, et al., 2023). Efficiency gains also emerge from workload reduction and improved predictive capabilities.

## III. CASE STUDIES AND BEST PRACTICES

### *3.1 Use Case: EUROCONTROL Network Manager*

EUROCONTROL's Network Manager (NM) coordinates European airspace, optimizing traffic flow, minimizing delays, and balancing sector capacity. AI models analyze historical flight data, live radar feeds, and weather forecasts to predict congestion points and recommend proactive re-routing (EUROCONTROL, 2023).

AI enhances situational awareness, reduces controller work- load during peak traffic periods, and supports collaborative planning among multiple ANSPs. Operational metrics indicate reductions in average delay minutes per flight and improvements in on-time performance when AI-assisted planning is applied.

Best Practices for AI Integration in EUROCONTROL NM

- Human-in-the-Loop: Controllers maintain oversight for all AI suggestions.
- Transparent Outputs: AI predictions should include confidence levels and rationale.
- Continuous Validation: Regular testing against historical and live scenarios.
- Collaborative Training: Staff trained to interpret AI outputs and collaborate effectively.
- Data Governance: High-quality, bias-free datasets; GDPR compliance.
- Feedback Loops: Controllers provide feedback to improve AI performance.
- Safety Culture Integration: Embed AI into existing safety management systems.

### *3.2 Case Study: AI in Flight Plan Receiving and Processing*

Flight plan (FPL) submission and validation is a cornerstone of Air Traffic Management (ATM). Traditionally, flight plans are manually reviewed by controllers and flight data operators, which can lead to delays, inconsistencies, or errors if incorrect information is submitted. AI systems are increasingly being used to automate the reception, parsing, validation, and optimization of flight plans, reducing workload and improving efficiency (ICAO, 2025; EUROCONTROL, 2023; Indra, 2022).

For example, EUROCONTROL's Network Manager (NM) has piloted AI-based validation tools that automatically check flight plans against regulatory and operational constraints, flagging inconsistencies such as routing errors, incorrect altitudes, or restricted airspace usage. INDRA and NATS have developed AI-powered tools that process large volumes of flight plans in real time, enabling dynamic slot allocation and trajectory optimization while ensuring compliance with ICAO rules (NATS, 2023; Indra, 2022).

These AI systems rely on natural language processing (NLP) to interpret free-text remarks, machine learning to predict potential bottlenecks, and optimization algorithms to propose environmentally efficient alternatives. Such capabilities not only speed up the pre-departure process but also reduce fuel consumption, delays, and controller workload.

Best Practices for AI in Flight Plan Receiving include the following:

- Automated validation - Use AI tools to check compliance with ICAO rules, local regulations, and airspace restrictions before controller review.
- Error detection and fagging - Flight plans with missing or inconsistent data should be highlighted with confidence levels for human validation.
- Dynamic optimization - Integrate AI algorithms that suggest fuel-efficient trajectories, weather-optimized routes, and slot allocation improvements.
- Human-in-the-loop - Ensure final responsibility lies with air traffic controllers or flight data operators, maintaining oversight of AI recommendations.
- Seamless integration - AI outputs should be compatible with existing ATM systems (e.g., EUROCONTROL IFPS, FAA flight plan services).
- Continuous learning - AI models should be updated with historical flight plan errors, seasonal patterns, and operational data to improve accuracy.
- Regulatory alignment - Systems must align with ICAO flight plan format (FPL 2012) and EASA/FAA regulatory frameworks.

*3.3 Use Case: Remote ATC Towers*

Remote or digital ATC towers enable air traffic services to be provided from a centralized location using high-definition cameras, sensors, and AI-assisted decision support. Airports equipped with remote towers, such as O¨ rnsko¨ldsvik (Sweden) and London City (UK), leverage AI for object detection, traffic movement prediction, and anomaly detection to augment human controllers (NATS, 2023; Saab, 2022).

AI systems in remote towers can automatically track aircraft and ground vehicles, detect runway incursions, and provide predictive alerts. This enhances situational awareness, allows a single controller to monitor multiple airports, and reduces operational costs without compromising safety. Challenges include maintaining operator trust, ensuring high reliability of video and sensor feeds, and addressing latency in communications (Cummings, 2014; Dekker, 2017).

Best Practices for AI Integration in Remote ATC Towers could include the following aspects:

- Human oversight - Always maintain a qualified controller supervising AI-generated alerts and decisions.
- Reliable sensor infrastructure - Ensure redundancy and continuous monitoring of cameras, radars, and sensors to avoid single points of failure.
- Explainable AI - AI recommendations should be transparent, with clear reasoning and confidence levels to facilitate trust and accountability.
- Latency management - Systems must minimize delays in video and data transmission to maintain real-time situational awareness.
- Continuous training - Controllers should receive ongoing training in interpreting AI outputs and handling system anomalies.
- Incident feedback loops - Document and analyze events where AI alerts were ignored or acted upon to improve system performance.
- Safety culture integration - AI in remote towers must align with existing safety management systems and regulatory standards (ICAO, EASA, FAA).

*3.4 Case Study: Voice Recognition AI in ATC*

Voice communication remains a critical element of Air Traffic Control, but it is also prone to errors caused by mishearing, accents, workload stress, or radio interference. AI-driven voice recognition systems are being deployed to automatically transcribe pilot-controller communications, detect anomalies, and support workload management (FAA, 2024; NATS, 2023; Indra, 2022).

For example, NATS in the UK has trialed speech recognition technology to automatically digitize clearances, reducing manual input and enabling faster updates to flight data systems. Similarly, FAA research explores AI-assisted transcription to improve situational awareness and detect miscommunications before they escalate into safety incidents. Indra has integrated speech recognition into its air traffic management suites, focusing on multilingual support and natural language processing (NLP) for global deployment (Indra, 2022).

AI models are trained in comprehensive language datasets of aviation-specific phraseology, accounting for variations in accents, background noise, and stress-induced speech patterns. These systems not only generate accurate transcriptions but can also flag potential readback errors or deviations from standard phraseology.

Best Practices for Voice Recognition AI in ATC include the following aspects:

- Standard phraseology training - AI models should be trained on ICAO-standardized ATC language while adapting to regional variations.
- Error detection and flagging - Systems must highlight uncertainties, mispronunciations, or potential readback errors for controller validation.
- Multilingual and accent adaptability - Ensure robust performance across diverse pilots and controlled populations.

- Real-time integration - Speech-to-text outputs should seamlessly update flight data and decision support systems without latency.
- Human validation - Controllers retain authority to con- firm or reject AI-generated transcriptions.
- Incident learning - Feedback from flagged communication errors should retrain AI models to continuously improve accuracy.
- Privacy and compliance - Systems must comply with GDPR and aviation data protection standards when handling voice recordings.

*3.5 Case Study: AI in Unmanned Aircraft Systems (UAS) Integration*

The growing presence of Unmanned Aircraft Systems (UAS) in national and international airspace introduces new challenges for Air Traffic Management (ATM). Unlike conventional aircraft, UAS often operates at lower altitudes, with higher densities, and across urban environments where surveillance and communication are more complex. AI is being leveraged to ensure safe integration of UAS into controlled and uncontrolled airspace, supporting functions such as detect-and-avoid (DAA), airspace access management, and real-time conflict resolution (ICAO, 2025; FAA, 2024).

For example, the FAA's UAS Traffic Management (UTM) program incorporates AI-based algorithms for strategic deconfliction and real-time monitoring of drone traffic. Similarly, EASA has promoted AI applications in U-space, focusing on autonomous conflict detection, geofencing, and compliance with airspace restrictions. Industrial providers such as INDRA and SAAB have piloted AI-enabled UAS monitoring platforms capable of processing radar, ADS-B, and telemetry data to predict trajectory conflicts and provide early warnings to controllers (Saab, 2022; Indra, 2022).

AI enables scalability in UAS operations, allowing thou- sands of small drones to be coordinated simultaneously while minimizing risks to conventional aviation. By learning from historical incident data, weather patterns, and operational constraints, AI enhances both safety and efficiency in UAS integration.

Best Practices for AI in UAS Integration should consider the following:

- Detect-and-Avoid (DAA) algorithms - AI systems must support autonomous conflict detection and resolution to prevent mid-air collisions with both manned and un- manned aircraft.
- Dynamic airspace management - AI should enable adaptive geofencing and real-time airspace access decisions based on traffic density and operational priorities.
- Integration with ATM - UAS AI outputs must interface seamlessly with existing ATC systems, ensuring con- trollers maintain awareness of UAS operations.
- Human oversight - Critical decisions should re- main under human supervision, especially in mixed manned–unmanned environments.
- Cybersecurity and data integrity - AI-driven UAS platforms must ensure secure communication and resilience against spoofing or data manipulation.
- Environmental awareness - AI should incorporate ter- rain, weather, and urban infrastructure data for safe routing of UAS in low-altitude corridors.
- Standardization and regulation - Systems must align with ICAO, EASA, and FAA frameworks for UAS traffic management (UTM/U-space).

Table 1 presents a summary of case studies and best practices, as discussed in the article.

*Table 1: Summary Of AI Case Studies and Key Best Practices in ATC/ATM*

| Case Study | Key Best Practices |
|---|---|
| EUROCONTROL Network Manager | Human-in-the-Loop, Transparent Outputs, Continuous Validation, Collaborative Training, Data Governance, Feedback Loops, Safety Culture Integration |
| Flight Plan Processing | Automated Validation, Error Detection, Dynamic Optimization, Human-in-the-Loop, Seam- less Integration, Continuous Learning, Regula- tory Alignment |
| Remote ATC Towers | Human Oversight, Reliable Sensor Infrastructure, Explainable AI, Latency Management, Continuous Training, Incident Feedback Loops |
| Voice Recognition AI | Standard Phraseology Training, Error Detection, Multilingual and Accent Adaptability, Real- Time Integration, Human Validation, Incident Learning, Privacy Compliance |
| UAS Integration | Detect-and-Avoid Algorithms, Dynamic Airspace Management, Integration with ATM, Human Oversight, Cybersecurity, Environmental Awareness, Standardization |

## IV. CONCLUSIONS AND FINAL REMARKS

Artificial Intelligence is no longer a distant concept but a practical enabler of change in Air Traffic Control (ATC) and Air Traffic Management (ATM). The case studies presented, ranging from EUROCONTROL's Network Manager and remote tower operations to voice recognition systems, AI-assisted flight plan processing, and UAS integration, demonstrate the breadth of AI's potential across aviation domains. These applications show measurable benefits in efficiency, safety, and capacity, while also revealing new challenges in trust, accountability, and cultural acceptance.

A consistent finding across all domains is that AI does not replace human expertise but reshapes it. Controllers evolve from tactical operators to supervisors of intelligent systems, requiring new skills in oversight, validation, and human–machine collaboration. This shift underscores the need for continuous training, updated competency frameworks, and integration of AI literacy into professional development.

Ethical and cultural considerations are equally critical. Issues of fairness, transparency, privacy, and social trust are not abstract but directly linked to operational scenarios, such as voice recognition accuracy across accents, or public acceptance of remote towers and UAS. Addressing these challenges requires embedding ethical principles from ICAO, EASA, FAA, and other regulators directly into AI design and deployment.

From a safety perspective, AI offers powerful tools for predictive risk management, congestion forecasting, anomaly detection, and collision avoidance. However, these advances must be matched with robust accountability frameworks, redundancy, and continuous validation to prevent over-reliance and ensure resilience in mixed human–AI environments.

Looking forward, AI adoption in ATC should follow a human-centered trajectory: systems must enhance, not erode, the professional role of controllers and pilots; decision-making authority must remain transparent and accountable; and cultural acceptance must be actively cultivated through engagement and communication. Future research should emphasize cross-disciplinary collaboration, combining engineering, hu- man factors, ethics, and policy, to ensure that AI supports aviation not only as a technical system but also as a social institution.

In conclusion, the integration of AI in ATC holds transformative promise for efficiency, safety, and sustainability. Yet its success depends on balancing innovation with responsibility, ensuring that human expertise, ethical oversight, and social trust remain at the heart of the aviation system.

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**TRANSACTIONS on ENGINEERING AND MANAGEMENT**

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# Developing Competencies and Training Skills Through Erasmus+ Programme

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**Abstract** – Erasmus+ programme influences the educational environment, encouraging students to actively engage, participate and collaborate in this extended mobility to develop their competencies and abilities in the learning process, for an academic and professional development. This research seeks a detailed analysis of the most important achievements that support collaboration in learning, among students, given the experience already gained through an Erasmus+ programme experience. The tools that support learning through an extended mobility programme for students facilitate communication in English, increase the opportunities for academic and professional development and provide students with valuable interactions with educators and peers. Academia researchers are analyzing the vulnerabilities of such an experience, seeking ways to improve the standards for experiential learning and at the same time, ways to implement a future grading system for students in order to gain credits for such a grant.

**Keywords:** academic and professional development, international collaboration, communication competencies, “lifelong learning” experience, personal growth

## I. INTRODUCTION

The Erasmus+ programmes are essential for the educational, professional, and cultural development of students and teachers across Europe. They offer opportunities for academic exchange and training abroad, providing numerous benefits. Academic and Professional Development allows students to study at prestigious universities in other countries, provides access to different courses and teaching methods, develops key skills such as adaptability and problem-solving, enhances job prospects through international experience. This programme contributes to personal and intercultural growth, helps participants become more independent and confident, enables them to discover new cultures, traditions, and languages, and increases tolerance and understanding between different communities. It provides international collaboration and innovation, contributes to the creation of academic and professional networks, facilitates the exchange of best practices between educational institutions, and supports research and development in various fields. (https://www.observatorcultural.ro/articol/erasmus-educatia-care-da-roade) Regarding the extended mobility, the Erasmus+ programmes, in addition to students, are available for teachers, researchers, and employees in various sectors. The programmes provide scholarships and funding to facilitate participation. Erasmus+ programmes help shape a generation of young people who are better prepared for global challenges, promoting education, collaboration, and cultural diversity. (https://revistaprofesorului.ro/erasmus-o-experienta-premergatoare-scolii-online)

Over the years, as innovations and investments in European extended mobility programmes have grown considerably, we have opportunities for universities to allow students to learn in their own rhythm, and benefit in credits for their Erasmus+ programme experience. Educators, as well as students, need a sustainable basis for adopting changes in education. For educators, the availability of Erasmus+ programmes is needed to increase “lifelong learning” and a way to exchange ideas with other educators. For students, receiving feedback on their language competencies and specialized training skills contributes to their personal growth that can be motivating and encouraging. This paper emphasizes the idea that programmes like Erasmus+ are innovative, developing multiple competencies and being an open window for future studies.

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## II. STUDY CASE: COLLABORATION IN HIGHER EDUCATION

Fumasoli and Rossi (2021) noticed that higher education institutions (HEIs) have a central role in transnational networks, being strategic partners and knowledge alliances in higher education. They engage in and contribute to innovation for teaching and learning within transnational networks.

HEIs play a central role within transnational networks. The authors discovered two types of transnational networks (1. strategic partnerships and 2. knowledge alliances) which were designed to involve higher education institutions as leading organizations. The intention of the European Commission was to use these two types of networks for scaling up processes of institutional innovation in teaching and learning. The research also showed that higher education institutions engage in different ways in the modernization of EU agenda.

### *2.1 Erasmus+ programme experience*

During the 2022-2023 school year, in the months of October-November, teachers from our school, together with 12$^{th}$ grade students from the Ion I. C. Brătianu Technological High School in Timisoara (Romania), participated in an Erasmus+ educational programme. The main objective of the programme was to engage high school students in exchange experience with the City Council of Lisbon. Practically, the students had to complete documentation tasks in their field of study, commerce and administration technician, within practical activities organized by the host institution.

Beyond the practical activities in their field of training, the main goal of the project was also to improve students' communication skills, both oral and written, in English. The entire two-week internship was conducted under the guidance of specialists from Lisbon, using English as the working language.

The students were selected from the technical specialization classes through an interview that assessed their oral communication skills in English, as well as a written test to verify their knowledge in the economic field. The selected group consisted of 13 students, and their internship period in Portugal was later recognized as a European grant.

Throughout the two weeks, students communicated in English, engaged in practical tasks related to completing administrative documents, and followed a structured daily schedule. Their day typically included practice sessions from 9 AM to 1 PM, followed by lunch and cultural activities in the afternoon, ending with dinner in the evening.

The practical training activities were highly valuable, as students gained insight into the functioning of institutions different from those in their home country. They also had the opportunity to apply for a simulated job interview with foreign evaluators, where they learned about the types of questions that could be asked when applying for a job abroad. Moreover, they actively used English in both formal and informal contexts, demonstrating the language's significance for their present and future endeavors. Another major benefit was the opportunity to familiarize themselves with Portuguese culture, traditions, customs, and the warm hospitality of the people.

The programme included visits to various landmarks, and we were warmly welcomed everywhere we went. We explored the Oceanarium, the Lisbon Zoo, the Art Museum, and participated in an excursion to a miniature town. We also reached the westernmost point of continental Europe, Cabo da Roca, where the Atlantic Ocean greeted us with a rainbow on the horizon. Additionally, we visited the royal gardens and the famous pilgrimage site of Fátima. Perhaps the most impressive aspect, at least for me, was the distinctive Portuguese architectural style known as „manuelin", which we encountered in Lisbon's buildings, churches, cathedrals, and monuments. Other delightful experiences included seeing the traditional Portuguese attire, tasting Porto wine, and trying the famous Portuguese drink, Sangria.

The students returned home full of joy, having had enriching and pleasant experiences both professionally and personally. The entire staff involved in managing the activities was exceptionally kind and went to great lengths to provide us with meaningful and valuable experiences. As a teacher, I found this experience to be not only an opportunity to learn about different traditions and customs but also a chance to observe the professional development of our students. Following this Erasmus+ project, all participating students applied the knowledge they gained by enrolling in university studies, mostly in the field of economics. They unanimously acknowledged that the experiences they had had enriched them both spiritually and professionally.

## III DEVELOPING COMPETENCIES AND TRAINING SKILLS

Participating students from the Hairstylist and Trade Technician specializations, as part of the Erasmus project, had a unique exchange experience in collaboration with other team members.

From the beginning of the project, students were involved in a series of theoretical and practical training activities at our high school (Ion I.C. Brătianu Technological High School).

They studied some of the key competencies included in the Hairstylist and Trade Technician specializations, which are described in the professional training standards specific to the fields of Aesthetics and Hygiene of the Human Body and Commerce.

These competencies can only be acquired through skill development, respecting the level of understanding and perception of the organizational and execution mechanisms of tasks that are centered on the student.

The Hairstylist qualification provides the necessary specialized training for delivering services such as designing and creating hairstyles, haircuts, and makeup, both conventional and stylized. The Trade Technician specialization requires filling-in accounting documents and completing a job interview project. Additionally, the first qualification offers the necessary training for managing a hair salon, organizing salon activities, and advising clients on selecting the most suitable haircuts, hairstyles, hair colors, and techniques to enhance their appearance.

Graduates who obtain this qualification can also pursue other occupations in the field, either at the same level or a lower level, depending on the employer's decision. Upon completing the training programme, they have the opportunity to enter the job market.

By participating in such a European project, students gained a valuable experience that broadened their perspective on professional training. They stepped out of their daily routine, focusing on personal care at required standards and following the schedule established by the coordinators.

Each day started with self-care in their accommodation, including a morning shower, preparing their attire and hair, and ensuring they wore protective equipment for their assigned workplace. Work safety regulations were a daily priority.

They adapted easily to the company environment and observed the differences in professional practices, which motivated them to become more dedicated to their profession and experience real-life working conditions.

Beyond their internship schedule, students also participated in extracurricular activities, visiting important landmarks in Lisbon.

*3.1 Research for the Project's Reliability and Relevance*

To illustrate the development of communication skills and specialized training skills, we conducted a questionnaire (https://forms.gle/ZL51xxLJyQVzaho29), administered to 41 students from the high school that demonstrated students' expectations. The development of communication skills in English (78 %) and specialized training skills (17.1 %) were their choices.

The students were asked to respond to three questions to illustrate the impact of such a programme and the relevance for their learning objectives related to their competencies developed through this programme. Most students admit that they have heard of such a programme and reflect upon the idea of taking part in such an experience in the near future.

It is also worth noting that all respondents (9th-grade students, newcomers to the high school level) consider the possibility of participating in such a European project in the near future and reflect on the competencies, skills, and cultural opportunities provided, as follows:

1. Number of participants who completed the questionnaire 41;
2. Number of participants aware of the project: 28 (68.3%);
3. Number of participants who would like to take part in the project: 21 (51.2%).

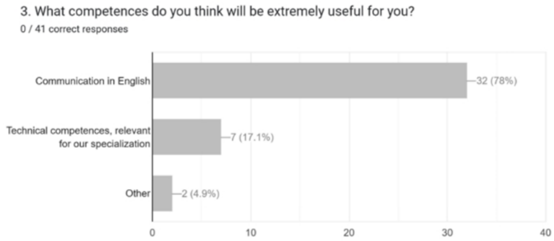


*Fig 1. Research results related to the extremely used competences*

The table illustrates that the development of communication skills is mostly valued by the participants in research.

Given all the implied limitations, this paper illustrates the impact of extended mobility programmes on education, emphasizing the importance of communication competencies in English and of those relevant for students' specialization. As Granato et al., (2024) state, Erasmus+ mobility programmes improve graduation results for undergraduate students enrolled in scientific and technical fields and for those who applied in their first year of their studies, especially when enrolled in more demanding degree courses.

## V. CONCLUSIONS

This paper explores how international mobility programs significantly enhance the educational, professional, and personal development of students. Based on the sources provided, here are the key insights from the research:

1. Enhancement of communication and language skills - A primary achievement of the Erasmus+ experience is the development of "communication competencies", particularly in English. The study highlights that 78% of surveyed students identified the development of English communication skills as a top priority or outcome. Students improved both oral and written English through daily interaction with foreign specialists and peers in both formal and informal settings.

2. Practical and specialized professional training - The program provides a bridge between theoretical knowledge and real-world application.

- Skill development - Students in technical fields (such as Commerce, Administration, and Hairstyling) engaged in practical tasks like completing administrative documents and managing salon-related activities.
- Job readiness - Participants underwent simulated job interviews with foreign evaluators, gaining insight into international employment standards and the types of questions asked by global employers.

- Workplace adaptability - Students learned to adapt to foreign organizational structures, follow strict professional schedules, and prioritize work safety regulations.

3. Personal growth and cultural awareness - Beyond academic metrics, the mobility experience fosters significant “personal and intercultural development”.

- Independence - The program helps participants become more independent, confident, and adaptable to global challenges.
- Cultural exchange - Students were exposed to Portuguese traditions, architecture (such as the "manuelin" style), and landmarks, which increased their tolerance and understanding of different communities.

4. Long-term academic impact - The research suggests that Erasmus+ participation acts as a powerful motivator for future education. In the specific case study of 12th-grade students from Timisoara, “all participating students” eventually enrolled in university studies, primarily in the field of economics, following their return from Lisbon. The research notes that such programs can improve graduation results, especially for students in demanding scientific and technical fields.

5. Institutional and academic evolution - The paper underscores a shift in how higher education institutions (HEIs) view these programs:

- Strategic partnerships - HEIs are increasingly acting as central nodes in transnational networks aimed at innovating teaching and learning.
- Credit recognition - There is an ongoing effort to implement grading systems and academic credits for mobility experiences, moving toward a sustainable "lifelong learning" model.

In summary, the paper concludes that the Erasmus+ program is an essential tool for creating a generation of young people who are better prepared for the professional world through “experientia docet” (experience teaches).

In conclusion, participating in Erasmus+ projects and programmes provides valuable educational experiences. Starting this school year, some university systems, including ours have even begun recognizing and equating such programmes with academic credits and other forms of evaluation. Beyond these formal recognitions, Erasmus+ experiences offer memorable moments to share with fellow students, foster friendships both abroad and at home, and promote lifelong learning - an experience that is not merely a memory but also an example to inspire others. As part of the lifelong learning (LL) experience, the Erasmus+ exchange in the fall of the 2022-2023 school year stands as a perfect illustration of the proverb “experientia docet” (experience teaches). It reminds us, as educators, of the values and attitudes we carry in our professional and personal journeys.

## IV. ACKNOWLEDGMENT

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**TRANSACTIONS on ENGINEERING AND MANAGEMENT**

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# Using ML.NET To Educate High School Students on Machine Learning for A Smoother Transition into Higher Education in Computer Science

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**Abstract –** Machine learning (ML) is a critical discipline in contemporary computing; however, its inherent complexity presents significant challenges in vocational high school education. ML.NET, a machine learning framework developed by Microsoft, provides an accessible and efficient platform for introducing ML concepts through practical, hands-on experiences. This paper investigates the use of ML.NET as an instructional tool in vocational high schools, focusing on its advantages, implementation strategies, and educational outcomes. Through project-based learning and real-world scenarios, students gain foundational knowledge of ML concepts without requiring advanced mathematical expertise or high-performance computing resources. Additionally, this study assesses the effectiveness of ML.NET in bridging the gap between theoretical instruction and industry requirements, thereby preparing students for future careers in artificial intelligence and software development.

**Keywords:** Machine Learning (ML), Artificial Intelligence (AI), ML.NET, Vocational Education, Vocational High Schools.

## I. INTRODUCTION

The swift expansion of artificial intelligence across everyday applications emphasizes the critical imperative to embedding machine learning principles within high school curricula, thereby equipping students more effectively for the rigors of university-level computer science programs (Marques et al., 2020; Martins & Wangenheim, 2022). Educators can harness the ML.NET framework to forge a conduit that converts abstract theoretical notions into concrete, project-oriented engagements, thereby diminishing the entry barriers to advanced computational endeavors (Martins & Wangenheim, 2022). This instructional paradigm addresses the prevailing deficiencies in K-12 education, where conventional syllabi often lag the technical demands of contemporary computing domains (Tedre et al., 2021). Moreover, deploying a mature, production-grade framework like ML.NET immerses students in authentic development pipelines, nurturing the technical autonomy and computational insight vital for excelling in higher education (Tedre et al., 2021). The embrace of such industry-caliber instruments further alleviates reliance on opaque "black-box" constructs, prompting learners to scrutinize and dynamically calibrate model parameters across the full development trajectory (Broll & Grover, 2023).

Artificial intelligence is a scientific field of computer science that deals with the creation of intelligent systems using information technology. Machine Learning (ML) is a field of artificial intelligence that deals with the development of systems that can learn from data: generalizing knowledge based on previous experience, that is, based on data about entities that are the subject of learning, where the acquired knowledge can provide answers to questions about entities that have not been seen before. Machine learning can be explained to students as a set of algorithms that draw conclusions from a data set, without the need for programming - a person gives the algorithm a data set, and it generates logic for new data that is not in that set.

Machine learning has become a crucial aspect of modern technology, driving innovations across various industries. However, teaching ML in vocational high schools presents challenges due to its complexity, the need for substantial computational resources, and the mathematical depth required for traditional ML frameworks. ML.NET, a cross-platform machine learning library by Microsoft, offers an accessible solution by allowing students to implement ML models with minimal coding and without deep theoretical prerequisites.

This research has an excellent approach for vocational education, as it transforms abstract theory into tangible digital skills. ML.NET is ideal for this context because it allows students who already know C# or F# to integrate artificial intelligence without

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having to learn a new language (like Python) from scratch.

## II. THE ROLE OF ML.NET IN VOCATIONAL EDUCATION

The target group of students in this case are students who need to be introduced to machine learning material - they are 3rd grade Information Technology Technician in the field of Electrical Engineering, in the high school education system of the Republic of Serbia. They have prior knowledge of programming in the C# (.NET) programming language for developing console, desktop, and web applications. They also have prior knowledge of designing and programming relational databases using Microsoft SQL Server. Given this, the logical choice of programming language and tools was the C# (.NET) programming language, Microsoft Visual Studio, and ML.NET with ML.NET Model Builder. ML.NET is specifically designed for .NET developers and enables easy integration of machine learning capabilities into existing applications. Its advantages in vocational education include:

- Ease of use, because ML.NET provides high-level APIs, enabling students to train and use ML models without deep knowledge of algorithms.
- Integration with .NET ecosystem, because many vocational programs already teach C# and .NET development, making ML.NET a natural extension.
- Low computational requirements, unlike other ML frameworks requiring GPUs, ML.NET can run efficiently on standard school computers.

By leveraging ML.NET, students can focus on practical applications rather than struggling with complex mathematical derivations.

## III. IMPLEMENTING ML.NET IN THE CLASSROOM

### *3.1. Introduction*

A structured curriculum using ML.NET should include introduction to machine learning concepts first, so the students can gain basic understanding of supervised learning, unsupervised learning, datasets etc. Supervised learning (usually regression and classification) involves learning to label new data based on a labeled data set. For example, given a data set with square footage, number of floors, locations, and prices of sold apartments.

The program determines the price of any apartment based on square footage, number of floors, and location. Unsupervised learning (usually clustering, pooling, and dimensionality reduction) involves learning to detect patterns in the data based on an unlabeled data set. For example, given a data set with square footage, number of floors, and locations of sold apartments.

The program determines which apartments sell the most and which ones sell the least in which location. In addition to supervised and unsupervised learning, there is also learning with incentives, deep learning, semi-supervised learning, subordinate learning, representational learning, etc.

ML.NET Model Builder is an intuitive graphical extension for Visual Studio that allows you to build, train, and deploy machine learning models. Model Builder uses automated machine learning (AutoML) to explore different machine learning algorithms and settings to help students find the one that best suits their scenario, as shown in Table 1 (example).

*Table 1 Mapping scenario with a machine learning task*

| **Task** | **Scenario** |
|---|---|
| Binary classification | Data classification |
| Multiclass classification | Data classification |
| Image classification | Image classification |
| Text classification | Text classification |
| Regression | Value prediction |
| Recommendation | Recommendation |
| Forecasting | Forecasting |

The next challenge is to find the datasets. Internet resources such as www.kaggle.com - one of the largest AI & ML communities - have proven to be a good source. Additionally, the ML.NET GitHub in the examples section can also be a good source. Teaching students how to preprocess data, train ML models, and interpret results, and after that, integrate trained models into desktop and web applications becomes easy.

### *3.2. Case study with hands-on project*

We did the case study as a practical example. How to explain regression in machine learning to high school students? In mathematics, linear functions are represented as f(x)=ax+b, where a,b∈R and a≠0. The graph of a linear function is a straight line. If a>0 then the line makes an acute angle with the positive part of the x-axis, or if a<0 then the angle is obtuse.

In statistics, a linear model can be represented by two approaches. The first approach, Y=aX+b, assumes that Y is completely determined if X is known. The observed labeled values are represented by (xi,yi). For example, if you look at the relationship between temperature in Celsius and Fahrenheit, for any given temperature in Celsius, you can accurately determine the temperature in Fahrenheit with the formula:

$$T_F = \left(\frac{9}{5}T_C\right) + 32 \quad (1)$$

The approach where the value of Y is completely determined by the value of X is not very "interesting". It would be interesting to predict the value of Y based on the value of X. For example, to predict the price of an apartment based on the square footage of the apartment. The price of an apartment cannot be determined precisely by a linear function based on the square footage of the apartment. This means that there are variations in the value of Y that are not completely determined by the value of X, so in the second approach:

$$E[Y/X]=aX+b, \quad (2)$$

E[Y|X] represents the conditional expectation expression - the expected value of Y for a given X is aX+b. The straight line on the graph does not pass through all the points on the graph, which means that there are differences between the expected and predicted values, that is, there are errors (some positive, some negative). The errors are first squared, then summed, and the result is divided by the total number of errors, which results in the mean squared error. X is often called the independent variable, predictor variable, factor or regressor, and Y the dependent variable or criterion variable. The independent variable is not always a single value, i.e. a scalar. It can also be a vector, matrix or tensor (the price of an apartment does not only depend on the square footage, but also on the floor, location, condition, equipment, age of the building, etc.).

Regression is a supervised machine learning task used to predict the value of a label from any real-world value. Regression algorithms model the dependence of a label on its related features to determine how the label will change as the feature values change. The input to the algorithm is a set of examples with labels of known values, while the output is a function that you can use to predict the value of the label for any new set of input features. Some examples of scenarios where students can apply a linear regression model:

- Predict house prices based on house attributes such as number of rooms, location, or size.
- Predict future stock prices based on historical data and current market trends.
- Predict product sales based on advertising budget.

The task is to create a C# console application (.NET 8.0 LTS) to predict taxi fares, where the dataset contains the following data: **vendor_id**: taxi vendor ID, **rate_code**: rate code, **passenger_count**: number of passengers, **trip_time_in_secs**: trip time in seconds (not important), **trip_distance**: distance traveled, **payment_type**: payment type (CRD for card or CSH for cash), and **fare_amount**: price.

In Microsoft Visual Studio, in Solution Explorer, students can simply add the Machine Learning Model, define a name, choose Value Prediction scenario, choose Local CPU environment, and add given dataset.

The training of this model can be done in 600 seconds with one million rows dataset, and then the model can be evaluated and used. In the presented classroom scenario, students did not manually select specific machine learning algorithms. Instead, they used ML.NET Model Builder, which relies on automated machine learning (AutoML) to choose, train, and evaluate multiple trainers automatically.

The AutoML process systematically tests various algorithms and combinations of hyperparameters, selecting an algorithm that provides the best performance for a given dataset and learning task. For the regression task of predicting taxi fares, AutoML typically evaluates several trainers from the ML.NET library, such as SdcaRegressionTrainer, FastTreeRegressionTrainer, LightGbmRegressionTrainer, and FastForestRegressionTrainer.

The final choice depends on the algorithm that produces the lowest mean square error and the best overall model values. This process allows students to focus on understanding the input data, features, and model evaluation rather than on algorithmic details. Such an approach is particularly effective in vocational high school education. It introduces students to the concept of model training and evaluation without requiring prior university-level mathematical knowledge of optimization or gradient descent. Once the model is trained, students can easily integrate it into a C# console or desktop application, as illustrated in the example in Fig 1.

```
using MLModel1_ConsoleApp1;

string vendor = Console.ReadLine();
float.TryParse(Console.ReadLine(), out float rate);
float.TryParse(Console.ReadLine(), out float passenger);
float.TryParse(Console.ReadLine(), out float trip);
string payment = Console.ReadLine();

var data = new MLModel1.ModelInput()
{
    Vendor_id = vendor,
    Rate_code = rate,
    Passenger_count = passenger,
    Trip_distance = trip,
    Payment_type = payment,
};

var predict = MLModel1.Predict(data);
Console.WriteLine("Price: {0:0.00}", predict.Score);
```

*Fig. 1. An example of how students integrate the model into a C# console*

The example in Fig 1 demonstrates how students can use the automatically trained model to make real-time predictions in a simple C# application. In this way, AutoML in ML.NET not only simplifies the model-building process but also enables students to experience the entire machine learning pipeline in an accessible and engaging manner - from data preprocessing to prediction.

## VI. CONCLUSIONS

ML.NET presents an opportunity to make machine learning education accessible in vocational high schools by offering a practical, hands-on approach. Its integration with existing .NET-based curricula and ease of use make this tool an ideal way to introduce students to ML. By incorporating ML.NET into professional education, schools are better preparing students for careers in artificial intelligence, software development, and data science. The conclusions of this paper highlight the transformative potential of ML.NET in pre-university technical education:

*Accessibility and Efficiency:* ML.NET removes the barrier of learning a new language, allowing students from computer science profiles to apply Machine Learning concepts directly in the familiar C# ecosystem.

*From Theory to Practice:* Through tools like AutoML and Model Builder, the learning process becomes an experimental one. Students do not just memorize definitions but observe in real time how algorithms like FastTree or LightGBM influence the accuracy of a prediction.

*Preparation for the Labor Market:* Integrating these technologies into vocational high schools aligns the curriculum with current industry requirements, giving students a competitive advantage in areas like Data Science and intelligent software development.

*Simplicity without Compromise:* The paper demonstrates that although the process is simplified through automation (AutoML), the scientific rigors of model evaluation (regression metrics, cross-validation) remain intact, ensuring a solid academic foundation.

## V. ACKNOWLEDGMENT

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# Applying Lean Principles to the Manufacturing of Air Intake Manifolds in the Automotive Industry: Improving Process Efficiency

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**Abstract** – The automotive industry is characterized by increasing competitive pressure, stringent quality requirements, and the need for high productivity at reduced costs. These challenges are particularly significant for automotive component suppliers, where production systems often combine automated and manual operations. This paper presents a case study on the application of Lean manufacturing principles to the production of air intake manifolds for internal combustion engines. The study focuses on process analysis, elimination of non-value-added activities, line balancing, and performance evaluation using key performance indicators. The results demonstrate measurable improvements in cycle time, labor productivity, and overall equipment effectiveness, confirming the effectiveness of Lean methodologies in semi-automated automotive manufacturing environments.

**Keywords:** Lean manufacturing, automotive industry, air intake manifold, process optimization, continuous improvement.

## I. INTRODUCTION

The Lean concept includes important works by Ohno and Deming. Lean production evolved from the Toyota Production System (TPS) over a period of several decades and was considered to improve company performance by eliminating waste.

Lean manufacturing is a manufacturing philosophy that is based on customer-oriented process improvements. As Holweg [1] emphasizes, its scope is to increase value for customers while reducing the number of resources consumed and cycle times by eliminating waste.

Beyond its classical definition, Lean has evolved into a multidimensional management philosophy studied extensively in literature. Shah & Ward [2] categorize Lean into key bundles such as just in time (JIT), total quality management (TQM), and human resource management, emphasizing that Lean success depends on organizational integration rather than isolated tools. Holweg [1] highlights the historical evolution of Lean from post-war TPS practices to global adoption, while recent studies focus on Lean adaptation in hybrid manual-automated environments.

According to Womack &Jones [3], lean manufacturing is guided by five key principles, namely by: identifying customers and specifying their value, identifying and mapping the value stream, creating flow by eliminating waste, responding to customer pull and pursuing perfection.

In the automotive sector, Lean methodologies have been widely adopted to improve manufacturing processes and gain competitive advantages. Specific applications of Lean in this industry focused on value stream mapping [4], using machine learning-based soft sensor approaches [5], even best practices assessment form employee motivation in the Lean implementation stages [6], all tailored to automotive manufacturing processes.

Understanding the versatile application of Lean strategies across diverse sectors provides insights into the adaptability and effectiveness of Lean methodologies beyond traditional manufacturing contexts.

## II. STUDY CASE

The research methodology adopted in this study follows a structured single-case study approach, which is generally used for analyzing complex industrial systems and for validating the practical applicability of improvement methodologies in real manufacturing environments. The selected case concerns a semi-automated production line for air intake manifolds used in internal combustion engines, operating within an automotive supplier certified according to IATF 16949 requirements. The analyzed production system is in a top-tier automotive manufacturing plant situated in the

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western region of Romania, integrated into the European automotive supply chain and supplying components to international original equipment manufacturers.

The production of air intake galleries influences both vehicle performance and the overall efficiency of production processes. As consumer demand for high-performance vehicles continues to grow, manufacturers face the challenge of optimizing the production of components to meet strict standards while maintaining cost efficiency.

To face these challenges, to these challenges, this paper explores the application of Lean manufacturing principles as a strategic approach to improving the manufacturing process of air intake modules.

For this study, a production line that manufactures air intake manifolds for internal combustion engines was selected for a customer in the automotive sector.

The initial state of the production line and the changes made to improve the assembly process will be analyzed.

The production line is semi-automated (each automated process also includes manual processes). The process was designed as a “one piece flow” without intermediate stocks, with 4 operators in the production cell and 5 workstations. The volumes quoted at the beginning of the project were 280,000 pieces/year, resulting in a calculated cycle time of 68 seconds/piece. With these considerations in mind, the process improvement analysis began.

*2.1 Presentation of the intake manifold*

The part is assembled from various components as screws, bolts, nuts, gaskets and metal bushings, purchased parts like throttle valves for regulating the air supply necessary for forming the fuel-air mixture to the engine intake manifold and pressure sensor for monitoring the air pressure in the manifold, finally in-house injected parts which form the subassembly housing on which the rest of the components are to be assembled.

The role of the part is to distribute the air that has already been filtered into each cylinder of the engine. It can be seen in Fig.1.

*Fig. 1 The air intake manifold*

*2.2 The assembly line*

One-piece-flow is particularly valuable in air intake manifold assembly because the product contains multiple sealing surfaces, torque-critical fasteners, and integrated electronics that benefit from reduced WIP handling. According to Hopp & Spearman [6], reducing buffer inventory improves defect detection and accelerates corrective feedback loops, critical advantages for complex automotive components.

The line integrates automated processes, such as leak testing and functional verification, with manual assembly tasks including component positioning, fastening, and visual inspection. The annual production volume is approximately 280,000 units, resulting in a takt time of 68 seconds per part, calculated based on available working time and customer demand.

Material supply to the line was originally organized through indirect feeding, requiring operators to perform additional walking and handling activities. Furthermore, the synchronization between automated equipment and manual operations was not fully optimized, leading to operator waiting times and local bottlenecks. These characteristics made the line suitable for Lean analysis and improvement.

The U-shaped assembly line, with production starting on the right-hand side (since most people are right-handed, it is designed to work from right to left), is installed on a 9x7-meter footprint. The line has a traceability process in place, which is able to track the part from the first to the last station, memorizing different parameters from each station.

It is designed to provide the latest standards of ergonomics and workplace safety with the implementation of various sensors to prevent accidents and optimize cycle time (e.g., optical barriers instead of doors).

*2.3 Lean Analysis and Improvement Framework*

The improvement approach was based on classical Lean manufacturing principles, focusing on waste identification and process flow optimization. To differentiate value-added from non-value-added activities, a detailed analysis of each workstation was executed. The seven types of waste: overproduction, waiting, transportation, overprocessing, inventory, motion, and defects, were used as a reference framework.

Lean tools applied during the study included line balancing, workstation layout redesign, implementation of chaku-chaku principles were applied to ensure that operators could load components into machines while the equipment automatically unloaded completed parts. This minimized operator waiting time during the automated cycles allowed manual tasks to be performed simultaneously, improving flow efficiency and supporting the required takt time.

Task redistribution amongst operators was carried out to improve workload balance and reduce idle time. In addition, the material flow was optimized through the introduction of gravity-fed racks positioned directly at the point of use, reducing unnecessary motion and handling.

*2.4 Performance Measurement*

To objectively evaluate the impact of the implemented improvements, a set of key performance indicators was defined in accordance with Lean performance measurement literature [7]. The indicators included cycle time, labor productivity expressed as parts per person per hour (PPH), line balance rate, and Overall Equipment Effectiveness (OEE). Data were collected before and after implementation to ensure comparability and to quantify performance improvements.

*2.5 Line balancing*

Recent research highlights that structured Lean implementation through line balancing can significantly improve production line performance by redistributing tasks and reducing idle times [8].

To increase productivity and reduce waste, it is essential to recognize and eliminate vital NVA tasks. In addition, this can lead to a decrease in the number of employees needed and faster project execution times. In the context of the analyzed air-intake-manifold assembly line, non-value-added (NVA) activities were primarily associated with unnecessary operator motion, excessive walking to retrieve components, waiting during automated cycles, and duplicated manual handling steps. Eliminating these NVAs is essential for improving flow and ensuring alignment with takt time. Lean literature emphasizes that NVA reduction must be based on direct observation and workstation-level analysis rather than generic assumptions.

Therefore, a structured waste assessment was conducted for each station, identifying the root causes of motion, waiting, and overprocessing. These insights supported the redistribution of tasks, redesign of material presentation, and introduction of Chaku-Chaku principles. Together, these actions provided a foundation for a more balanced workload and a smoother, more predictable one-piece flow operation.

Table 1 highlights three key areas for process improvement: improving non-value-added (NVA) and value-added (VA) activities, and better redistributing assembly activities among the three operators. These measures are essential for optimizing efficiency and productivity in production activities.

Fig. 2 presents the initial process, and Fig 3. marks the activities after the process improvements. The elimination of non-value-added (NVA) processes sets a new target of 65 seconds.

Reconfiguring activities and optimizing the material flow led to a reduction in operator workload by eliminating non-value-added activities, such as unnecessary movements and material transport time. This also enables better line balancing.

*Table 1: Main characteristics of the air intake manifold production line before Lean implementation*

| **Parameter** | **Value** |
|---|---|
| Annual production volume | 280,000 units/year |
| Number of workstations | 5 |
| Number of operators | 4 |
| Takt time | 68 s/part |
| Production concept | One-piece flow |

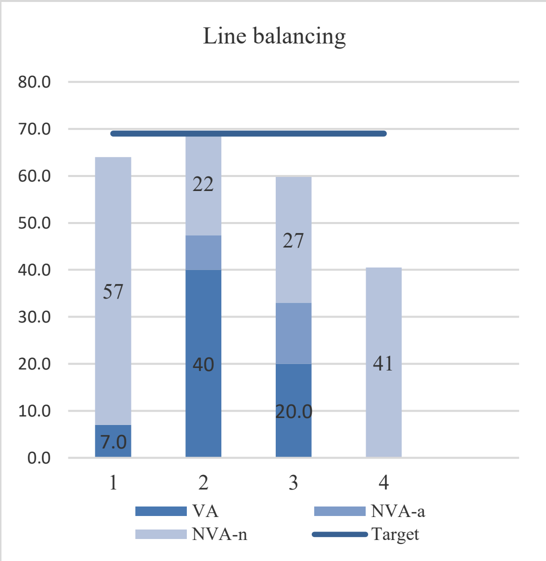


*Fig.2 Initial distribution of activities*

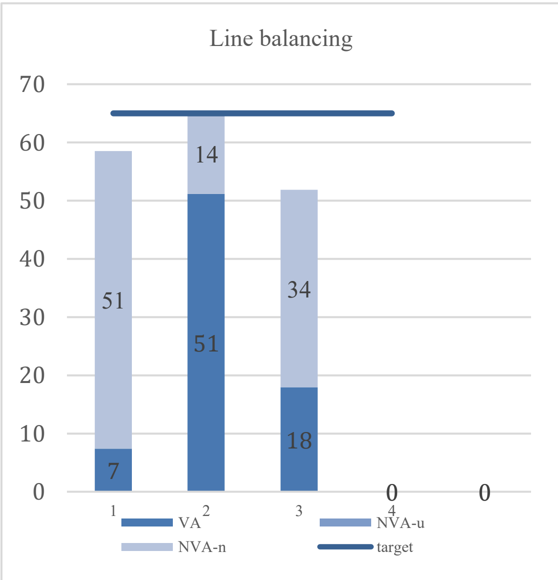


*Fig.3 Distribution of activities after improvements*

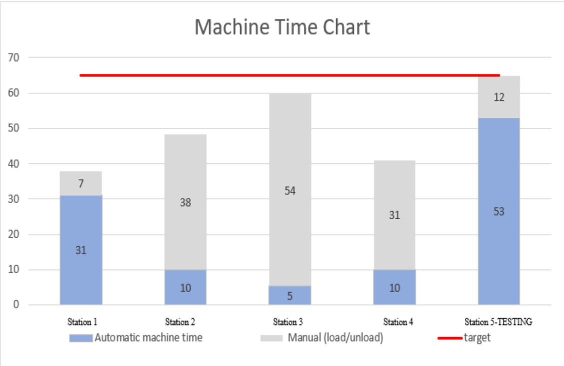


*Fig. 4 Man-Machine chart after optimization*

*Table 2: Comparison of KPIs before and after Lean implementation*

| Indicator | Before Lean | After Lean | Improvement |
|---|---|---|---|
| Cycle time (s) | 69 | 65 | -5,8% |
| Number of operators | 4 | 3 | -25% |
| Labor productivity (PPH) | 13 | 19 | +46% |
| Line balance rate (%) | 83 | 90 | +7% |

*2.6 Machine times*

The man-machine chart is a clear and systematic study of human and machine resources available in an industry. It also deals with guiding them in an optimized way to increase productivity. This method proves to be better and superior to the existing practice, without making huge leaps in technology and without investing much more in the project. Improvement methods may include improving production with a fixed workforce of people and machines, maintaining production by reducing the workforce, and reducing processing time for a fixed workforce. During the study process, the bottleneck process should be considered [9].

The optimization of the automatic leak testing times of the part at the last station was achieved by reducing the time from 58 to 53 seconds, which represents an 8% improvement. This performance was achieved by reducing the marking time, increasing the test pressure, and optimizing the automatic movements inside the machine. Thus, the testing process became more efficient, contributing to an increase in overall productivity.

## III. RESULTS AND ANALYSIS

The implementation of Lean improvement actions led to significant and measurable enhancements in production performance. The most notable improvement was observed in cycle time, which decreased from an average value of 69 seconds to 65 seconds per unit. This reduction ensured compliance with the required takt time of 68 seconds and enabled a more stable one-piece-flow operation, reducing the risk of line stoppages.

*3.1 Labor Productivity and Line Balancing*

Through task redistribution and improved synchronization between manual and automated operations, the number of operators required to run the line was reduced from four to three, without negatively affecting production output. As a result, labor productivity increased substantially, with PPH rising from 13 to 19. The line balance rate improved from

83% to 90%, indicating a more even distribution of work content across stations.

The elimination of operator waiting times at automated stations played a key role in achieving these results. By applying chaku-chaku principles, operators were enabled to perform manual tasks during machine cycles, thus increasing effective working time and reducing idle periods [4].

*3.2 Reduction of Non-Value-Added Activities*

Significant reductions in non-value-added activities were achieved through layout optimization and improved material presentation. The introduction of gravity-fed racks at workstations eliminated the need for operators to leave their stations to retrieve components, thereby reducing unnecessary motion and transportation waste. The results of this study are consistent with previous research highlighting the effectiveness of Lean principles in improving operational performance in automotive manufacturing environments.

A key contribution of this study is the demonstration that Lean tools can be successfully adapted to semi-automated production lines, where human–machine interaction is a dominant factor. The automation of repetitive manual movements significantly reduced non-value-added time.

Furthermore, using KPIs such as OEE and PPH offered clear, objective evidence of ongoing improvement, reinforcing the emphasis that Lean literature places on performance measurement. The results also validate that Lean implementation is an iterative, continuous process rather than a one-time initiative. For example, a 6% reduction in cycle time increases annual production capacity by approximately 18,000 units without requiring additional labor or equipment. This directly enhances the organization's ability to respond flexibly to customer demand.

## IV. CONCLUSIONS

The objective of the research was to analyze the initial production system, identify non-value-added activities, and implement targeted Lean improvements to enhance operational efficiency and productivity. The study demonstrated that Lean tools such as line balancing, waste elimination, chaku-chaku principles, and optimized material presentation can be effectively adapted to semi-automated manufacturing environments, where human–machine interaction plays a critical role. Through a systematic analysis of manual and automated operations, significant inefficiencies related to operator waiting times, unnecessary motion, and suboptimal task distribution were identified and addressed.

The implementation of Lean improvement actions resulted in measurable and quantifiable performance gains. Cycle time was reduced from 69 seconds to 65 seconds, ensuring compliance with the calculated takt time and enabling a more stable one-piece-flow operation. At the same time, the number of operators required to run the line was reduced from four to three without compromising output, leading to a substantial increase in labor productivity from 13 to 19 parts per person per hour. Furthermore, the line balance rate improved from 83% to 90%, reflecting a more even distribution of workload across workstations and a reduction in operator idle time.

In addition to productivity improvements, the optimization of automated machine cycles contributed to enhanced equipment performance. The reduction of leak testing time by approximately 8% improved synchronization between manual and automated processes and had a positive impact on overall equipment effectiveness. These results confirm that Lean manufacturing should be viewed not only as a cost-reduction approach, but also as a structured methodology for improving system stability, process transparency, and resource utilization.

A key contribution of this research lies in its focus on a semi-automated automotive component production line, a context that is less frequently addressed in Lean manufacturing literature compared to fully automated or fully manual systems. The findings confirm that Lean implementation in such environments requires careful coordination between human and machine activities and that partial automation of repetitive, non-value-added manual tasks can significantly enhance both efficiency and operator ergonomics.

In conclusion, the results of this study confirm that Lean manufacturing remains a powerful and practical approach for improving competitiveness in the automotive industry. When applied systematically and supported by objective performance indicators, Lean principles can deliver significant efficiency gains even in complex semi-automated production environments. The presented case study provides valuable insights for both researchers and practitioners seeking to optimize automotive component manufacturing processes through continuous improvement.

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# Digital and Sustainability Solutions in Higher Education for Circular Economy Awareness. A Theoretical Approach with Case Study Debate

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**Abstract -** This paper explores the role of higher education institutions (HEIs) in fostering the transition to a circular economy (CE) by integrating digital and sustainability solutions into curricula, campus operations, and research. It highlights the necessity of shifting from the traditional linear economic model to a circular approach to minimize resource depletion and environmental degradation. The study introduces a holistic framework designed to guide universities in implementing digital and sustainable practices that enhance awareness of CE principles. Furthermore, the research presents a case study from Politehnica University of Timişoara (UPT), Romania, analyzing its Sustainability@UPT initiative using the UIGreenMetric framework and a diagnosis of the implementation of "Digital and Sustainable HEI to Raise Awareness of the CE" proposed framework (discussing key dimensions such as governance, interdisciplinary education, smart campus infrastructure, stakeholder engagement, and innovative digital tools like IoT, AI, and blockchain). The findings emphasize that HEIs play a pivotal role in promoting sustainable development and accelerating progress toward the CE by embedding sustainability into institutional strategies and leveraging digital technology-driven solutions.

**Keywords:** Sustainable development, circular economy, education, higher education, strategic framework, projects.

## I. INTRODUCTION

The imperative for a transition from a linear "take-make-dispose" economy to a circular economy (CE) to support sustainable development (SD) management (with low carbon emission) is increasingly urgent. Multiple arguments are presented in the literature and business practices. First, the actions of decoupling economic growth from resource depletion and environmental degradation have become of great interest for business practice in different industries. Research and development have reacted accordingly and considering the new legal framework (at the European level), complex and integrated solutions were provided (UNEP, 2011; Addai et al., 2023).

The linear model of transforming input into output relies on an ever-increasing extraction of virgin resources, which are finite. Recent literature emphasizes that continued reliance on this model is unsustainable as global population and consumption grow, leading to resource scarcity and price volatility. Thus, CE aims to keep products and materials in use for as long as possible, minimizing the demand for new resources.

This directly reduces the environmental impacts associated with extraction, processing, and manufacturing, including habitat destruction, biodiversity loss, and pollution (Araújo et al., 2023; McCabe, 2025). In addition, a critical argument from recent literature highlights the CE's fundamental contribution to halting and reversing biodiversity loss. Over 90% of biodiversity loss is linked to resource extraction and processing. By eliminating waste and pollution, and circulating products and materials, the CE leaves more room for natural systems to regenerate (McCabe, 2025).

Second, the new and dynamic environmental context is crucial for climate change mitigation (low carbon-emission, and other greenhouse gases, GHG). Thus, recent studies confirm that the CE offers substantial potential for GHG emission reductions. By focusing on "narrower, slower, and more closed material cycles" (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recovery), the CE

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lessens demand for virgin materials and new products, directly reducing emissions from production (Cantzler et al., 2020). In addition, while renewable energy is vital, the CE addresses emissions embedded in materials and products. The Intergovernmental Panel on Climate Change (IPCC, 2022) for the first time explicitly recognized the CE as a solution for climate change mitigation, highlighting its role in transforming production and consumption systems. Estimates suggest the CE could help achieve a significant percentage (e.g., 45%) of global GHG emission reductions needed to mitigate climate change.

Another important aspect to be considered is waste management emissions. The CE also tackles emissions from waste management, particularly by reducing landfilling and incineration, which release potent GHGs like methane and carbon dioxide (Imran et al., 2023). Circular practices, such as the use of organic fertilizers from carbon waste in agriculture or the utilization of biomass (e.g., seaweed) to capture CO2, offer opportunities for carbon sequestration and recycling (Yong et al., 2022; Kumar Sarangi et al., 2022).

The third phenomena observed by researchers and the business consultants is the accelerating progress on sustainable development goals (SDGs). Recent literature emphasizes that the circular economy and the United Nations's Sustainable Development Goals (SDGs) are "naturally complementary". The CE provides a powerful framework to accelerate progress on the SDGs, especially given that the current SDG agenda is often "faltering" (Khargonekar & Samad, 2024). Thus, addressing the "Triple Planetary Crisis" has become a reality in different industries; the CE is increasingly seen as a catalyst for more effective action on the "triple planetary crisis" of pollution, climate change, and biodiversity loss – issues that directly undermine many SDGs (Miao & Nduneseokwu, 2025).

While some SDGs have a clear link to the CE (e.g., SDG 12: Responsible Consumption and Production), research shows the CE can also positively impact other, more socially related goals (e.g., decent work and economic growth, reduced inequalities) by creating new jobs, ensuring equitable resource management, and fostering resilient local economies (Pradhan et al., 2017; Schroeder et al., 2019; Ortiz-de-Montellano et al., 2023).

The fourth aspect to be considered is related to the economic and social benefits. Moving away from reliance on finite resources can increase economic competitiveness, stimulate innovation in product design and business models (e.g., product-as-a-service), and provide more secure supply chains (Sakao et al., 2023; Bag et al., 2024). In this context, while there may be shifts in employment, the transition to a CE is projected to create a significant number of new jobs, particularly in sectors related to repair, remanufacturing, recycling, and new circular business models (ILO, 2023). Further, consumers can benefit from more durable, higher-quality products, reduced costs through repair and sharing models, and increased disposable income. From the practical perspective of the businesses, by reducing pollution from resource extraction, manufacturing, and waste, the CE can lead to improved air and water quality and overall public health and occupational safety and health (Sharma & Bangur, 2025). Recent literature also highlights the importance of embedding principles of justice and inclusivity into the circular transition, addressing issues like environmental injustices and ensuring decent work conditions (Passaro et al., 2024; Eiselein & Langenus, 2025).

In this dynamic context, higher education institutions (HEIs) play a pivotal role in fostering the transition to CE by educating future leaders and promoting sustainable practices (Vargas-Merino et al., 2024). Many studies presented in the literature focus only on education for sustainability (promoting research and popularizing practices for changing young people's behavior into a responsible one or awareness of the effects of climate change, the need for systems resilience etc.) or how HEIs adapt their educational offer to the demand of organizations/labor market actors regarding knowledge in areas such as SD management, CE, climate change (with extensive debates on different fields of study, for different specializations and/or different academic research group) (Atici et al., 2021; Fissi et al., 2021; Leal Filho et al., 2021; Žalėnienė & Pereira, 2021; Abo-Khalil, 2024; Shange et al., 2025), but fewer studies are focused on demonstrating how HEIs (as a whole) can be transformed into sustainable or green spaces/communities, that can support a real change in the behaviors and mentality (associated with their experience within the HEIs) of young people and the preparation for real life of new generations of responsible professionals. Moreover, the consideration of the digital dimension in the HEIs transformation to CE is not discussed in literature, and not in a holistic manner.

This is the core topic of the presented research aiming to demonstrate how HEIs/universities can be active actors in promoting CE transition and practices. This research explores how digital and sustainability solutions within HEIs/universities can effectively raise awareness and facilitate the adoption of SD and CE principles. By leveraging technology and integrating sustainability into curricula and campus operations, HEIs can create a powerful ecosystem for SD, CE education and implementation.

The methodological research approach is presented after a brief overview of the theoretical background together with the introduction of the proposed holistic framework for digital and SD solutions in HEIs to raise awareness of the CE. The applicative research (case study with examples of different projects implementations and best practices) is related to Politehnica University of Timisoara (UPT), Romania and the defined initiative "Sustainability@UPT". The last section is dedicated to conclusions and final remarks.

The present paper combines bibliographical study and theoretical arguments with a practical example of a Romanian public university who succeed in achieving a high degree of sustainable practices.

## II. THEORETICAL BACKGROUND

Understanding the dynamic context of the CE implementation, in association with the main tendencies (as explained before) creates the premises for connecting them with the space and fields of action of HEIs/universities. Despite growing recognition of sustainable development and the CE's importance, awareness among students and staff in HEIs remains limited.

Traditional educational approaches often struggle to convey the complexities and practical applications of sustainable management and CE and the presentation of classical existed frameworks in the literature or sharing local best cases and experiences developed with local stakeholders (Kopnina, 2020; Anthony Jnr, 2021; Figueiró et al., 2022; Acosta Castellanos & Queiruga-Dios, 2022). Furthermore, the integration of sustainability into campus operations and decision-making processes is often fragmented and lacks a holistic approach. This necessitates innovative solutions that effectively combine digital tools and sustainability practices to enhance sustainability and CE awareness and drive behavioral change. The holistic framework is introduced and explained.

### *2.1 HEIs and CE*

HEIs are pivotal in fostering the transition to a CE due to their unique position as centers of learning, research, and community engagement; they serve as microcosms of society, where innovative CE practices can be developed, tested, and disseminated. In addition, HEIs influence future leaders and professionals, equipping them with the necessary skills and knowledge to implement CE principles in various sectors. This multifaceted role positions HEIs as key drivers in the systemic transformation required for a sustainable future (Renfors, 2024; Vargas-Merino et al., 2024). In the following the debate will be debated the specific roles and contributions of HEIs in this transition.

Regarding education and curriculum development, HEIs are instrumental in integrating CE principles into educational curricula, thereby equipping students with the necessary competencies to address CE challenges. This includes developing courses and modules that focus on systems thinking and sustainable practices (Giannoccaro et al., 2021; Renfors, 2024). Furthermore, the implementation of Education for Sustainable Development (ESD) theories in HEIs helps overcome barriers in designing CE educational materials, fostering a deeper understanding of sustainability among students (Bendle, 2023). HEIs also play a role in training future educators, ensuring that sustainability and CE concepts are incorporated into various educational levels, thus broadening the impact of CE education (Bugallo-Rodríguez & Vega-Marcote, 2020).

In the activities domain of research and innovation (knowledge and innovation transfer), HEIs/universities conduct research that advances CE knowledge and practices, often serving as living labs where sustainable solutions are tested in real-world contexts. This research not only contributes to academic knowledge but also provides practical solutions that can be implemented across sectors (Hidalgo-Carvajal, 2024). Collaboration with industry and policymakers is facilitated by HEIs, which helps in the co-creation of innovative CE strategies and solutions (Salas et al., 2021).

Related to the HEIS/universities campus operations and community engagement, HEIs can implement CE practices on their campuses, such as waste management, energy efficiency, and sustainable procurement, serving as models for other institutions and communities (Hidalgo-Carvajal, 2024). Engaging students in on-campus CE activities, such as borrowing and repairing practices, helps inculcate sustainable habits and reduces the environmental footprint of the institution (Hobson & O'Byrne, 2024). HEIs also engage with local communities and stakeholders, promoting CE initiatives beyond the campus and fostering broader societal change (Binytska & Shcherbiak, 2022).

Furthermore, it has been recognized that HEIs/universities are active actors at the global, regional and local perspectives. While CE has gained significant traction in developed countries, HEIs in regions like Latin America are beginning to explore their role in this transition. These institutions are crucial in addressing unique regional challenges and promoting inclusive CE discourse (Salas et al., 2021). In addition, the development of frameworks and methodologies for CE implementation in HEIs, such as the Circular Economy Living Lab (CELL), provides replicable models for other institutions globally (Hidalgo-Carvajal, 2024).

Despite the significant potential of HEIs in promoting CE, challenges remain. There is a need for a more organized approach to CE implementation within HEIs, as well as a deeper understanding of how to apply CE practices effectively across different institutional systems (Vergani, 2024). Additionally, while HEIs are making strides in integrating CE into their operations and curricula, there is still a gap in aligning research and education with practical applications, particularly in collaboration with external stakeholders (Hidalgo-Carvajal, 2024). Addressing these challenges will be crucial for HEIs to fully realize their potential as catalysts for the transition to CE generalized practices.

### *2.2 The Holistic Framework for Digital and Sustainability Solutions in Higher Education to Raise Awareness of the CE*

The designed framework expressed a comprehensive approach for HEIs to integrate digital solutions and sustainability practices to raise awareness of CE principles. It interconnect three layers which are highly influence by the HEIs activities (considering universities actual missions): the university/HEIs as an institution (providing educational and research activities, including transfer of knowledge and innovation to different stakeholders), the physical campus (related to the HEIs infrastructure and support services), and the broader university/HEIs community (related to the manifestation of university third mission, recognized as crucial for universities to remain relevant and impactful in the 21st century) (as mentioned by (Abramowitz et al., 2024). Thus, the proposed framework is a holistic one because of the aspects considered in the multilayer space of HEIs. By leveraging digital technologies and sustainability initiatives across these domains, universities can create a holistic ecosystem that not only teaches CE concepts but embodies them in practice. The designed framework is presented in Fig 1 and described in Table 1.

As observed in Fig. 1, the layers 1 - 3 of the framework are related to HEIs/universities missions as supported by the synthesis of the studies of (Haj Taieb, 2024; Abramowitz et al., 2024; Ruano-Borbalan, 2024). The fourth layer consists of dimensions and related components activities to support digital processes of layer 1 – 3 and 5; layer five relates to the HEI/university management philosophy. The proposed multilayer framework aims to achieve “Digital and Sustainable HEI to Raise Awareness of the CE”.

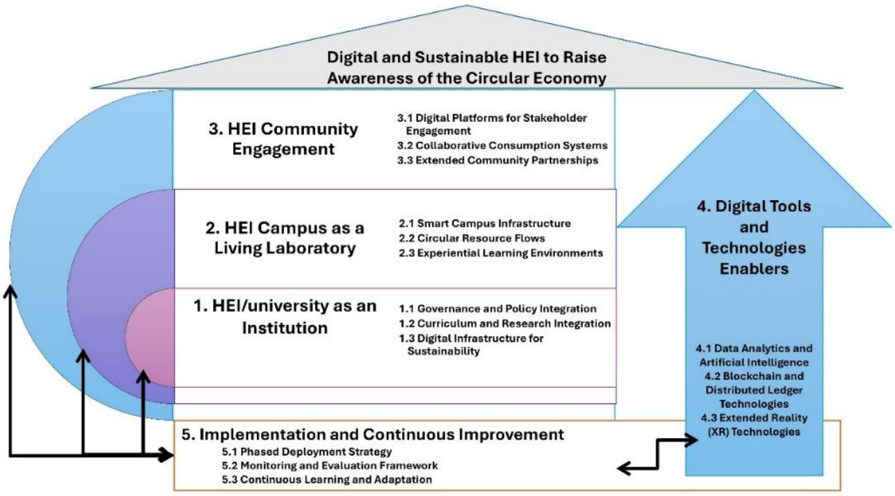


*Fig. 1. The Holistic Framework for Digital and Sustainability Solutions in HEI to Raise Awareness of the CE.*

*Table 1: Description of the Framework Components considering the defined 1 – 5 layers (Fig. 1)*

| Layer | Dimensions considered in the layer | Components considered in the dimensions | Brief description |
|---|---|---|---|
| 1. HEI/University as an Institution | 1.1 Governance and policy integration | Digital CE strategy | Develop an institution-wide digital strategy that explicitly incorporates CE principles into the university's mission, vision, and strategic plans. |
| | | Sustainability metrics dashboard | Implement a digital dashboard tracking key sustainability metrics (energy usage, waste reduction, resource efficiency) accessible to all stakeholders |
| | | Circular and green procurement policies | Establish digital procurement systems that prioritize suppliers adhering to CE economy principles, with transparent tracking and reporting. |
| | 1.2 Curriculum and research integration | Interdisciplinary CE courses | Develop digital learning modules on CE principles that can be integrated across disciplines. |
| | | Virtual research collaborations | Create digital platforms for cross- departmental and inter-university research collaborations on CE innovations. |
| | | Digital certification programs | Establish micro-credentials and certificates in circular economy practices that students can earn alongside traditional degrees. |
| | | Open educational resources | Develop and share digital open educational resources on CE topics, making knowledge freely accessible. |
| | 1.3 Digital infrastructure for sustainability | Green IT policies | Implement sustainable digital infrastructure practices, including energy-efficient data centers, equipment lifecycle management, and responsible e-waste handling. |
| | | Digital Twin technology | Create digital twins of university operations to model and optimize resource flows, energy usage, and waste management. |
| | | Sustainability- focused learning management systems | Integrate CE principles into digital learning platforms, reducing digital waste and promoting efficient resource use. |

| | | | |
|---|---|---|---|
| 2. HEI/University Campus as a Living Laboratory | 2.1 Smart Campus infrastructure | IoT-enabled resource monitoring | Deploy sensors and IoT devices to monitor and optimize resource consumption (energy, water, materials) across campus buildings. |
| | | Digital waste management systems | Implement smart waste bins with real-time monitoring and analytics to improve waste sorting and reduction. |
| | | Renewable energy integration | Use digital systems to manage and optimize renewable energy generation and consumption on campus. |
| | | Smart building management | Deploy AI-driven building management systems that optimize energy use based on occupancy patterns and environmental conditions. |
| | 2.2 Circular resource flows | Digital material passport system | Create a digital inventory of materials and assets on campus, tracking their lifecycle and facilitating reuse and repurposing. |
| | | Campus resource sharing platforms | Develop digital platforms for sharing equipment, spaces, and resources across departments to maximize utilization. |
| | | Food system digitalization | Implement digital tracking of food procurement, preparation, consumption, and waste to create closed-loop food systems on campus. |
| | | Water recycling monitoring | Use digital systems to track and optimize water recycling and reuse across campus operations. |
| | 2.3 Experiential learning environments | Augmented reality campus tours | Create AR experiences highlighting CE initiatives across campus, making sustainable infrastructure visible and educational. |
| | | Living Lab projects | Establish digitally monitored experimental zones where students can test and implement CE innovations in real-world settings. |
| | | Digital sustainability challenges | Host hackathons and innovation competitions focused on developing digital solutions for campus sustainability challenges. |
| 3. HEI/University Community Engagement | 3.1 Digital platforms for stakeholder engagement | Community CE App | Develop a mobile application connecting university stakeholders (students, faculty, staff) with local businesses and organizations practicing CE principles. |
| | | Virtual sustainability forums | Host regular online events and discussion forums on circular economy topics, engaging both campus and external community members. |
| | | Digital storytelling initiatives | Create multimedia content showcasing CE success stories and innovations from within the university community. |
| | 3.2 Collaborative consumption systems | Digital sharing economy platforms | Establish platforms for sharing, swapping, and reusing goods within the university community (textbooks, furniture, electronics, etc.). |
| | | Repair café scheduling system | Create digital scheduling and knowledge- sharing platforms for community repair initiatives, extending product lifecycles. |
| | | Skills exchange network | Develop a digital platform where community members can exchange skills and services related to sustainable practices. |
| | 3.3 Extended community partnerships | Industry- university digital collaboration | Create digital platforms connecting students and researchers with businesses seeking CE innovations. |
| | | Local government data sharing | Establish data sharing agreements with local municipalities to align university CE initiatives with broader community sustainability goals. |
| | | Digital citizen science projects | Engage the broader community in data collection and analysis related to resource flows, waste management, and environmental impacts. |
| | | Virtual knowledge transfer | Host webinars, online courses, and digital resources for local businesses and community organizations on implementing CE practices. |

| | | | |
|---|---|---|---|
| 4. Digital Tools and Technologies Enablers | 4.1 Data analytics and artificial intelligence | Predictive resource management | Use AI to predict resource needs and optimize procurement, reducing waste and overproduction. |
| | | Waste Stream Analysis | Apply machine learning to analyze waste composition and identify opportunities for reduction and better sorting. |
| | | CE impact assessment | Develop AI tools to measure and visualize the environmental, social, and economic impacts of circular initiatives. |
| | 4.2 Blockchain and distributed ledger technologies | Supply chain transparency | Implement blockchain solutions to track the origin and lifecycle of products and materials used on campus. |
| | | CE credentials | Use blockchain to verify and share sustainability achievements and CE competencies of students and staff. |
| | | Tokenized incentive systems | Create digital token systems rewarding sustainable behaviors and contributions to CE initiatives. |
| | 4.3 Extended reality (XR) technologies | Virtual CE simulations | Develop VR/AR simulations demonstrating the impacts of linear versus circular economic models. |
| | | Digital Twin visualizations | Create immersive visualizations of campus resource flows and circular systems for educational purposes. |
| | | Mixed reality training | Implement XR training programs for maintenance, repair, and proper waste sorting to extend product lifecycles. |
| 5. Implementation and Continuous Improvement | 5.1 Phased deployment strategy | Digital readiness assessment | Evaluate the university's current digital infrastructure and identify gaps for supporting CE initiatives. |
| | | Pilot project selection | Identify high-impact, visible projects that demonstrate the integration of digital solutions and CE principles. |
| | | Scalability planning | Design initiatives with clear pathways for scaling successful pilots across the institution. |
| | 5.2 Monitoring and evaluation framework | Key Performance Indicators (KPIs) | Establish digital tracking of specific KPIs related to circular economy awareness and implementation. |
| | | Real-time feedback mechanisms | Implement digital tools for continuous feedback from university community members on CE initiatives. |
| | | Annual sustainability reporting | Produce comprehensive digital reports on progress toward CE goals, accessible to all stakeholders. |
| | 5.3 Continuous learning and adaptation | Digital knowledge repository | Create a centralized digital platform documenting lessons learned, best practices, and case studies from circular economy initiatives. |
| | | Community of practice (CoP) | Establish online communities where stakeholders can share experiences and innovations in digital sustainability. |
| | | External benchmarking | Use digital tools to compare the university's CE performance against peer institutions and industry standards. |

The designed framework (Fig 1 and Table 1) provides a comprehensive and holistic approach for HEIs/universities to leverage digital solutions in promoting CE awareness and implementation across the institution, campus, and community. By integrating these elements (activities and solutions as briefly described in column fourth in Table 1), HEIs organizations can serve as powerful catalysts for broader societal transition toward CE principles, while preparing students (as next generation professionals) with the knowledge and skills needed for a sustainable future. The success of this framework implementation depends on strong leadership commitment (connected with the layer five of the framework), adequate resource allocation and governance, and active participation and implication of all HEIs/universities stakeholders. By embracing both digital transformation and sustainability principles, HEIs/universities can create a powerful synergy that accelerates the transition to a CE while fulfilling their educational mission.

## III. RESEARCH METHODOLOGIES

The aim of the research methodology is to provide coherent logic for testing and validation of the proposed holistic framework for “Digital and Sustainable HEI to Raise Awareness of the CE” (as described in Fig. 1 and Table 2). The research approach proposes a multi-faceted approach (associated with a strategic framework at HEIs/university level) that integrates five dimensions as presented in Fig. 2, considered a strategic framework of the research methodology. This is considered an operational approach for the diagnosis of the implementation status of the “Digital and Sustainable HEI to Raise Awareness of the CE” at the HEIs level.

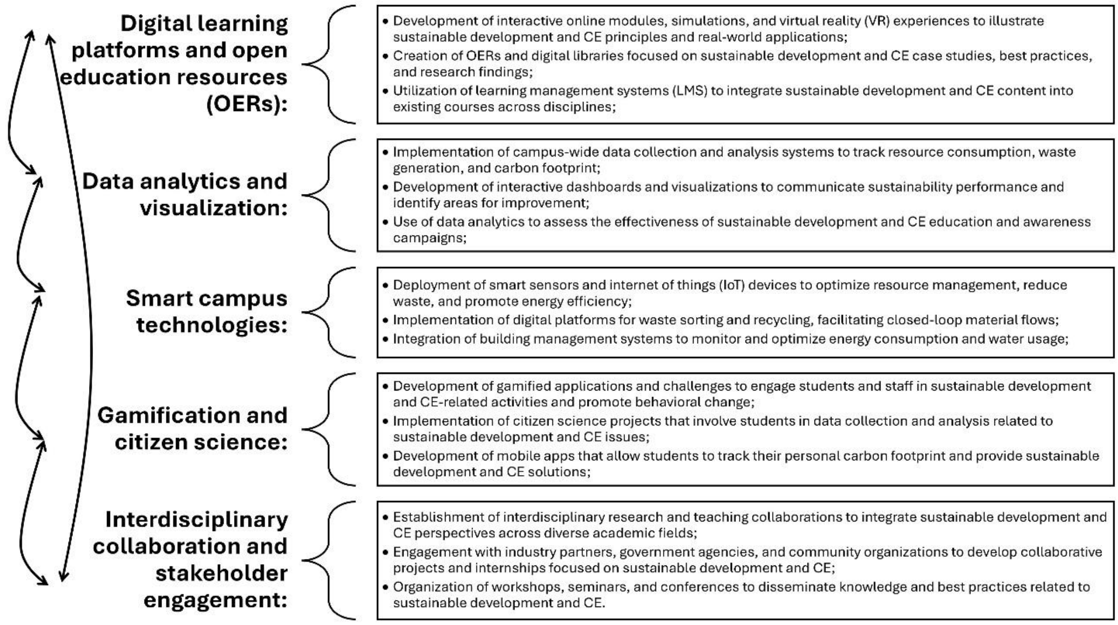


*Fig. 2. Research methodology for the diagnosis (monitor and control) of the "Digital and Sustainable HEI to Raise Awareness of the CE" framework implementation.*

As depicted in Fig. 2, the proposed methodology is related to the monitoring and control managerial functions for developing and implementing innovative solutions that enhance sustainable development, CE awareness and promote the adoption of green practices within the HEIs/universities. In addition, the proposed methodology can be considered extremely useful for several reasons:

1. It allows and supports structured analysis and systematic assessment. As can be observed, the proposed methodology offers a clear, organized structure to analyze HEI's/university's current state and potential for implementing CE initiatives by considering the integration of the digital technologies. By breaking down the complex topic into five key areas: digital learning platforms, data analytics, smart campus technologies, gamification and citizen science and interdisciplinary collaboration.

2. The methodology highlights the essential components required for a "Digital and Sustainable HEI to Raise Awareness of the CE ". This ensures that all critical aspects and key pillars (identified and practically recognized) are/should be considered, from technological and digital infrastructure to educational approaches and stakeholder engagement and active participation.

3. For each pillar, the framework provides concrete examples of initiatives. This directly informs and guides implementation initiative/strategies with recommendations for HEIs/universities, offering actionable steps and specific areas where the management team of the organization can focus its efforts to integrate CE principles via digitalization.

4. By comparing HEI's/university's existing activities (as found in their strategic plan or other public information from their web pages, reports etc.) against the methodology's components, it becomes easier to identify strengths, weaknesses, and areas where new initiatives are needed. This allows for a targeted approach to development and facilitates the gap analysis.

5. The methodology encourages a comprehensive approach to sustainability and CE, moving beyond isolated projects to an integrated strategy that leverages digital tools and engages various stakeholders across the HEI/university. Thus, the proposed methodology promotes holistic development of HEIs sustainability and its pass to CE via digitalization.

In essence, the methodology served as a valuable blueprint, enabling a thorough and practical analysis of how HEIs/universities can advance its CE awareness and implementation efforts. The applicative research and the results achieved will support these ideas, too.

## IV. RESULTS AND DISCUSSIONS

By strategically integrating digital technologies and sustainability principles, HEIs can effectively cultivate a culture of circularity and empower future generations to drive the transition towards a sustainable, CE and regenerative economy. The aims of the applicative research are:

- To provide a deep understanding and analyzing UPT initiative: Sustainability@UPT using UI GreenMetric World University Rankings framework (discover and characterized the gaps and provide recommendations for improvements);

- To test and validate the proposed methodology (Fig. 2) for monitoring and controlling the UPT progress.

The applicative research will present the efforts of Politehnica University of Timisoara (UPT), Romania. Thus, applicative research is developed in two stages:

1. The analysis of the effectiveness of the solutions and identifying best practices for scaling up SD and CE education and implementation. The research results will demonstrate the efforts of UPT to define and support "Sustainability@UPT";

2. The diagnosis of the implementation of "Digital and Sustainable HEI to Raise Awareness of the CE" at UPT.

*4.1 Analysis of UPT Initiative: Sustainability@UPT*

This analysis focuses on the sustainability initiatives and performance of UPT utilizing the UI GreenMetric World University Rankings framework. The UI GreenMetric framework assesses universities. In the following will be evaluated UPT's strategic plan and publicly available information against these categories to provide a comprehensive overview of their commitment and progress in sustainability.

*1. Analytical Framework: UI GreenMetric World University Rankings*

The UI GreenMetric World University Rankings framework (https://greenmetric.ui.ac.id/) is chosen for its comprehensive approach to evaluating university sustainability. The six key categories are:

1. Setting and infrastructure (SI) - This category assesses the university's commitment to a green environment and sustainable infrastructure;

2. Energy and climate change (EC) - This category evaluates energy efficiency, renewable energy use, and climate change mitigation programs;

3. Waste (WS) - This category focuses on waste management, recycling, and waste reduction initiatives;

4. Water (WR) - This category examines water conservation, recycling, and efficient water usage;

5. Transportation (TR) - This category assesses sustainable transportation options and efforts to reduce carbon footprint from commuting;

6. Education (ED) - This category evaluates the integration of sustainability into the curriculum, research, and campus activities.

*2. Analysis of Sustainability@UPT*

1. Setting and Infrastructure (SI) - Based on the provided strategic plan of UPT, there are indirect mentions related to setting and infrastructure. The plan emphasizes the importance of adapting study programs to new developments in fields like environmental engineering, which inherently requires modern infrastructure and facilities. However, explicit initiatives or objectives directly addressing green building practices, land use, or campus greening are not detailed within this specific strategic plan. The plan mentions "infrastructure" as a general section, but no specific details related to green infrastructure is provided. Further investigation into the broader university's strategic plan or dedicated sustainability reports would be necessary to fully assess this category.

Preliminary assessment underlined limited information directly addressing green setting and infrastructure in the UPT strategic plan. More data from the university-level strategic plan or dedicated sustainability reports is needed for a comprehensive assessment.

2. Energy and Climate Change (EC) - Within the UPT strategic plan, direct mentions of energy efficiency, renewable energy use, or specific climate change mitigation programs are not explicitly detailed. However, the university's focus on Environmental Engineering and related research areas (dispersed in different departments, faculties) suggests an underlying commitment to addressing environmental challenges, which would include climate change. The plan emphasizes scientific research and innovation, which could encompass projects related to sustainable energy solutions or climate impact assessment. Without more specific information on university-wide energy policies or initiatives, it is difficult to fully assess UPT's performance in this category based solely on the strategic plan.

Preliminary assessment underlined limited direct information on energy and climate change initiatives in the UPT strategic plan. Further investigation into university-wide sustainability reports or dedicated environmental departments is required.

3. Waste (WS) - The UPT strategic plan does not contain explicit details regarding waste management, reduction, or recycling initiatives within the university or faculty operations. While the university's focus on Environmental Engineering and related research areas (dispersed in different departments, faculties) implies an understanding of waste-related issues, the document primarily outlines academic and research objectives rather than operational sustainability practices. To assess UPT's performance in this category, information on campus-wide waste policies, recycling programs, and waste reduction targets would be necessary, which is not available in this specific strategic plan.

Preliminary assessment shows no direct information on waste management initiatives in the UPT strategic plan. A broader university sustainability report or environmental policy document would be needed for a comprehensive assessment.

4. Water (WR) - Like waste management, the UPT strategic plan does not explicitly detail water conservation or efficient water usage initiatives within the university's operations. The university's expertise in environmental engineering and related research areas (dispersed in different departments, faculties) suggests an awareness of water resource management, likely to be integrated into their academic programs and research. However, for a comprehensive assessment of UPT's performance in this category, information on campus-wide water policies, water-saving technologies, and water recycling efforts would be required, which is not present in this specific document.

Preliminary assessment shows no direct information on water conservation initiatives in the UPT strategic plan. A broader university sustainability report or environmental policy document would be needed for a comprehensive assessment.

5. Transportation (TR) - The UPT strategic plan does not provide specific details on transportation initiatives aimed at reducing the carbon footprint of commuting or promoting sustainable transportation options for students and staff. While the university is in an urban area, information on public transport accessibility, cycling infrastructure, or incentives for eco-friendly commuting is not included in this document. A comprehensive assessment of UPT's performance in this category would require data on campus transportation policies and infrastructure.

Preliminary assessment underlines no direct information on transportation initiatives in the UPT strategic plan. Further investigation into university-wide transportation policies and infrastructure is needed.

6. Education (ED) - The UPT strategic plan provides significant insights into the integration of sustainability into education, research, and campus activities. The very existence of the Faculty of Industrial Chemistry and Environmental Engineering, with its focus on Environmental Engineering demonstrates a strong commitment to environmental education. Also, other positive practices are presented in different research areas related to SD management, occupational health an safety, corporate social responsibility, sustainability and leadership or risk management (subject of teaching and research disperse in different master programs of different faculties) The plan highlights the development of different subjects of teaching included in different study programs (mostly at the master and PhD levels), research activities, and the training of specialists in environmental fields.

Preliminary assessment underlines that UPT strategic plan demonstrates a strong commitment to integrating sustainability into education and research through specialized programs, research initiatives, and student involvement. This category appears to be a strength for UPT, at least within this specific faculty.

*3. Overall Assessment Conclusions and Recommendations*

Based on the analysis of the UPT strategic plan against the UI GreenMetric framework, the university demonstrates a clear commitment to sustainability, particularly within the realm of environmental education and research. The presence of dedicated environmental engineering programs and the development of other teaching subjects related to SD and CE all disperses in different master programs provide a clear focus on education and scientific inquiry into environmental and sustainability management issues which are significant strengths. However, the current analysis is limited by the information provided in the strategic and operational plans of UPT and the engagement "Declaration of sustainability" of the rector (https://www.upt.ro/img/files/Sustenabilitate/Declaratie%20sustenabilitate%20(1).pdf) and the associated documents (https://www.upt.ro/Informatii_sustenabilitate-upt_2289_ro.html). To provide a truly comprehensive assessment of UPT's overall sustainability performance, further information is needed, especially regarding university-wide policies and initiatives in the following areas:

- Setting and infrastructure - Details on green building standards, sustainable campus planning, and land use. This would include information on green spaces, biodiversity, and sustainable construction practices across the entire university;
- Energy and climate change - Comprehensive data on energy consumption, sources of energy (renewable vs. non-renewable), greenhouse gas emissions, and specific climate action plans for the entire university. This would also include energy efficiency measures implemented in buildings and operations;
- Waste - University-wide waste management policies, waste reduction targets, recycling rates, composting programs, and initiatives to minimize hazardous waste;
- Water - Campus-wide water conservation strategies, water recycling and reuse initiatives, and efficient water management practices;
- Transportation - Policies promoting sustainable transportation (e.g., public transport incentives, cycling infrastructure, pedestrian-friendly campuses), data on commuting patterns, and efforts to reduce transportation-related emissions.

Finaly, recommendations for UPT to enhance its Sustainability Profile and UI GreenMetric Ranking are formulated and presented in the following:

1. A comprehensive plan that outlines clear goals, targets, and initiatives across all UI GreenMetric categories would provide a unified vision and facilitate coordinated efforts (e.g., University-Wide Sustainability Strategic Plan). This plan should involve all faculties, administrative departments, and student bodies;

2. Systematically collect data on all UI GreenMetric indicators across the entire university. This data should be publicly accessible, ideally through a dedicated sustainability report or website, to demonstrate transparency and progress. The data collection could be of great support for periodical reporting;

3. Invest in green building certifications for new constructions and renovations, enhance green spaces on campus, and implement sustainable landscaping practices that could support the promotion of green infrastructure having a positive impact on reducing the exploitation costs;

4. Set ambitious targets for renewable energy adoption and implement energy-saving measures across all university buildings and operations. Considering conducting regular energy audits is related to good practice of governance;

5. Implement robust waste segregation and recycling programs, explore composting initiatives, and aim for significant waste reduction through reuse and responsible consumption campaigns;

6. Install water-efficient fixtures, promote water-saving behaviors, and explore rainwater harvesting or

greywater recycling systems. These initiatives have been partially adopted and they support the water management initiative;

7. Develop and promote sustainable commuting options, such as improved public transport access, safe cycling routes, and electric vehicle charging stations. Consider car-sharing programs or incentives for eco-friendly transport for all members of the UPT community;

8. There is a strong need to integrate sustainability across a large variety of teaching subjects and curricula by encouraging faculties to integrate SD and CE concepts into their study and research programs, fostering a holistic approach to sustainability across the university;

9. Launch campaigns to raise awareness about SD and CE among students, staff, and the wider community. Organize events, workshops, and initiatives that promote sustainable practices, thus increasing public engagement and awareness.

By considering these recommendations, UPT can significantly strengthen its sustainability profile and improve its standing in international rankings like UI GreenMetric, further solidifying its role as a leader in environmental responsibility.

*4.1 Diagnosis of the Implementation of "Digital and Sustainable HEI to Raise Awareness of the Circular Economy" at Politehnica University of Timisoara*

This applicative study outlines how UPT can implement the methodological approach for "Digital and Sustainable HEI to Raise Awareness of the CE " based on the provided methodology (Fig. 2). There have been considered five key areas: digital learning platforms and open education resources (OERs), data analytics and visualization, smart campus technologies, gamification and citizen science, and interdisciplinary collaboration and stakeholder engagement. This analysis will assess UPT's current capabilities, primarily drawn from the Faculty of Industrial Chemistry and Environmental Engineering (FCIIM) strategic plan which has been considered by the top management team and extended at the organizational level, included in the strategic and operational plans of all faculties and administrative units. In addition, there will be proposed strategies for each component.

*1. Digital learning platforms and Open Education Resources (OERs) Current State at UPT*

In the strategic documents, there are mentions about the "widespread use of digital systems provided by the university" and the redesign of the university's website for better information dissemination and for mobile phones optimization. This indicates a foundational digital infrastructure and a recognition of the importance of online presence and digital tools in education. However, the plan does not explicitly detail the development of interactive online modules, simulations, VR experiences, or dedicated OERs and digital libraries specifically focused on SD and CE principles. Implementation Strategies for UPT:

- Develop CE-focused digital content - Create interactive online modules, simulations, and potentially VR/AR experiences that illustrate CE principles, sustainable development concepts, and real-world applications. These could be integrated into existing courses in environmental engineering, chemical engineering, and other relevant disciplines;

- Curate and create OERs - Establish a dedicated initiative to curate existing open educational resources related to sustainable development and CE. Simultaneously, encourage university teaching staff to develop new OERs, including case studies, best practices, and research findings from UPT, making them freely accessible to students and the wider community;

- Leverage Learning Management Systems (LMS) - Fully utilize the university's existing LMS (Moodle application update and customize for engineering education mainly which is so called the Virtual Campus) to host and deliver CE content. This includes embedding interactive modules, providing access to OERs, facilitating online discussions, and tracking student engagement with sustainability topics across various courses in different faculties and departments;

- Faculties members training and support (with the support of the Teaching staff training department) - Provide training and resources for faculties/departments members to develop and integrate digital learning materials and OERs into their curricula. This could include workshops on instructional design for online learning, tools for creating interactive content, and guidance on copyright and licensing for OERs;

- Promote digital libraries - Enhance the university library's digital resources to include a comprehensive collection of e-books, journals, and databases on sustainable development and CE. The UPT Central Library has started to an extend scale the process of digitalization using space online repository (https://dspace.upt.ro/jspui/) and the application PRIMO for OPAC (Online Public Acces Catalogue) (http://primo.upt.ro:1701/primo-explore/search?vid=40TUT_V1&sortby=rank&lang=ro_RO). These already created digital spaces in the library promote educational and research resources to students, teaching staff and researchers.

*2. Data Analytics and Visualization Current State at UPT (based on UPT Strategic Plan)*

The UPT strategic plan does not explicitly detail campus-wide data collection and analysis systems for resource consumption, waste generation, or carbon footprint. While the university likely collects some operational data, there is no mention of integrated systems or interactive dashboards for communicating sustainability performance. The focus of the strategic plan is more on academic and research objectives rather than operational sustainability data management. In this field, implementation strategies for UPT could consider the following recommendations:

- Implement campus-wide data collection - Establish a centralized system for collecting data on key sustainability indicators, including energy consumption (electricity, heating), water usage, waste generation (by type), recycling rates, and carbon emissions. This requires collaboration across various university departments (e.g., facilities, finance, student affairs);

- Develop interactive dashboards - Create user-friendly, interactive dashboards that visualize UPT's sustainability performance. These dashboards (that could be available online on the university web page) should be accessible to the university community and potentially the public, showcasing progress, identifying areas for improvement, and fostering transparency. This application could support the non-financial reporting/declaration regulation on HEI's Environmental, Social, and Governance (ESG);

- Utilize data for performance assessment - Employ data analytics to assess the effectiveness of SD and CE education and awareness campaigns. This could involve analyzing student engagement with CE-related courses, participation in sustainability initiatives, and changes in behavior (e.g., waste sorting habits; responsible consumption; green mobility etc.);

- Integrate data into research and teaching - Encourage students, technical staff and researchers to use campus sustainability data for projects, theses, and research. This provides real-world data for analysis and problem-solving, enhancing the practical relevance of their studies;

- Benchmark and set targets - Use collected data to benchmark UPT's sustainability performance against other HEIs (e.g., through UI GreenMetric which is the world universities ranking of green campus and environmental sustainability initiated by Universitas Indonesia, https://greenmetric.ui.ac.id/) and set ambitious, data driven targets for improvement in resource efficiency, waste reduction, and carbon footprint.

*3. Smart Campus Technologies Current State at UPT*

UPT's strategic plan mentions the widespread use of digital systems provided by the university and the importance of infrastructure. However, it does not specifically detail the deployment of smart sensors, IoT devices, digital platforms for waste sorting, or integrated building management systems for optimizing resource consumption. While a modern university would likely have some level of digital infrastructure, explicit smart campus initiatives related to circular economy are not evident in this specific strategic document of the university. Implementation Strategies for UPT in this field could include the following:

- Deploy smart sensors and Internet of Things (IoT) devices - Implement smart sensors and IoT devices across campus buildings and facilities to monitor resource consumption (electricity, water, gas), waste generation, and indoor environmental quality. This data can be used to identify inefficiencies, optimize resource use, and promote energy efficiency. Also, developing such infrastructure will be contributed to the smart and sustainable university concept development (Cavus et al., 2022; Kandil et al., 2025);

- Develop digital platforms for waste management - Introduce digital platforms or mobile applications to facilitate waste sorting and recycling on campus. These platforms could provide real-time information on waste streams, collection schedules, and recycling guidelines, thereby promoting closed-loop material flows and reducing contamination;

- Integrate Building Management Systems (BMS) - Enhance and integrate existing or new BMS to monitor and optimize energy consumption, water usage, and indoor climate control. A smart BMS can automate lighting, heating, ventilation, and air conditioning (HVAC) systems based on occupancy and real-time data, leading to significant resource savings;

- Smart Labs and research facilities - Equip laboratories and research facilities with smart technologies to monitor and manage resource-intensive processes, such as fume hoods, specialized equipment, and chemical storage. This can help reduce waste, optimize energy use, and improve safety;

- Pilot projects and demonstrations - Initiate pilot projects for smart campus technologies in specific buildings or areas to demonstrate their effectiveness and gather data for wider implementation. These projects can also serve as living labs for students and researchers.

Regarding the UPT Campus, a recent initiative of transformation is "UPT Creative Campus" (https://campuscreativ.upt.ro/) that can be considered a solution for SD on campus, although its primary focus is on cultural and social regeneration. This initiative has been defined and started in 2023, with the occasion and integrated in the "Timisoara, cultural capital of Europe" project. "UPT Creative Campus" explicitly states its care for nature and orientation towards a sustainable future. This direct commitment to sustainability is a strong indicator of its potential usefulness.

Furthermore, the initiative aims to regenerate the UPT campus as both a built and social space. This implies improvements to the physical infrastructure, which can encompass sustainable building practices, green spaces, and efficient resource management. Regenerating social spaces can also foster a sense of community and shared responsibility towards environmental goals. By engaging the university community through creative activities, the program can foster a sense of ownership and responsibility towards sustainability initiatives. Student-initiated and co-created activities promote active participation and can lead to behavioral changes that support sustainable practices on campus. The "UPT Creative Campus" program's emphasis on openness, inclusion, and multidisciplinarity in the educational process aligns with the idea of integrating sustainability across various disciplines and making it accessible to a wider audience. This has contributed to raising awareness and understanding of SD principles among students and staff. Concluding, "UPT Campus Creativ" acts as a catalyst for SD by integrating these principles into the campus's cultural and social fabric, fostering a sustainable mindset, improving the built environment, and engaging the community in these efforts.

*4. Gamification and Citizen Science Current State at UPT*

The UPT strategic documents emphasize student involvement in academic activities, scientific circles, and research mostly in connection with existing research centers in all faculties of UPT. It also encourages student participation in volunteer research activities related to different projects implementation. This indicates a culture of engagement and a potential foundation for gamification and citizen science initiatives (that has been intensified in the last three years because of UPT involvement in the European university network E³UDRES², https://eudres.eu/ and the related sub-projects and activities). However, there is no explicit mention of gamified applications, challenges, or citizen science projects specifically focused on SD or CE issues. Potential implementation strategies for UPT are:

- Develop gamified applications and challenges - Create engaging gamified applications or platforms that challenge students and staff to adopt sustainable behaviors. This could include competitions for reducing energy consumption, improving waste sorting, or promoting sustainable transportation or green mobility. Rewards, leaderboards, and progress tracking can motivate participation;

- Intensify citizen science projects – First discussions in this topic were startedwithin the E³UDRES² – Ent-re-novators project (https://www.entrenovators.eu/). Engage students and the wider community in citizen science projects related to SD and CE should be a strategic priority. These projects could involve data collection (e.g., waste audits, energy consumption monitoring, biodiversity mapping), analysis, and reporting, providing hands-on learning experiences and contributing to real-world research;

- Mobile Apps for Personal footprint tracking - Develop mobile applications that allow students and staff to track their personal environmental footprint (e.g., carbon emissions from transport, waste generated). These apps could also provide personalized tips and solutions for reducing their impact and promoting CE principles;

- Integrate into coursework - Incorporate gamification and citizen science activities into relevant courses, making them part of assignments or extra-curricular projects. This can enhance learning outcomes and foster a sense of responsibility towards sustainability;

- Intensify the collaboration with student organizations – UPT should establish strong and long-term partnership with existing student organizations as the Student Leagues existing in all faculties. The partnership should address SD and CE topics to design and implement gamification and citizen science initiatives, leveraging their enthusiasm and networks.

*5. Interdisciplinary Collaboration and Stakeholder Engagement Current State at UPT*

UPT strategic plan strongly emphasizes collaboration with academic, economic, and social environments at local, national, and international levels, being a "mundus vivendi" for UPT community. It highlights the development of interdisciplinary master's programs, alignment with European University Association (EUA) standards, and consultation with industry representatives for professional practice and research. This demonstrates a robust existing framework for interdisciplinary collaboration and stakeholder engagement, which can be leveraged for CE initiatives. Suggested implementation strategies for UPT:

- Establish an interdisciplinary CE Hub - Create a dedicated interdisciplinary hub or center focused on CE, bringing together researchers and educators from diverse academic fields (e.g., engineering, chemistry, economics, social sciences, design etc.). This hub would foster collaborative research, teaching, and knowledge exchange on CE;

- Generalization of integrating CE into diverse curricula - Encourage and support the integration of CE principles and case studies into curricula across all relevant disciplines, not just environmental engineering. This ensures that all UPT graduates have a foundational understanding of CE, regardless of their major;

- Continue strengthen industry partnerships for CE - Deepen engagement with industry partners, government agencies, and community organizations to develop collaborative projects, internships, and research focused on CE. This could involve co-creating solutions for waste reduction, resource efficiency, and sustainable product design;

- Organize workshops, seminars, and conferences - Regularly organize workshops, seminars, and conferences on CE topics, inviting experts from academia, industry, and government. These events would serve to disseminate knowledge, share best practices, and foster dialogue among stakeholders;

- Promote more SD and CE-focused research - Allocate more resources and incentivize research projects that address key challenges and opportunities in the SD and CE, particularly those with practical applications and potential for real-world impact. This strategic direction could be better supported by PhD students and their supervisor's research teams;

- International collaboration - Leverage existing international partnerships (e.g., Erasmus+) to collaborate with other HEIs on SD and CE-related research, student exchanges, and joint educational programs, fostering a global perspective on circularity.

*6. Conclusions of the analysis*

UPT, with its strong foundation in engineering and a demonstrated commitment to environmental education, is well-positioned to implement the methodological approach for "Digital and Sustainable HEI to Raise Awareness of the CE". By strategically investing in digital learning platforms, data analytics, smart campus technologies, gamification, and by strengthening interdisciplinary collaboration and stakeholder engagement, UPT can significantly enhance its role as a leader in promoting CE principles and fostering a more sustainable future. The key will be to move beyond faculty-specific initiatives to a university-wide, integrated approach, leveraging its existing strengths and embracing digital innovation to drive circularity.

## V. CONCLUSIONS AND FINAL REMARKS

### *5.1 General Conclusions*

HEIs must align their strategies with broader sustainability goals. Universities should adopt structured approaches, establish clear governance policies, and collaborate with external stakeholders to maximize their contributions to CE and sustainable development. These conclusions emphasize the transformative role of universities in driving sustainability and CE adoption while leveraging digital technologies for greater impact.

As discussed in the paper, HEIs are essential players in promoting the SD and CE. They must serve as hubs for education, research, and practical implementation of CE principles. By integrating sustainability into their operations and curricula, they can foster future professionals who are aware of circular strategies. Furthermore, the presented study considered digital technologies as enhancing sustainability awareness and implementation in HEIs. Advanced tools like IoT, AI, blockchain, and digital learning platforms enable universities to manage resources more efficiently, track sustainability metrics, and educate students in innovative ways. Thus, a holistic framework is required for successful CE integration in HEIs.

The study proposes a structured approach that combines governance, interdisciplinary education, campus infrastructure, stakeholder engagement, and digital solutions to ensure impactful CE transitions. These are parts of the proposed designed “holistic framework for digital and sustainability solutions in higher education to raise awareness of the CE”. Further, a research methodology for the diagnosis (monitor and control) of the proposed holistic framework implementation has been proposed, tested and validated using the case of Politehnica University of Timisoara (UPT) from Romania.

The applicative research has been developed in two stages. First, UPT’s Sustainability@UPT initiative has been assessed using the UI GreenMetric World University Rankings; by analyzing its implementation, the study highlights the best practices and areas that need improvement to create a truly circular university environment. Second, a diagnosis analysis has been developed for UPT showing the degree of implementation of “Digital and Sustainable HEI to Raise Awareness of the CE” demonstrating the need for additional efforts to be done for embracing digital innovation to drive circularity.

The implementation of these digital and sustainability solutions provided by different projects implemented at UPT, Romania demonstrating the following implications (supported by qualitative and quantitative results):

- Enhance awareness and understanding of sustainable development and CE principles among students and staff;
- Promote the adoption of sustainable behaviors and practices within the campus community and demonstrating the idea of Creative Campus of UPT;
- Integrate and transfer knowledge and wisdom (generated from the Erasmus+ projects implementation and other type of projects of Politehnica University of Timisoara, Romania) into curriculum development and research activities;
- Improve the efficiency and sustainability of campus operations;
- Foster interdisciplinary collaboration and stakeholder engagement;
- Generate data-driven insights to inform CE policy and decision-making;
- Increase the number of graduates (from Bachelor, master and PhD study programs) having a strong understanding of sustainability management and how to implement CE principles in their future professional life.

The added value of research focusing on digital and sustainability solutions in higher education for circular economy awareness is multifaceted, contributing to both academic advancement and real-world impact. Here's a breakdown of key areas: (1) Enhanced educational practices (innovative pedagogy; syllabus, and curriculum development); (2) Improved sustainability performance (via data-driven decision-making; smart campus innovation); (3) Societal and economic impact (strongly supporting behavioral change; knowledge dissemination; advancing in SD and CE research). This research bridges the gap between theory and practice, providing valuable insights and tools for HEIs to become catalysts for SD and CE transition.

### *5.2 Limits of Study. Future Research*

The study primarily focuses on UPT as a case study. While it provides valuable insights, the findings may not be fully generalizable to other universities with different governance structures, resources, or regional contexts. More testing and validation of the proposed methodology and framework are needed with other types of HEIs/universities. In addition, the research proposes a holistic framework (Fig. 1, Table 1), its practical validation is primarily based on UPT’s Sustainability@UPT initiative. Broader empirical studies across multiple higher education institutions would be needed to test the framework’s effectiveness at a larger scale. This could be the subject of future research.

Related to the digital transformation challenges, the study acknowledges the role of IoT, AI, and blockchain, but does not explore the technical, financial, and organizational challenges that universities might face in adopting these technologies. These could be the subject of other collaborative studies focused on digital solutions for SD and CE practices in HEIs/universities.

Another limitation of the presented research is related to the behavioral and cultural aspects. The study does not deeply investigate students' and faculty's behavioral changes, attitudes, or resistance toward CE principles, which could influence implementation success. These aspects are subject of the actual implementation project EDU4PlastiCircular (https://microplastics.today/) exploring the change behavior of students and teaching staff of UPT and other universities, considering the topic of plastic circularity. Thus, we suggest that behavioral and cultural aspects should be addressed and investigated in relation to different topics of SD and CE.

Finally, future longitudinal analysis to measure long-term effectiveness and sustainability of the proposed "holistic framework for digital and sustainability solutions in higher education to raise awareness of the CE" should be developed. Also, while the study provides a solid foundation for digital sustainability solutions in higher education, addressing these limitations in future research could enhance its practical application and impact.

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# Circular Economy Principles Applied to the Recycling of Used Cooking Oil: The OilRight Case Study

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**Abstract -** The transition from linear to circular economic systems represents a key strategy for reducing waste, improving resource efficiency, and supporting sustainable development. Used Cooking Oil (UCO) is a common waste stream generated by households, restaurants, and the food industry, yet it represents a valuable secondary resource for the pro-duction of biofuels, biochemicals, and other value-added products. Improper disposal of UCO leads to environmental pollution, sewer blockages, and increased wastewater treatment costs. This paper explores how circular economy principles can be applied to the collection and recycling of UCO, focusing on the local initiative OilRight in Timișoara, Romania.

**Keywords:** circular economy; used cooking oil; waste management; biodiesel; sustainability; Oil-Right; community engagement.

## I. INTRODUCTION

The circular economy has emerged as a central concept in sustainable development strategies. Un-like the traditional linear economic model based on extraction, production, consumption, and disposal, the circular economy aims to keep materials and re-sources in productive use for as long as possible. This is achieved through strategies such as reuse, recycling, repair, and regeneration.

Food-related waste streams represent an important opportunity for circular transformation. Among them, used cooking oil (UCO) is particularly relevant because it is generated in large quantities by households, restaurants, and food processing industries. Despite its potential as a resource, UCO is frequently disposed of improperly, often poured into sinks or drainage systems.

Improper disposal can cause severe environmental problems. When oil enters sewage systems it solidifies and forms blockages, increasing maintenance costs for municipal infrastructure. Additionally, even small quantities of oil can contaminate large volumes of water, affecting aquatic ecosystems.

However, when collected and processed correctly, UCO can be transformed into biodiesel, bio-lubricants, soaps and detergents, candles, and other products. This makes it an important element in circular economy systems that transform waste into valuable resources. This paper investigates how circular economy principles can be applied to the recycling of UCO through local initiatives. The research focuses on OilRight, a community-based initiative operating in Timișoara, Romania.

## II. CIRCULAR ECONOMY FRAMEWORK

### *2.1. General Considerations*

The circular economy concept has gained increasing importance in policy frameworks and academic research. It is built upon three fundamental principles: eliminating waste and pollution, circulating products and materials, and regenerating natural systems.

In the European Union, circular economy strategies are strongly connected to climate neutrality goals and resource efficiency policies. Waste streams that were previously considered environmental liabilities are now viewed as potential resources.

Waste oils represent a particularly suitable material for circular valorization. Unlike many other waste streams, oils maintain their chemical properties even after use, allowing them to be transformed into a wide range of products. Biodiesel production from UCO is one of the most common examples.

Beyond energy production, UCO can be used to manufacture soaps, lubricants, surfactants, and other industrial materials. Advances in biotechnology have

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also opened possibilities for transforming waste oils into bioplastics and green chemicals.

The circular management of UCO requires efficient collection systems, public awareness, and supportive policy frameworks. Community participation is especially important for household-level waste streams, where behavioral change plays a major role.

*2.2. Environmental Impacts of Improper Uco Disposal*

Improper disposal of used cooking oil generates several environmental problems. One of the most common issues is the formation of fat deposits in sewer systems. These deposits can accumulate with other waste materials to form large blockages commonly known as "fatbergs."

Such blockages require costly maintenance and cleaning operations for municipal utilities. In some cases, sewer overflows can occur, leading to contamination of nearby water bodies.

Another important impact relates to water pollution. Oil forms a thin film on water surfaces that limits oxygen transfer, affecting aquatic life. Even small quantities of oil can therefore have significant eco-logical consequences.

Furthermore, when oil enters wastewater treatment plants, it increases operational complexity and costs. Removing oils from wastewater requires additional treatment steps and energy consumption.

For these reasons, proper collection and recycling systems for UCO are essential components of sustainable urban waste management.

## III. METHODOLOGY

The research combines literature review, case study analysis, and examination of international practices in UCO recycling.

The literature review focuses on academic publications related to circular economy, waste oil recy-cling, and sustainable waste management systems. Additional information was obtained from public reports, environmental organizations, and industry sources.

The case study method was chosen to examine how circular economy principles can be implemented at a local level. OilRight was selected as the main case study due to its innovative approach to community engagement and environmental education.

Comparative analysis was also conducted using examples of international companies operating in the UCO recycling sector. These examples help identify best practices and potential development pathways for similar initiatives.

Results highlight the importance of community engagement, educational programs, and partnerships between municipalities, NGOs, and private sector actors. The study also proposes innovative directions for expanding UCO valorization, including urban biodiesel production, circular cosmetics, bioplastics, and digital waste-collection platforms. The findings demonstrate that local initiatives such as OilRight can play a significant role in advancing circular economy models and promoting civic participation in sustainable waste management.

## IV. CASE STUDY: OILRGHT

OilRight is a community initiative (Fig. 1) based in Timișoara that promotes the collection and recycling of used cooking oil from households and restaurants. The initiative aims to reduce environmental pollution while increasing public awareness about responsible waste management. It transforms it into value-added products, such as scented candles and feedstock for biodiesel production.

The social enterprise encourages citizens to collect their used oil in plastic bottles and bring it to designated collection points. These collection points are often located in populated neighborhoods, com-munity centers, or partner institutions.

OilRight combines environmental education with practical infrastructure. Workshops, school activities, and public events are organized to inform citizens about the environmental impact of improper oil disposal.

One of the strengths of the initiative is its focus on community participation. Instead of relying solely on institutional actors, OilRight empowers citizens to become active contributors to environmental protection.

The initiative also builds partnerships with local organizations, NGOs, and authorities. Such collaborations are essential for scaling circular economy initiatives and ensuring long-term sustainability.

The organization applies circular economy principle, including waste valorization, resource efficiency, and closed-loop material flows, to convert a problematic household and commercial waste stream into economically and environmentally beneficial out-puts.

The process begins with the collection of UCO. In conventional linear systems, used cooking oil is frequently discarded through sewage systems or mixed municipal waste streams, contributing to water contamination, infrastructure blockages, and in-creased wastewater treatment costs. OilRight intervenes at this stage by establishing localized collection networks and awareness campaigns that encourage responsible disposal practices. By capturing UCO before it enters the waste stream, the organization effectively redirects a pollutant into a productive material cycle.

*Fig. 1. The logo of the initiative*

Once collected, the oil undergoes sorting, filtration, and basic purification processes designed to remove food residues, water content, and other contaminants. This preparation stage is essential to ensure the suitability of the oil for downstream valorization processes. After pretreatment, the collected UCO is allocated into two primary resource streams based on quality and processing requirements.

The first stream involves the upcycling of UCO into scented candles. In this process, treated oil is blended with natural waxes to produce decorative and functional candles. This transformation exemplifies the circular economy principle of product value retention, where a waste material is reintegrated into the market as a consumer product with higher added value. By extending the life cycle of the original resource, OilRight reduces the demand for virgin raw materials typically used in candle manufacturing, such as paraffin derived from petroleum. Additionally, the candle production process is designed to operate at small scale and can support inclusive employment opportunities, reinforcing the social dimension of circular economy practices.

The second resource stream directs collected UCO toward biodiesel production through partner-ships with specialized processing facilities. Biodiesel is produced via transesterification, a chemical reaction in which triglycerides contained in the oil react with an alcohol (commonly methanol) in the presence of a catalyst to form fatty acid methyl esters (FAME), the primary component of biodiesel. In this context, UCO serves as a renewable feedstock, re-placing virgin vegetable oils or fossil-based fuels in energy production systems. The resulting biodiesel can be used as a cleaner-burning alternative to conventional diesel, contributing to reductions in green-house gas emissions and supporting the transition toward more sustainable energy systems.

Through these parallel valorization pathways, OilRight creates a multi-loop circular model that maximizes resource recovery from UCO. Lower-grade oils are directed toward energy production, while higher-quality fractions can be utilized in consumer product manufacturing. This cascading use of materials aligns with circular economy frameworks that emphasize maintaining resources at their highest possible value for as long as possible.

Beyond material transformation, OilRight also contributes to behavioral and systemic change within the urban waste management ecosystem. Public awareness campaigns and community engagement initiatives educate citizens about the environmental impacts of improper oil disposal and promote participation in collection programs. These educational efforts strengthen the upstream component of the circular system by increasing resource recovery rates and improving the quality of collected materials.

From a sustainability perspective, the OilRight model generates multiple environmental benefits:

- Reduction of water and soil pollution caused by improper oil disposal;
- Diversion of waste from sewage systems and landfills;
- Substitution of fossil-derived materials in candle production;
- Provision of renewable feedstock for biodiesel production.

Moreover, the initiative integrates social inclusion into circular economy practices by creating employment opportunities for individuals from vulnerable groups and fostering community participation. This integration reflects the emerging concept of the social circular economy, where ecological resource management is combined with social value creation.

In summary, OilRight demonstrates how decentralized collection systems, community engagement, and multi-pathway resource valorization can operationalize circular economy principles in the management of used cooking oil. By transforming waste into both consumer goods and renewable energy feedstock, the organization illustrates a scalable model for closing material loops while simultaneously generating environmental, economic, and social value.

## V. CONCLUSIONS AND FINAL REMARKS

The OilRight case study demonstrates how local initiatives can contribute to (social) circular economy transitions. While large industrial actors play a crucial role in processing waste streams, community-based initiatives are essential for collection and awareness.

The integration of education, civic engagement, and practical infrastructure represents a powerful approach to promoting sustainable behaviors. By encouraging citizens to participate in waste collection, initiatives like OilRight strengthen environmental responsibility at the community level.

Expanding circular applications of UCO will require collaboration between municipalities, private companies, educational institutions, and citizens. With appropriate policies and innovative business models, UCO recycling can become an integral part of sustainable urban ecosystems. However, scaling such initiatives requires, beyond policy support, financial resources, and partnerships with industry actors capable of processing collected materials.

Future research could explore quantitative assessments of environmental benefits, including re-ductions in water pollution or greenhouse gas emissions associated with UCO recycling systems.

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