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PLENARY SESSION

The Interplay between Economic (In)security and Human Well-being in the 21st Century

Laura Diaconu (Maxim)[1]

Abstract

While well-being is the utmost human desiderate, economic insecurity has generally been related to poverty and inequality, reason for which it can be considered an essential determinant of the human well-being. In this context, researchers from various fields of studies tried to investigate the link between economic (in)security and human well-being. While the economists focused on the income levels and employment status as proxies for individual welfare, the psychologists and sociologists furthered this link, considering that the perceived risk of income loss, job instability and inadequate access to social safety nets have significant negative effects on mental health and life satisfaction. Despite the growing body of literature linking economic (in)security to human well-being, there is still a critical need for further research in order to highlight the evolution of this relationship in the context of the challenges occurred in the 21st century. Therefore, the purpose of the present paper is to analyse the impact of the economic (in)security on several dimensions of the human well-being, including mental health, life satisfaction and perceived social cohesion, in the context of the long-term effects of the COVID-19 pandemic and of the geopolitical instability from the beginning of the 21st century.

Keywords: Well-being, economic security, COVID-19 pandemic, geopolitical instability.

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While Europe Regulates, America Innovates: Can EU Businesses Keep Up in the Age of AI?

Neringa Gaubiene[1] Rita Remeikienė[2]

Abstract

As the EU enacts the world's first comprehensive AI regulation (the AI Act), the U.S. and China continue to prioritize rapid AI innovation and commercialization. This research examines the growing divide between governance and growth, asking: Can European businesses remain globally competitive while meeting strict compliance demands, and what is the EU doing to support them? To balance regulation with innovation, the EU launched the AI Continental Action Plan in 2025, focusing on five pillars: computing infrastructure, high-quality data, AI adoption in key sectors, skills development, and regulatory streamlining. Through the InvestAI initiative, €200 billion will be mobilized to support AI development, including €20 billion for up to five AI gigafactories — large-scale data centers equipped for frontier model training. These efforts build on existing infrastructure like 13 EuroHPC AI Factories and newly established Data Labs. The plan also promotes AI adoption in sectors like health, climate, and mobility, while enhancing AI literacy and cross-functional skills. Regulatory simplifications — such as a proposed Cloud & AI Development Act and the AI Act Service Desk — aim to reduce burdens and encourage private sector uptake. Ultimately, regulatory rigor can be both a strength and a challenge. The key lies in empowering European companies to not just comply, but to strategically adapt and lead in responsible AI — turning regulation into a competitive advantage.

Keywords: AI Act, AI Literacy, Responsible AI, Innovation vs Regulation, EU Competitiveness

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ABSTRACTS

Mitigating Agricultural Catastrophic Risks: A Global Analysis of Insurance Solutions and Policy Frameworks

Marius Dan Gavriletea[1] Alexandru Gruia[2]

Abstract

The global agricultural sector faces increasingly complex and catastrophic risks driven by climate change, economic instability, and geopolitical factors. This paper explores the diverse range of catastrophic risks impacting agriculture worldwide, including extreme weather events, pest infestations, and market fluctuations. We examine the effectiveness of current agricultural insurance frameworks in mitigating these risks, highlighting challenges in policy design, coverage accessibility, and financial sustainability. Through a comparative analysis of regional approaches to agricultural insurance, we identify the best practices and propose innovative solutions to improve resilience and protect livelihoods. Ultimately, this research underscores the urgent need for adaptive insurance models that can respond dynamically to the evolving nature of agricultural catastrophes and provide comprehensive safety nets for farmers across the globe.

Keywords: Agricultural catastrophic risks, insurance sector.

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AI-Driven Sustainability in Tourism - A Smart Future for Montenegro

Marica Melović[1]

Abstract

Artificial intelligence (AI) plays a pivotal role in advancing sustainable tourism in Montenegro by harnessing technological innovations to preserve cultural heritage, optimize resource management, and enhance tourist experiences. As tourism remains a vital contributor to Montenegro's GDP, the integration of AI solutions presents an opportunity to overcome existing challenges and stimulate sustainable growth. Emerging technologies such as generative AI and intelligent automation can support cultural preservation, environmental protection, and personalized services for visitors. Furthermore, the synergy of AI and the Internet of Things (IoT) paves the way for the development of smart tourism destinations, enabling data-driven decision-making and efficient travel planning. These advancements not only elevate the quality of tourist services but also improve the well-being of local communities and contribute to the long-term economic and ecological sustainability of tourism. By positioning AI as a catalyst for smart and green tourism, Montenegro can accelerate its transition towards a more resilient, innovative, and sustainability-oriented tourism model, in line with its smart specialization strategy and broader development goals.

Keywords: Artificial intelligence, sustainable tourism, smart tourism, Montenegro.

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The Role of Artificial Intelligence in Personalized Brand Communication

Boban Melović[1] Savica Vujičić[2]

Abstract

Artificial Intelligence (AI) is increasingly transforming how brands communicate with consumers, enabling real-time personalization, automation of communication processes, and deeper insights into user needs. The aim of this research is to analyze how AI influences the development of modern brand communication strategies, focusing on hyper-personalized content, customer experience optimization, and trust-building. Special attention is given to the potential of AI in market segmentation, predictive consumer behavior modeling, and tailoring brand messages to individual preferences. The originality of this paper lies in linking brand personalization with the evolution of advanced algorithms and automated systems that allow one-to-one communication. The methodology includes an analysis of recent literature, case studies of global brands that apply AI in communication, and a consumer survey on perceptions of personalized brand approaches. The results show that AI-based branding increases engagement, loyalty, and customer satisfaction, while also raising concerns about ethics, transparency, and data protection. The conclusion emphasizes that continuous investment in AI technologies, alongside the development of ethical frameworks for their use, is crucial for maintaining competitive advantage in the digital marketplace.

Keywords: Brand communication, artificial intelligence, personalization, digital marketing, customer experience.

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The Impact of the Platform Economy on Gender and Social Inequalities

Rita Remeikienė[1]

Abstract

The digital labor economy reflects the same inequalities present in the traditional labor market, including gender disparities. Numerous studies show that the gender wage gap continues to exist on digital labor platforms. Additionally, women in the platform economy often find themselves in roles traditionally associated with 'feminine' work, such as teaching and domestic services. Gender differences in working patterns are a significant driver of the wage gap (Adams-Prassl, et. al., 2023). Women are more likely to interrupt their working time on the platform with consequences for their task completion speed. Online marketplaces can actually reinforce gender stereotypes. In a digital environment where information and time are limited, employers may rely on stereotypes when making hiring decisions - for example, choosing women for writing and translation jobs but not for software design roles.

The statement that "the digital labor economy reflects the same inequalities that exist in the traditional labor market" is based on the observation that digital labor platforms often reinforce existing disparities rather than eliminate them. In response to the question of how digital labor platforms shape workers' experiences and why they may generate additional inequalities, we present the ways in which digital labor platforms increase differences among workers:

1. Reinforcement of Existing Inequalities. For example, individuals from privileged backgrounds are more likely to have access to the skills, resources, and networks necessary to succeed on digital platforms. This can perpetuate social, racial, and gender inequalities that already exist in the traditional labor market. Additionally, individuals with higher education may occupy higher-paying positions, while those with lower educational attainment face limited opportunities and lower wages.
2. Algorithmic Bias and Discrimination. In cases where platform algorithms prioritize workers with positive ratings, new entrants or those belonging to ethnic minorities, immigrant groups, or individuals with disabilities may find it more difficult to obtain jobs. Negative reviews can also disproportionately affect certain demographic groups, limiting their job opportunities.
3. Independent Contractor Status. Many digital labor platforms classify workers as independent contractors, which denies them access to benefits typically afforded to traditional employees, such as health insurance, unemployment benefits, and retirement savings. This classification often adversely impacts lower-income workers, as well as women planning to take maternity leave. Gig workers lack collective bargaining power, making it harder for them to negotiate better working conditions.
4. Job Insecurity. The gig economy's reliance on short-term contracts creates a sense of insecurity, making it challenging for workers to achieve financial stability and obtain bank loans or mortgages.

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5. Mental Health. The constant need to meet performance metrics and maintain high ratings can lead to stress and anxiety. Workers may feel compelled to overwork, leading to burnout.
6. Lack of Digital Literacy. Workers need to be able to navigate technology, which can disadvantage those with lower digital literacy or access to technology, particularly older adults or those from lower socioeconomic backgrounds. Jobs requiring specialized skills may be inaccessible to all, further entrenching disparities as some workers may lack the necessary qualifications.

While digital labor platforms provide new opportunities for workers, they also reflect and exacerbate existing inequalities found in traditional labor markets.

Article aims to investigate how the platform economy affects gender and social inequalities in the specific contexts of Moldova and Lithuania. By focusing on these two countries, we will examine the unique ways in which digital labor platforms shape the experiences of workers, particularly in relation to gender dynamics and broader social disparities. Our study will explore into the challenges faced by public policies as they attempt to address issues such as the formalization of work, fair remuneration, the quality of working conditions, and the social protection of workers operating within digital platforms. Additionally, we will also look at how the platform economy either continues or worsens existing inequalities in these areas. Additionally, we'll consider what this means for future policy development and implementation. Through this research, we hope to provide valuable insights that can inform more fair and inclusive policy responses in the rapidly evolving digital labor market of Moldova and Lithuania.

Online platform work, and freelancing in general, is not yet widespread in the Republic of Moldova. As noted in a report by the World Bank, relatively few Moldovans – especially those residing outside Chisinau – use the internet for economically productive purposes (Guvernul Republicii Moldova, 2020). The main reason for this is related to the fact that Moldova is one of the lower ranked countries in terms of its Digital Readiness Index score, positioned in 80th place out of 146 countries in 2021. Nonetheless, there are signs that this situation is changing gradually.

Neither platform work nor freelancing activities in general are recognised or regulated in the Republic of Moldova yet. In the absence of specific legal provisions to recognise freelancing activities, potential employers/clients and Moldovan workers have several options to declare their economic activities:

• Employment contracts (Contract individual de muncă), regulated under the Labour Code. However, the Moldovan Labour Code is considered to be one of the most protective for employees in the region and is generally seen as providing strong protections for traditional forms of employment. However, the same level of protection is unlikely to be extended to individuals working in the gig economy or in other forms of non-standard employment. This fact can create challenges for workers in the economy platform, as they may not be covered by traditional employment protection in such areas as minimum wage, working time, rest periods, social security benefits, and collective bargaining rights. Additionally, the legal framework for the economy platform in Moldova not be well developed, leading to uncertainty for both workers and platform providers. As the economy platform continues to grow in Moldova and other countries, it is important for policymakers to consider the specific needs of workers in this sector, and to take steps to ensure that they have access to appropriate protections and benefits. This may involve updating existing labour laws and regulations, or developing new frameworks specifically designed for the economy platform.

• Registration as an individual entrepreneur (Intreprindere Invidivuala), regulated under the Civil Code. This option is unattractive to platform workers due to the high administrative burden of setting up an individual enterprise, as well as higher taxes (a level similar to taxes paid by legal business entities).

• Service agreements (Contract de prestări servicii) governed by the provisions of the Civil Code. Both for platforms and platform workers, these are associated with several disadvantages. The tax rates are very similar to those applied to income from economic activities under employment contracts (so, there is no economic incentive to prefer them over an employment contract, which exists in most other countries). However, unlike the employment contract, a service provider is not entitled to social benefits, such as annual /medical leave, a pension calculated on the salary paid.

Many platform workers in Moldova, particularly those who offer remote services, may operate in the "grey" sector of the country's economy. This refers to the informal or unregulated sector of the economy, where workers do not have access to the same protection and social benefits as those in the formal sector. In the case of platform workers, this often means that they are not covered by the country's labour laws or social security systems, and may not have access to benefits such as minimum wage laws, overtime pay, and paid leave. Additionally, they may face challenges in securing payment for their services, as they do not have the same legal protection as traditional employees. This situation can create a number of risks and challenges for platform workers in Moldova, including income insecurity, limited access to social benefits, and exposure to exploitation and abuse. It also raises broader questions about the need to regulate the economy platform and ensure that platform workers have access to adequate protections and benefits. This is consistent with the general direction of the labour market in Moldova. For instance, the ILO estimates that in Moldova, 32.5% of those who were employed in 2014 worked mostly in the informal sector (Popa et. al., 2016). Transport, art and recreation, and professional services - activities typical of platform work- were some of the sectors with notable levels of informality. Furthermore, 74.5% of the self-employed were employed informally. Due to their inability to take use of privileges given by Moldovan legislation under employment contracts and the possibility of Moldovan tax inspections, this group of workers is at a disadvantage.

In order to combat the informal labor market, the EC on 22 March 2021 adopted Council Directive (EU) 2021/514 amending Directive 2011/16/EU on administrative cooperation in the field of taxation. Before the adoption of the directive, the most relevant areas for EU member countries were housing rental platforms (AirBnb, Booking) and transportation platforms (Uber, Taxify/Bolt).

If we look to Lithuania, this problem was partially solved by changing the Road Transport Code of the Republic of Lithuania, which from 2020 obliged operators of shuttle platforms operating in Lithuania, i.e. including foreign registered platforms Uber, Bolt) to provide the tax administrator with data on the income of the drivers. After the implementation of the requirements of this legal act, the declared income of persons engaged in the activity of couriers increased significantly: in 2017 - 6 million EUR, 2018 - 14 million EUR, 2019 - 19 million EUR, 2020 - 51 million EUR, 2021 79 million EUR, 2022 - 86 million Eur. According to the data of Tax Disputes Commission under the Government of the Republic of Lithuania violations are still detected during control actions, e.g. in 2021, throughout Lithuania, 21 control actions were carried out related to the operation of the Shuttle service. 26 violations of legal acts were identified during the control actions of the taxi service. A specific problem in this area can be singled out: a foreigner who has performed activities lives in Lithuania for a short time, performs activities after registering an individual activity, but when the declaration deadline is due (May 1 of the following year) no longer lives in the country, does not declare income and does not pay resident income tax. Cases are also identified when individuals do not declare and pay VAT on commissions paid to platforms registered abroad, cases are identified when individuals transfer/rent cars registered in their name on the platform to other individuals without notifying the platform, thus having to pay taxes on income earned by other persons etc[2].

Since 2004, Lithuania has been a member of the European Union with a developed economy and technology sector, while Moldova (an EU candidate member) is still grappling with many economic challenges. Comparing these countries will allow us to analyze how different economic contexts influence the development of digital labor platforms and workers' experiences. In both countries, an increasing number of young people are seeking job opportunities through digital platforms, so the comparison will reveal how demographic factors, such as age and education, affect workers' success in the digital economy. The labor market in Lithuania is more strictly regulated, while Moldova is still striving for transparency and lower corruption in labor market relationships. The comparison can help understand how different policies and legal regulations shape the dynamics of the digital labor market and protect workers' rights.

Keywords: Platform economy, gender inequalities, social inequalities.

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Ethics and Artificial Intelligence in Supply Chain Management: Theoretical Considerations and Practical Challenges

Wanja Wellbrock[1] Margarita Malinovska[2] Daniela Ludin[3]

Abstract

The integration of artificial intelligence (AI) into supply chain management (SCM) practices has the potential to increase operational efficiency, optimize decision-making, and improve overall supply chain resilience. However, the increasing reliance on AI-driven systems also raises significant ethical concerns, particularly with regard to bias, transparency, explainability, and data protection. This paper systematically examines the interface between AI and ethics in SCM by analysing both theoretical considerations and practical challenges.

Based on a comprehensive literature and case study review, the paper analyses AI applications in four key areas of SCM: procurement, production planning, quality control, and predictive maintenance. The published case studies show how AI-driven systems contribute to process automation, cost reduction, and improved decision-making. However, they also reveal critical ethical problems, including non-transparent decision-making processes, algorithmic biases that can reinforce existing inequalities, and potential violations of data protection regulations. In addition, the findings show that there is often a lack of sufficient regulatory transparency in the implementation of AI, which can lead to trust deficits among stakeholders.

The study highlights that despite AI`s transformative potentials for SCM, its deployment requires carefully designed governance frameworks that ensure ethical integrity. To address these challenges, transparent AI models, bias mitigation strategies, and improved regulatory compliance measures must be developed. In addition, promoting AI literacy among supply chain professionals is critical to ensure responsible and informed decision-making practices. Future research should examine sector-specific ethical implications and develop standardized methods to assess the impact of AI on supply chain ethics and governance.

Keywords: Artificial intelligence, supply chain management, ethics, transparency, case study analysis.

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FULL PAPERS

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Explainable AI for Sustainable Engineering: Interpreting Cementitious Waste Mixtures based on UCS for Economic and Social Impact

Ayşe Nur Adıgüzel Tüylü[1]

Abstract

Today, artificial intelligence (AI) is transforming traditional engineering practices into more efficient and technologically advanced ones by enabling data-driven, efficient, and transparent decision-making processes. In this study, we aimed to demonstrate the social and economic impacts of explainable AI (XAI) in the sustainable design of cementitious materials derived from mining waste.

Using an interpretable XGBoost model enhanced with SHAP analysis, we analyze how key mix parameters such as curing time, cement dosage, and fly ash types affect the uniaxial compressive strength (UCS) of environmentally friendly binders. The model demonstrates strong performance ($R^2 = 0.871$), and the insights provided by XAI highlight the most influential factors in AI development. This not only supports technical optimization but also strengthens stakeholder confidence in AI-enabled systems by enabling stakeholders to understand why certain mixes perform better.

From an economic perspective, this approach increases resource efficiency by reducing cement content, one of the most carbon-intensive materials, without compromising performance. The reuse of fly ash and other industrial byproducts enables cost-effective solutions that align with circular economy principles.

From a social perspective, XAI promotes transparency and accountability in engineering decisions, making AI tools more accessible and acceptable to policymakers, practitioners, and local communities. This is particularly critical in sustainability-focused sectors where public trust and evidence-based justification are crucial.

By combining engineering performance with economic viability and social validity, this study demonstrates how XAI can play a significant role in shaping sustainable infrastructure development in the AI era.

Keywords: Sustainable engineering, mining waste management, recycling of mining waste

1. Introductionş

Today, engineering practices within the framework of sustainability have entered a rapid transformation process, driven by the goals of reducing negative environmental impacts, using resources more efficiently, and complying with circular economy principles. In this transformation, artificial intelligence (AI) technologies are creating data-driven decision support systems, making engineering processes more efficient, flexible, and optimized. Explainable AI (XAI), in particular, creates transparency between expertise and social acceptance, making it possible to make complex model outputs understandable and interpretable.

In the development of sustainable backfill materials, the search for alternative raw materials is gaining prominence to reduce the negative environmental impact of traditional binders. Transforming waste from mining activities into sustainable backfill materials offers an important solution for both waste disposal and reducing carbon emissions. Due to their high content of silicates, aluminates, and other pozzolanic components, mining waste can acquire binding properties through appropriate activation methods and can be used as a cement substitute.

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Uniaxial compressive strength (UCS) is one of the mechanical properties critical to the performance evaluation of such materials, and it is a fundamental criterion for the safety and durability of the product to be used as a construction material in engineering applications. Accurate and reliable estimation of the UCS value is strategically important for both reducing experimental costs and accelerating the material design process. However, interpreting the complex data obtained in such material designs directly impacts the reliability of decision support systems. This is where XAI comes into play.

This study develops an XGBoost-based machine learning model to predict the UCS performance of cement-based backfill mixtures and to make this estimation process explainable. It visualizes the model's decision-making processes using SHAP (SHapley Additive Explanations) analysis. This aims to contribute holistically to the engineering design process at economic, social, and environmental levels by ensuring not only technical accuracy but also the interpretability of model outputs.

2. Background and Literature Review

2.1 Mining Wastes and Sustainable Binding Material Development

The mining industry generates a large amount of waste with a high environmental impact. Wastes such as fly ash exhibit pozzolanic properties due to their high content of silica, alumina, and other oxides. However, these wastes are generally unsuitable for direct use due to their low reactivity, heterogeneous structure, and high heavy metal content.

The production of traditional binders results in both high energy consumption and significant carbon emissions (CO_2). In this context, utilizing mining wastes as cement additives or substitutes is strategically important for both waste disposal and reducing the carbon footprint. Appropriate activation methods (mechanical, chemical, and thermal) can improve the binding properties of these wastes and enhance their strength performance. However, performance prediction of such systems is limited by conventional methods due to their multivariable and nonlinear relationships.

2.2 Explainable Artificial Intelligence (XAI)

Machine learning (ML) and deep learning algorithms are increasingly being used to develop predictive models based on multivariate and large datasets. However, the "black box" nature of these models makes their outputs difficult to interpret and reliable. Explainable Artificial Intelligence (XAI) methods, developed to overcome this problem, provide transparency and accountability, particularly in engineering and materials science applications.

SHAP (SHapley Additive Explanations) is a powerful XAI tool that mathematically evaluates the contributions of features to a model. By explaining the positive or negative impact of each input on the prediction, SHAP enables visualization and optimization of the model's decision-making process. It provides valuable insights to decision-makers, particularly in stages such as feature selection, model checking, and design guidance.

2.3 Machine Learning Applications in UCS Prediction of Mining Waste

In recent years, various machine learning techniques have been used to estimate the uniaxial compressive strength (UCS) of waste-based binder systems. The literature demonstrates the successful application of algorithms such as artificial neural networks (ANN), support vector machines (SVM), random forests (RF), and XGBoost to different binder mixtures. However, most of these studies focus solely on achieving high accuracy; the internal workings of the model, the influence of features, or the explainability of decision-making processes are often overlooked.

Some studies on this topic in the literature include the RF model by He et al. (2022); Bayesian networks by Mishra et al. (2022); deep neural networks (DNN) by Qi et al. (2023); long-short-term memory neural networks (LSTM) by Hu et al. (2023); Tran (2023) used XGBoost, gradient boosting, RF, decision trees (DT), k-nearest neighbor (KNN), and support vector machine (SVM); Xiong et al. (2023) used XGBoost; and Kurniati et al. (2024) used linear regression and RF methods to predict the compressive strength of cement paste with high accuracy. Tuylu (2022) obtained the strength results of CPB samples with various C and F class fly ash (FA) ratios in his study. Adiguzel Tuylu et al. (2025) used a dataset containing the observed physical and chemical properties of samples with various FA ratios to predict the strength with various ML and ensemble ML (EML) models. They created the highest-accuracy prediction model based on features such as mixing ratios and curing time, depending on the constraints of each mixture. Furthermore, most UCS prediction studies are limited to limited curing times (e.g., only 28 days), fixed cement ratios, or only a single waste type. This complicates the development of generalizable models and their effective use in engineering design processes. However, there is a growing need for explainable and generalizable ML models that systematically address different fly ash types (such as CFA, YFA, TFA, SFA), cement ratios, and curing conditions.

This study fills this gap by presenting a highly accurate UCS prediction model that provides transparent decision-making processes on a comprehensive dataset.

3. Data and Method

3.1 Data

This study used a dataset consisting of 116 experimental samples obtained from past laboratory studies on the use of mining waste in cement-based binder systems. The samples were prepared with fly ash subjected to various activation processes at different replacement rates (Tuylu, 2022; Adiguzel Tuylu et al., 2025).

The dataset includes the following variables:

- Continuous variables: curing time (days), proportion of fly ash added as cement replacement (%), cement ratio (%), UCS value, replacement ratio, water ratio
- Categorical variables: Fly ash type (CFA, SFA, YFA, and TFA)

The dataset was structured to be balanced and multivariate. The number of replicates for each activation type and binder composition was planned with a minimum of 5. Curing times cover a wide time range: 28, 56, 90, and 200 days. In this way, modeling of strength trends and environmental interactions that develop over time has become possible.

3.2 Model Development Process

During the modeling phase, the uniaxial compressive strength (UCS) of the samples was estimated using the XGBoost algorithm. XGBoost is a tree-based gradient boosting method that stands out for its high accuracy and fast learning ability in both regression and classification problems (Chen and Guestrin, 2016; Adiguzel Tuylu et al., 2025).

The dataset was randomly but proportionally divided into training (70%), validation (15%), and test (15%) subsets. Model performance was evaluated using three key performance metrics:

- R^2 (Determination Coefficient): 0.871
- Mean Absolute Error (MAE): 0.640
- Root Mean Square Error (RMSE): 0.861

3.3 Explainability Analysis with SHAP

SHapley Additive Explanations (SHAP) analysis was conducted to ensure the model's explainability and visualize the impact of each input on the prediction. SHAP offers powerful interpretations, particularly when integrated with tree-based algorithms such as XGBoost.

These explainability analyses provide insight not only into how well the model predicts but also into why it makes these predictions. This increases the model's reliability and acceptance in engineering applications.

4. Empirical Analysis

The XGBoost model developed in this study predicted the uniaxial compressive strength (UCS) values of 116 experimentally obtained samples with high accuracy. The model's coefficient of determination ($R^2 = 0.871$) demonstrates a strong overall accuracy. Furthermore, SHAP analyses were conducted to understand the model's decision-making processes and ensure engineering interpretability. In this context, the determinant role of curing time in the model confirms the critical role of long-term hydration on UCS. The findings provide important insights for both technical optimization and sustainability objectives.

The SHAP Bar Plot presents the ranking of variables with mean SHAP values. Within the analysis, the SHAP bar plot (Figure 1) shows the average contribution of the variables to the UCS prediction. In particular, tailing rate and curing time appear to have a direct positive effect on UCS. The results reveal the dominant effect of curing time on strength development and demonstrate that the model reflects physical reality, consistent with the experimental literature. The high positive effect of cement demonstrates that cement maintains its binding function and is the primary additive even in systems containing additives. Furthermore, the significant contributions of fly ash type variables indicate that careful selection of these factors can significantly impact mechanical performance.

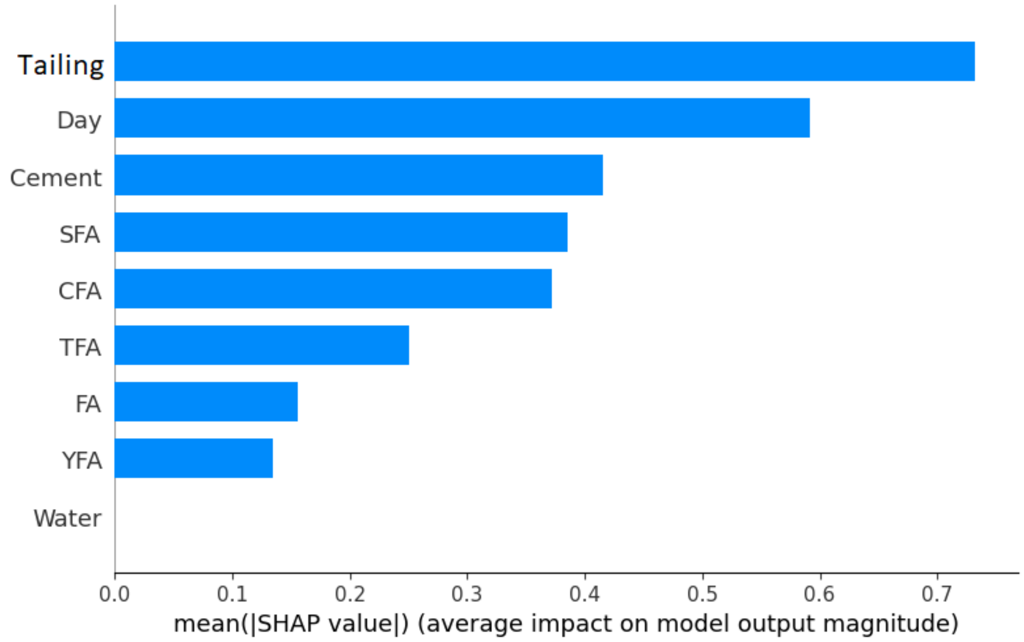

Figure 1: SHAP Bar Plot

5. Conclusion

This study demonstrates the contributions of AI-based explainable modeling approaches to the evaluation of mining waste in sustainable binder systems, both at technical and socioeconomic levels. The prediction model developed with the XGBoost algorithm predicted the uniaxial compressive strength (UCS) of cement-based backfill mixtures with high accuracy (R^2 = 0.871); SHAP analysis made the model's decision-making mechanisms transparent and interpretable.

SHAP analyses quantitatively and visually demonstrated the impact of parameters such as curing time, tailing ratio, cement ratio, waste ratio, and fly ash type on UCS, enabling explainable engineering decisions. The dominant variables of curing time and cement dosage in UCS, in particular, demonstrate that these parameters should be prioritized in material design.

From an economic perspective, reducing the amount of cement not only reduces material costs but also reduces the use of binders with high carbon footprints. This approach thus contributes to the circular economy and carbon reduction goals. Socially, the decision transparency provided by XAI tools like SHAP increases the acceptance of such engineering solutions by policymakers and society.

6. Sustainability and Socio-Economic Impact

The integration of AI-supported decision-making processes into sustainable engineering practices enables the maximization of not only technical performance but also environmental and societal benefits. The SHAP-based explainable AI approach used in this study enables the evaluation of secondary raw materials such as fly ash (CFA, SFA, YFA, and TFA) that have the potential to reduce the environmental impact of cement-based materials.

The findings show that despite reducing the amount of cement, strength values can be maintained, and even increased in some variants. This offers a significant advantage in terms of both cost reduction and carbon footprint reduction. Since cement is a component that causes high CO_2 emissions in its production, the use of mining waste instead is strongly aligned with SDG 9: Industry, Innovation and Infrastructure and SDG 12: Responsible Consumption and Production.

Furthermore, the transparency provided by explainable AI (XAI) supports not only engineering optimization but also decision-making aligned with public policy. Scientific and accountable reporting of environmental impacts, particularly within the context of environmental regulations (e.g., the EU Green Deal and the draft Turkish Climate Law), is critical for the viability of projects and their public acceptance.

From an economic perspective, the reuse of mining waste not only reduces waste management costs but also offers the construction sector low-cost alternative binding systems. This contributes to the development of highly affordable backfill materials, particularly in developing regions.

In conclusion, the XAI-based modeling approach developed in this study provides a multidimensional framework that aligns with the principles of social responsibility and economic efficiency while generating engineering solutions focused on sustainability.

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Deep Learning Models Optimized by Archimedes Optimization Algorithm for Sustainable Household Energy Forecasting in the Digital Era

Ömer Algorabi[1] Mustafa Güler[2]

Abstract

Buildings consume a significant portion of global energy resources, causing various environmental problems that negatively impact human life. Accurately estimating building energy use is seen as a critical strategy for improving energy efficiency and supporting informed decision-making processes, thereby contributing to reducing total energy consumption. In particular, the implementation of environmentally friendly architectural designs in newly constructed buildings plays an important role in reducing energy demand and promoting sustainable development. In this study, residential energy consumption was estimated using deep learning-based forecasting models. Hourly prediction methods were developed with Recurrent Neural Network (RNN), Long Short-Term Memory (LSTM), and Gated Recurrent Unit (GRU) architectures, and their hyperparameters were optimized through the Archimedes Optimization Algorithm (AOA). Comparative analyses demonstrated that the AOA-LSTM model achieved the best predictive performance, with a Root Mean Square Error (RMSE) of 0.0199 and a Coefficient of Determination (R^2) of 0.9993, surpassing both baseline and other optimized models. These results highlight the effectiveness of integrating deep learning with metaheuristic optimization for robust energy forecasting, thereby contributing to the advancement of smart and sustainable energy management systems. The findings provide a scientific basis for shaping resilient energy management strategies focused on environmental sustainability and digitalization.

Keywords: Household Energy Forecasting, Archimeds Optimization Algorithm, Deep Learning, Sustainable Energy.

1. Introduction

The concept of smart buildings has been extensively studied and developed in recent years, and today it has become one of the fundamental components of the smart living concept (Bhatt et al., 2021). Since people spend a large part of their lives at home, smart buildings are considered one of the most critical elements among smart spaces.

Energy consumption in buildings is one of the main reasons for the need for energy efficiency projects in many countries (Abdelhamid et al., 2022). Inefficient management of thermal comfort, inappropriate use of electrical equipment, and excessive consumption of air conditioning systems lead to significant energy waste. In this regard, smart homes supported by various control methods and sensors play a critical role in the efficient management of energy consumption. Accurate estimation of individual household energy consumption is particularly important for the effective implementation of demand-side management and short-term load planning by public service providers.

Short-term forecasts for total energy consumption can generally be made with high accuracy because they are based on regular consumption patterns, but household-level consumption is highly variable and uncertain (Syed et al., 2021). This situation stems from the unpredictability of weather conditions and individual consumer behavior. Therefore, short-term energy forecasting at the building level poses a significant challenge due to the stochastic nature of

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consumption behavior and environmental impacts. In this context, deep learning techniques stand out in developing high-accuracy prediction models by better capturing variability.

In this study, deep learning-based prediction models were developed for a smart household energy system. Hourly energy consumption predictions were performed using RNN, LSTM, and GRU architectures, and the hyperparameters of these models were optimized using the Archimedes Optimization Algorithm. Optimization resulted in significant improvements in error metrics and a marked increase in accuracy indicators. Thus, a robust and reliable prediction model with high accuracy and generalization capacity has been established for use in energy management by smart systems.

2. Related Works

A review of the literature reveals that there are numerous studies on household energy consumption estimation. Recent research highlights the prominence of machine learning and deep learning-based approaches. Among these approaches, regression-based models, tree-based methods, and artificial neural networks play a significant role and are widely used to improve estimation performance across different data types and time scales. Zhang et al. (2018) used Support Vector Regression (SVR) to predict individual household energy consumption and reported that the model yielded successful results with a MAPE value of 12% in daily predictions. In another study, Wang et al. (2018) used the Random Forest (RF) method to predict the hourly electricity consumption of educational buildings and demonstrated that the RF model was more successful than the regression tree and SVR methods, with an R^2 value of 0.73 and a MAPE value of 7.75%. In a study conducted in 2022, the XGBoost algorithm was used to predict household electricity consumption. In hourly and daily predictions, it was reported that hyperparameter optimization resulted in a significant increase in the model's accuracy (Elhouda et al., 2022). In a study, an LSTM-based model was developed using data collected at 15-minute intervals from five home appliances equipped with smart meters. The model was reported to have yielded successful results with an MSE value of 0.0169, demonstrating that LSTM can be an effective prediction tool in smart home energy management (Severiche-Maury et al., 2024). In a study, entropy-weighted k-means clustering and random forest methods were combined to select factors affecting energy consumption, and a bidirectional LSTM (BiLSTM) model optimized using the Sparrow Search Algorithm was developed with these data. Experiments conducted on public building data in Dalian showed that the proposed model reduced the error rate by 24.55% and provided higher accuracy and robustness compared to other hybrid models (Lei et al., 2024). Sulaiman and Mustaffa (2024) proposed a model integrating a feedforward neural network deep learning model with a Teaching-Learning-Based Optimization (TLBO) algorithm to predict the energy consumption of cooling systems in commercial buildings. The study conducted comparative analyses with different heuristic methods such as genetic algorithms, particle swarm optimization, and ant colony optimization, demonstrating that TLBO stood out with higher accuracy, thereby offering significant contributions in terms of energy management and sustainability.

3. Materials and Methods

3.1 Data Collection

In this study, the effectiveness of the proposed models was tested using the Individual Household Electric Power Consumption dataset available in the UCI Machine Learning Repository (Hebrail and Berard, 2006). The dataset covers a four-year period from December 2006 to November 2010 and contains a total of 2,075,259 observations. The records are kept at a minute-by-minute frequency and contain nine key features, including active power, reactive power, voltage, current intensity, and three different sub-metering measurements.

Before proceeding to the modeling stage, the data were preprocessed. First, the minute-by-minute observations in the study were converted to hourly averages, and the problem was defined as estimating household energy consumption on an hourly basis. Subsequently, missing records in the dataset were identified and addressed using the mean imputation technique. To improve time series forecasting performance, lagged variables were created, thus including consumption information from the previous hour, day, and week in the model. Additionally, time-based features such as hour, day of the week, and month information were added to the dataset to capture seasonal patterns in consumption. In the final stage, all variables were transformed to the [0,1] range using the Min-Max normalization method to eliminate imbalances arising from different scales. This ensured stability during the models' learning process and made it possible to compare the parameters with each other.

The dataset was split into 80% training and 20% testing, ensuring that the models' prediction performance could be evaluated on independent test data.

3.2 Archimedes Optimization Algorithm

The Archimedes Optimization Algorithm is a physics-based meta-heuristic algorithm proposed by Hashim et al. (2021). The algorithm was developed inspired by Archimedes' Principle: The buoyant force exerted on an object immersed in a fluid is equal to the weight of the displaced fluid. This principle is modeled in AOA using properties such as density, volume, and acceleration of the solution candidates (objects). These parameters are updated throughout the search process to determine the new positions of the solutions. The algorithm initially emphasizes the exploration phase, but shifts towards exploitation as the iterations progress. This allows it to both scan the vast solution space and focus on promising regions for better solutions.

3.3 Simple Recurrent Neural Network

Recurrent neural networks represent a class of deep learning models designed to process sequential data (Mienye et al., 2024). This architecture incorporates past information into the network structure through hidden states to capture dependencies between observations in time series. The simplest form of RNN, the Simple RNN, consists of input, hidden, and output layers. At each time step, it processes the current input and the previous hidden state together to produce a new hidden state. This enables the modeling of short-term dependencies in time series. However, Simple RNN has limitations in learning long-term dependencies; in particular, the vanishing and exploding gradient problems that arise during the backpropagation process lead to performance loss. For this reason, more advanced architectures such as LSTM and GRU have been proposed in the literature.

3.4 Long Short-Term Memory

Long Short-Term Memory is an approach that provides superiority in sequential data analysis thanks to special memory blocks added to the internal architecture of recurrent neural networks (Wang et al., 2020). LSTM overcomes vanishing/exploding gradient problems through these memory structures, enabling more effective modeling of dependencies in time series. This structure, consisting of input, output, and forget gates, determines which information is retained in memory, which is forgotten, and which is transferred to the output, ensuring that both short-term and long-term dependencies are captured.

3.5 Gated Recurrent Unit

The Gated Recurrent Unit is one of the most widely used advanced types of recurrent neural networks, developed based on the LSTM architecture (Mahjoub et al., 2022). While the internal structure of the GRU resembles that of the LSTM, it offers a simpler structure by combining the input gate and the forget gate under a single update gate. Additionally, there is a reset gate that determines the extent to which past information is preserved or reset. Thanks to these two gate mechanisms, the GRU can effectively learn both short-term and long-term dependencies while operating with lower computational costs compared to LSTM. For this reason, the GRU is widely preferred in sequential data problems such as time series prediction.

4. Experiments and Results

In this study, deep learning methods based on RNN, LSTM, and GRU were used for smart household energy consumption prediction. These methods were subjected to hyperparameter optimization using the Archimedes Optimization Algorithm, and the obtained performance results were evaluated comparatively with unoptimized models.

The RNN, LSTM, and GRU architectures used as base models were designed with a similar structure. The models consist of a single hidden layer with 64 neurons, a dropout layer at a rate of 20% to prevent overfitting, and a single-neuron dense layer that produces the output prediction. The models were trained using the Adam optimization algorithm with a learning rate of 0.001 and the mean squared error (MSE) loss function. The training process was run for 30 epochs, and model performance was evaluated using an 80% training – 20% validation split.

The basic parameters used in the AOA during the model optimization process were set as follows: population size 5, maximum iteration count 20, and control coefficients C1=2, C2=6, C3=2, and C4=0.5. The optimal hyperparameter values obtained for the RNN, LSTM, and GRU models as a result of the optimization performed under these parameters are presented in the Table 1. According to the table, each model achieved the lowest MSE performance with different unit counts, dropout rates, learning rates, and batch size values. These results demonstrate that AOA plays an effective role in hyperparameter optimization for different network architectures.

Table 1: Optimal hyperparameters and error values obtained with AOA

Model	Units	Dropout	Learning Rate	Batch Size	Best MSE
AOA-RNN	128	0.15	0.0011	120	0.00046
AOA-LSTM	87	0.19	0.0005	32	0.00036
AOA-GRU	95	0.16	0.0004	48	0.00038

Table 2: Prediction performance metrics for deep learning models

Model	RMSE	MAE	RRMSE	NSE	R^2
RNN	0.0418	0.0326	0.0403	0.9970	0.9970
LSTM	0.0397	0.0362	0.0382	0.9973	0.9973
GRU	0.0514	0.0408	0.0495	0.9954	0.9954
AOA-RNN	0.0219	0.0147	0.0211	0.9992	0.9992
AOA-LSTM	**0.0199**	**0.0120**	**0.0192**	**0.9993**	**0.9993**
AOA-GRU	0.0310	0.0243	0.0299	0.9983	0.9983

The prediction performance of the models was compared in terms of Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Relative Root Mean Square Error (RRMSE), Nash-Sutcliffe Efficiency Coefficient (NSE), and Coefficient of Determination (R^2) metrics, and the findings are presented in Table 2. According to the results, models optimized with AOA exhibited lower error rates and higher accuracy values compared to the base models without optimization. Specifically, the AOA-LSTM model showed the highest accuracy and lowest error rate with an RMSE value of 0.0199, MAE value of 0.0120, RRMSE value of 0.0192, NSE value of 0.9993, and R^2 value of 0.9993. The AOA-RNN model provided a significant improvement in error values and showed progress, particularly by reducing the RMSE value by approximately half compared to the base RNN. The AOA-GRU model produced more stable results with the flexible structure of the GRU architecture and offered improvements in error metrics compared to the base GRU. These findings reveal that AOA-based hyperparameter optimization consistently improves performance across different deep learning architectures and provides the most successful results, especially when combined with the LSTM architecture.

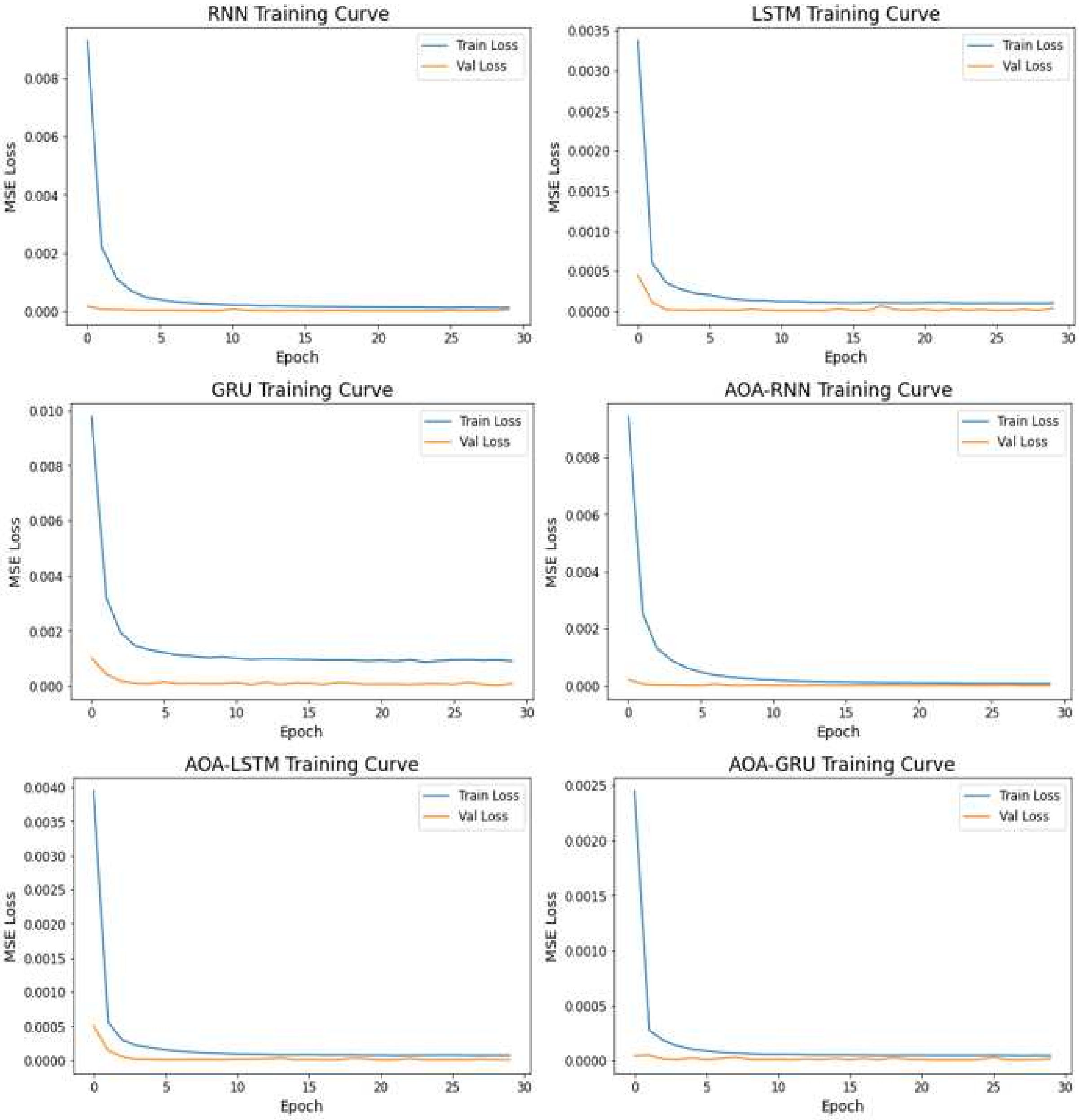

Figure 1: Training and validation loss curves

Figure 1 shows the training and validation loss curves for the base RNN, LSTM, and GRU models and their versions optimized with AOA. Upon examining the graphs, it can be seen that the loss values for all models decrease rapidly within the first few epochs and then stabilize in subsequent epochs. It is noteworthy that the validation loss remains at lower levels in the models optimized with AOA. Figure 2 shows a comparative display of the actual and predicted values on the test data for the base models RNN, LSTM, and GRU, along with their versions optimized with AOA. Upon examining the graphs, it is evident that all models successfully capture the overall consumption pattern.

Figure 3 shows the convergence curves for the AOA optimization process for the RNN, LSTM, and GRU models. Examining the graphs, it is observed that in all three models, the MSE values decrease rapidly within the first few iterations, and then stabilize in subsequent iterations. In the RNN model, the error values reached a stable level after the 4th iteration; in the LSTM model, after approximately the 9th iteration; and in the GRU model, after the 17th iteration. These results indicate that the AOA algorithm effectively searches for suitable parameter combinations in the early iterations.

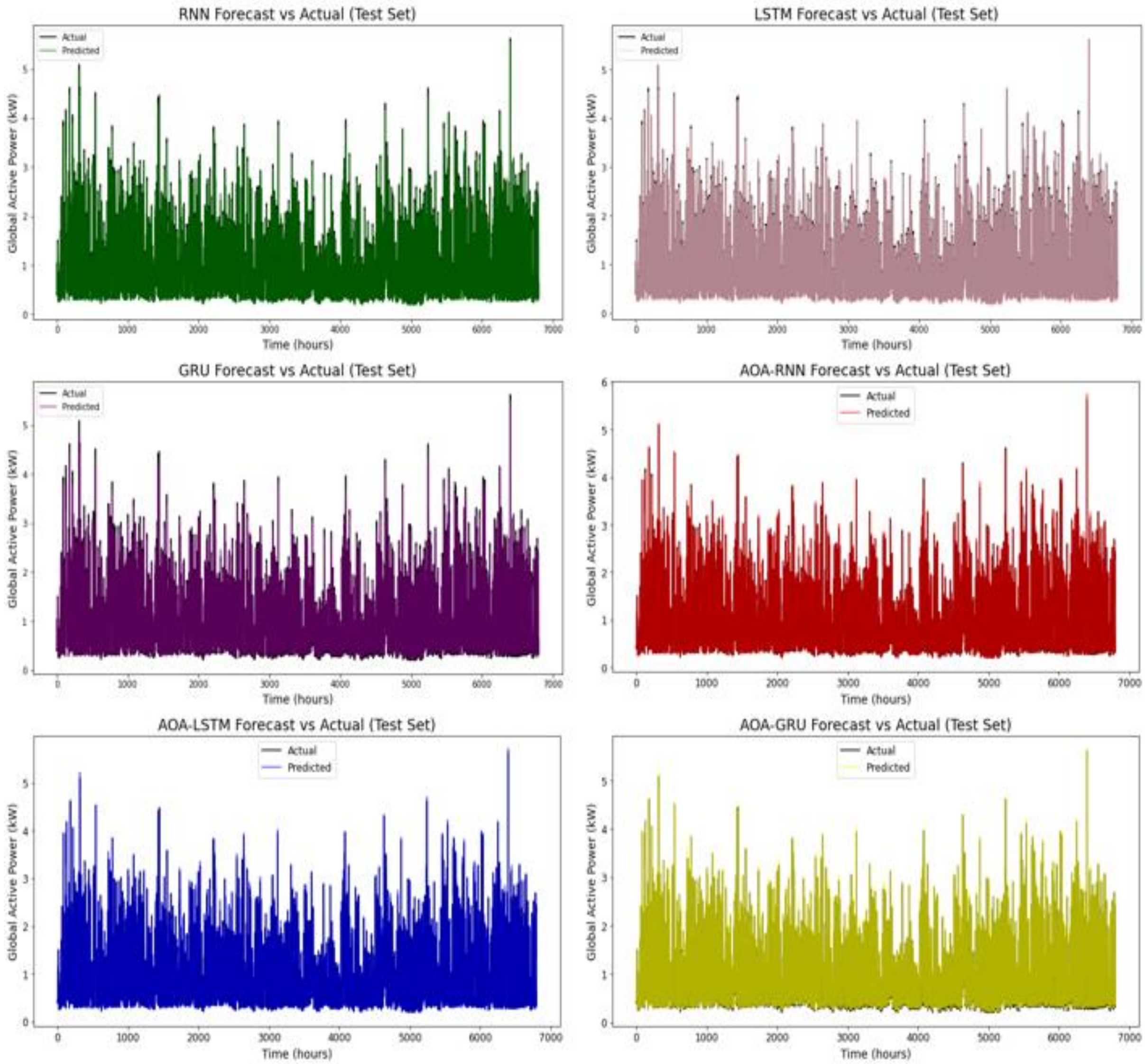

Figure 2: Comparison of actual and estimated values

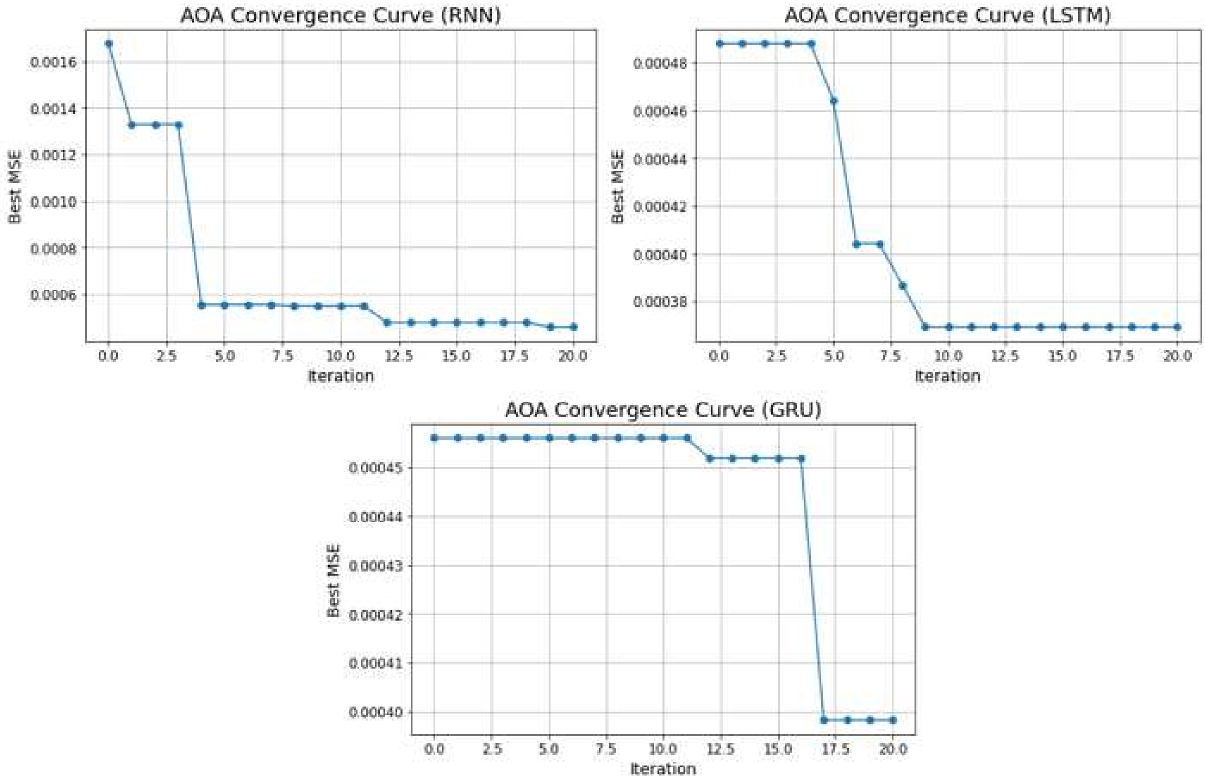

Figure 3: AOA convergence curves

5. Conclusion

Accurate forecasting of household energy consumption is of crucial importance in terms of digital transformation, smart systems, and sustainability. The contributions of such forecasts are highly valuable for increasing energy efficiency, strengthening demand-side management, and reducing carbon emissions.

The findings obtained in this study have demonstrated the superior performance of the AOA-LSTM model in particular. The results show that deep learning approaches are effective in household energy forecasting and that the use of metaheuristic algorithms in hyperparameter optimization significantly improves prediction accuracy.

Future studies may consider integrating different variables into the model, such as weather conditions, socio-economic indicators, or user behavior. Thus, deep learning-based prediction applications in smart energy systems can be further developed to make a strong impact on sustainable energy management.

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The Interaction between Renewable Energy Consumption and Economic Growth: Empirical Evidence from the MINT Countries

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Abstract

This study examines the causal interaction between renewable energy consumption and economic growth in the MINT countries for the 1990-2021 period through the JKS causality test. The results of the JKS causality test uncover a unidirectional causality from renewable energy consumption to economic growth in the MINT countries. In other words, renewable energy consumption has a significant influence on economic growth.

Keywords: Renewable energy consumption, economic growth, MINT countries, panel causality analysis.

1. Introduction

Energy is one of the main requirements of economic activities and nearly 80% of global energy consumption has been met by non-renewable energy sources of oil, coal, and gas (Enerdata, 2025). However, fossil fuel consumption is one of the dominant factors underlying environmental degradation, global warming, climate change, and health problems (Perera, 2017). On the other hand, there have been significant problems in global supply of fossil fuels due to geopolitical risks, political instability, and conflicts. Consequently, countries have begun to transit renewable energy production and consumption considering the concerns related to the environment, health, and energy security.

Renewable energy sources such as water, sunlight, and wind are abundant, replenished by nature, and emit little to no greenhouse gases or air pollutants (United Nations, 2025). However, economic, technological, legal and/or regulators barriers including high investment costs, lack of specialized technical staff, insufficient legal and regulatory framework have made renewable energy transition difficult (Pereira, 2025). The share of renewable energy in global energy supply was 32% in 2024 in response to these barriers (Enerdata, 2025).

In this context, environmental and economic effects of renewable energy have been extensively explored during the recent years. This study investigates the nexus between renewable energy consumption and economic growth in the MINT countries considering the inconclusive related empirical literature. The next section introduces the recent empirical literature, and then data and methodology are described. Section 4 conducts the econometric tests and presents their outcomes and the study is finalized with the Conclusion.

2. Literature Review

The empirical studies on the nexus between renewable energy consumption and eonomic growth have concluded with mixed results in consistent with the associated theoretical views. On the one hand, Chen et al. (2022), Jia et al. (2023), Xie et al. (2023), Dirma et al. (2024), and Koru and Sunal (2025) disclosed a positive relationship between renewable energy use and economic growth, but Lahrech et al. (2024) unveiled a negative effect of renewable energy consumption economic growth. Further, Gyimah et al. (2022), Jia et al. (2023), Xie et al. (2023), and Koru and Sunal (2025) revealed a bidirectional causality between renewable energy

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consumption and economic growth. On the other hand, Steve et al. (2022) revealed a bidirectional causality for Central Africa and a unilateral causality from renewable energy consumption to economic growth in East and West Africa. Fotourehch (2017) also revealed a unilateral causality from renewable energy consumption to economic growth in the developing economies.

Table 1 The recent empirical studies on the connection between renewable energy consumption and economic growth.

Research	Countries; Time	Methodology	Effect of renewable energy consumption on economic growth
Fotourehch (2017)	42 developing countries; 1990-2012	Causality	A unidirectional causality from renewable energy use to economic growth
Chen et al. (2022)	Asian countries; 1992-2018	Cointegration	Positive
Gyimah et al. (2022)	Ghana; 1990-2015	Causality	A bidirectional causality
Steve et al. (2022)	Sub-Saharan African countries; 1990-2018	Cointegration and causality methods	Negative (GDP per capita); bidirectional causality for Central Africa and unidirectional causality from renewable energy use to per capita GDP in East and West Africa.
Jia et al. (2023)	Belt and Road countries; 2000-2019	Cointegration and causality methods	Positive; bidirectional causality
Xie et al. (2023)	N-11 countries; 1990-2020	Regression and causality	Positive; bidirectional causality
Dirma et al. (2024)	EU members; 2000-2021	Regression	Positive
Lahrech et al. (2024)	GCC countries; 2001-2019	Regression	Negative (GDP)
Koru and Sunal (2025)	10 largest renewable energy producing countries; 1990-2020	Cointegration and causality methods	Positive; bidirectional causality

3. Data and Method

In this study, the causal nexus between renewable energy consumption and economic growth in the MINT countries for the years of 1990-2021 is investigated through causality test. Economic growth (GRWTH) is proxied by GDP per capita (constant 2015 US$) and obtained from World Bank (2025a). On the other hand, renewable energy consumption (RNW) is represented by renewable energy use as a percent of total final energy consumption and acquired from World Bank (2025b).

The sample of the research is MINT countries (Mexico, Indonesia, Nigeria, and Turkey) and the dataset's period is between 1990 and 2021 because data of renewable energy consumption is present between 1990 and 2021 for the MINT countries. The econometric tests are carried out by means of Stata 17.0.

The mean values of GRWTH and RNW are USD 5477.988 and 37.975%, respectively as seen in Table 2. However, both series display a significant variation amongst the MINT countries.

Table 2. Descriptive statistics.

Variables	Mean	Std. Dev.	Min	Max
GRWTH	5477.988	3598.546	1390.469	13670.94
RNW	37.975	29.7205	9	88.6

The causal nexus between renewable energy consumption and economic growth is examined through the JKS (Juodis-Karavias-Sarafidis) causality test, developed for heterogeneous panels (Juodis et al., 2021). The JKS causality test is rest upon HPJ approach of Dhaene and Jochmans (2015) to reduce the bias of pooled fixed effects estimator.

4. Empirical Analysis

In the empirical analysis, first, the pre-tests of cross-sectional dependence (CSD) and heterogeneity are carried out. The presence of CSD and heterogeneity is explored through LM and delta tests and their outcomes are introduced in Table 3. The findings reveal the presence of CSD and heterogeneity because the probability values of CSD and delta tests are found to be lower 5%.

Table 3. Outcomes of LM and delta tests.

Test	Test Statistic	Test	Test Statistic
LM	24.41***	Delta	14.196***
LM adj.	16.43***	Adj. delta	14.912***
LM CD	2.06**		

*** and ** significant at 1% and 5%, respectively.

The stationarity analysis of GRWTH and RNWM is conducted through CIPS unit root test of Pesaran (2007), and its outcomes are introduced in Table 4. The integration levels of GRWTH and RNW are identified to be one.

Table 4. CIPS panel unit root test results

Variables	Constant	Constant + Trend
GRWTH	0.930	1.230
d(GRWTH)	-4.047***	-4.633***
RNW	2.648	3.126
d(RNW)	-5.438***	-6.114***

*** significant at 1%

The causal interaction between renewable energy consumption and economic growth is analyzed with the JKS causality test and its outcomes are reported in Table 5. The outcomes indicate a significant causal relation from renewable energy consumption to economic growth, but economic growth does not have a significant effect on renewable energy consumption.

Table 5. Results of JKS causality test

Null Hypothesis	HPJ Wald test	Test statistic
RNW does not Granger-cause GRWTH.	2.4e+03	0.0000
GRWTH does not Granger-cause RNW.	0.5364	0.4639

The empirical studies analyzing the causal nexus between renewable energy consumption and economic growth have uncovered mixed results. On the one hand, Gyimah et al. (2022), Jia et al. (2023), Xie et al. (2023), and Koru and Sunal (2025) identified a bidirectional causality between renewable energy consumption and economic growth. On the other hand, Steve et al.

(2022) revealed a bidirectional causality for Central Africa and a unilateral causality from renewable energy consumption to economic growth in East and West Africa. Fotourehch (2017) also revealed a unilateral causality from renewable energy consumption to economic growth in the developing economies. Therefore, our results are compatible with the associated theoretical views and are supported by outcomes of Fotourehch (2017) and Steve et al. (2022).

5. Conclusion

Environmental degradation, global warming, climate change, and energy security have directed the countries to produce and consume renewable energy. Therefore, the share of renewable energy consumption in total energy use has been increasing although especially economic and technological barriers slow down the renewable energy transition of developing countries. In this context, this study investigates the causal interaction between renewable energy consumption and economic growth in the MINT countries during the 1990-2021 years by means of panel causality test. The outcomes of the test uncover a significant causal relation from renewable energy consumption to economic growth in the MINT countries. In other words, renewable energy use has a significant effect on economic growth. In conclusion, policies in terms of regulations and financial incentives to improve renewable energy consumption will be useful for economic growth, environmental protection, and energy security.

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The Interplay between Energy Poverty Alleviation and Life Expectancy at Birth: Empirical Evidence from the MINT Countries

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Abstract

Life expectancy is one of the leading indicators of public health. Therefore, this study examines the causal interplay between energy poverty alleviation and life expectancy at birth in the MINT countries for the 2000-2023 period through the JKS causality test. The results of the JKS causality test uncover a bidirectional causal connection between energy poverty alleviation and life expectancy at birth. The results emphasize the significance effect of energy access for life expectancy at birth.

Keywords: Energy poverty, life expectancy, MINT countries, panel causality analysis.

1. Introduction

Life expectancy is one of the significant indicators of a country's overall health status and good health and well-being is amongst sustainable development goals (SDGs) (United Nations, 2025). Therefore, countries have implemented various economic, institutional, and environmental, and health policies to make progress in life expectancy. Furthermore, the researchers have widely explored the effect of economic, institutional, and environmental factors on life expectancy in the associated empirical literature. In this regard, this study concentrates on the nexus between energy poverty and life expectancy at birth in the MINT countries given the related literature.

Energy poverty can affect health through diverse channels such as indoor warmth, sleep duration, physical and mental health, education, and employment opportunities (Wang et al., 2024). Therefore, problems in energy access can be resulted in physical and mental health problems (Liddell and Morris, 2010; Zhang et al., 2021; Wang et al., 2024). On the other hand, increases in life expectancy can increase the energy requirement. In conclusion, a bidirectional causality between energy poverty alleviation and life expectancy at birth is theoretically expected.

In this context, this study investigates the causal connection between energy poverty alleviation and life expectancy birth in the MINT countries considering the gap in the associated empirical literature. The next section introduces the results of the limited empirical studies, and then data and methodology are explained. Section 4 performs the econometric tests and presents their outcomes and the study is finalized with the Conclusion.

2. Literature Review

The effect of energy poverty alleviation on life expectancy at birth has been investigated by a few researchers and these researchers have usually identified a negative impact of energy poverty on health. In this context, Banerjee et al. (2021) explored the impact of energy poverty on health and education indicators in 50 countries for the 1990-2017 period by means of regression analysis and disclosed that lower energy poverty is related to the higher health

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outcomes. On the other hand, Aina (2025) examined the effect of energy poverty on life expectancy in Nigeria between 1981 and 2023 by means of ARDL method and uncovered a negative impact of energy poverty on life expectancy in Nigeria.

Yu et al. (2025) investigated the effect of energy poverty on health capital in China through ordered logit model and found that energy poverty had a negative effect on health capital, Wali et al. (2025) also analyzed the effect of energy deprivation on health and education in Kano State, Nigeria through Tobit regression method and revealed a significant effect of energy poverty on health and education outcomes.

In another study, Nyame-Baafi et al. (2025) examined the effect of energy poverty on health in Ghana through regression approach and identified a negative effect of energy poverty on health. Lastly, Compaore et al. (2025) examined the nexus between energy poverty and women's health in Burkina Faso and discovered a negative effect of enegy poverty on women's health.

3. Data and Method

In the paper, the interaction between energy poverty and life expectancy at birth in the MINT countries for the years of 2000-2023 is analyzed through causality test. In the analyses, life expectancy (LIFEX) is represented by life expectancy at birth (years) and provided from UNDP (2025). On the other side, energy poverty (ENPOV) is proxied by SDG (sustainable development goal)7 index (affordable and clean energy). SDG7 index is figured considering electricity access, access to clean fuels and technology for cooking, ratio of renewable energy in total energy use, and CO_2 emissions from fuel combustion (greater values indicate higher energy access)(Sachs et al., 2025).

The sample of the research is MINT countries (Mexico, Indonesia, Nigeria, and Turkey) and the dataset's period is between 2000 and 2023 because SDG7 index is calculated as of 2000 and the series of life expectancy at birth lasts in 2023 for the MINT countries. The econometric tests are carried out by means of Stata 17.0.

The mean values of LIFEX and ENPOV are 67.093 years and 53.398, respectively as seen in Table 1. However, both life expectancy at birth and energy poverty remarkably differs among the MINT countries.

Table 1. Descriptive statistics.

Variables	Mean	Std. Dev.	Min	Max
LIFEX	67.093	9.713	47.143	77.737
ENPOV	53.398	20.364	10.148	73.078

The causal nexus between life expectancy and energy poverty is analyzedthrough the JKS (Juodis-Karavias-Sarafidis) causality test considering the dataset's characteristics.

4. Empirical Analysis

In the empirical analysis, first, the pre-tests of cross-sectional dependence (CSD) and heterogeneity are carried out. The presence of CSD and heterogeneity is explored through LM and delta tests and their outcomes are introduced in Table 2. The findings reveal the presence of CSD and heterogeneity because the probability values of CSD and delta tests are found to be lower 5%.

Table 2. Outcomes of LM and delta tests.

Test	Test Statistic	Test	Test Statistic
LM	24.1***	Delta	10.220***

Test	Test Statistic	Test	Test Statistic
LM adj.	13.71***	Adj. delta	10.926***
LM CD	4.015***		

*** significant at 1%.

The stationarity analysis of LIFEX and ENPOV is implemented by means of CIPS unit root test of Pesaran (2007), and its outcomes are introduced in Table 3. The integration levels of LIFEX and ENPOV are identified to be one.

Table 4. CIPS panel unit root test results

Variables	Constant	Constant + Trend
LIFEX	-0.854	0.781
d(LIFEX)	-5.215***	-4.654***
ENPOV	-0.500	-1.037
d(ENPOV)	-3.842***	-2.415***

*** significant at 1%

The causal connection between energy poverty and life expectancy at birth is tested with the JKS causality test and its outcomes are reported in Table 5. The outcomes indicate a significant bidirectional causal connection between energy poverty and life expectancy at birth. In other words, there exists a mutual connection between energy poverty and life expectancy.

Table 5. Results of JKS causality test

Null Hypothesis	HPJ Wald test	Test statistic
ENPOV does not Granger-cause LIFEX.	12.6287	0.0018
LIFEX does not Granger-cause ENPOV.	6.4950	0.0389

The researchers have generally focused on the effect of energy poverty alleviation on health, but the effect of life expectancy on energy has been generally disregarded. In this regard, Banerjee et al. (2021), Aina (2025), Yu et al. (2025), Wali et al. (2025), and Nyame-Baafi et al. (2025) disclosed a significant effect of energy poverty on life expectancy at birth and these results also support our outcomes.

5. Conclusion

The progress in public health is a significant indicator of welfare and also important for human capital, one of the main determinants of economic growth and development. Therefore, economic, environmental, institutional, and social factors underlying public health have been explored by the researchers. This study investigates the nexus between energy poverty alleviation and life expectancy at birth in the sample of MINT countries through panel causality analysis. The outcomes of the causality analysis uncover a bidirectional causal nexus between energy poverty alleviation and life expectancy at birth. Therefore, there exists a feedback between two variables. On the one hand, improvements in energy access have a positive influence on life expectancy at birth. On the other hand, life expectancy also affects energy poverty alleviation.

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Considerations regarding the Use of Digital Services in the Republic of Moldova through the Lens of the Digital Transformation Strategy

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Abstract

The Republic of Moldova has placed the digitalization of public services among its development priorities. In 2010, the Electronic Government Agency (AGE) was created, with the aim of developing technological innovations in government institutions, rethinking administrative processes and streamlining public services through digital solutions. The current government includes the Ministry of Economic Development and Digitalization (MDED), and the minister has the status of deputy prime minister, which demonstrates the transversal and inter-institutional nature of the issues related to digital transformation.

On September 14, 2023, the Government approved the National Digital Transformation Strategy 2023-2030 provides, among the performance indicators, that by the end of 2024, 75% of all public services will be digitalized, and by 2030 - all public services will be digital At the same time, the Strategy, as a fundamental document in the field of digital transformation, the elements of which are mandatory for implementation by government institutions, highlights the inclusive nature of e-government, ensuring distributed responsibility and assumed by all institutions, the role of the human factor, educational aspects, the development of digital skills in public institutions, but also a series of fundamental preconditions for the development of an authentic digital society, at all its levels. This analytical note aims to analyze the degree of use of digital services in the Republic of Moldova and to provide a better understanding of the existing challenges in terms of promoting these services among society. Based on the analysis of data provided by MDED and AGE, following requests for information sent by the Institute for European Policies and Reforms, the document proposes a series of recommendations for the popularization of digital services among society, the business environment and public institutions (https://www.speedtest.net/global-index).

Keywords: Artificial intelligence, digital services, transformation digital, sustainability, profession, business environment.

1. Digital Services in the Republic of Moldova

According to data provided by AGE, the government portal of public services contains information on 714 available public services, of which 283 e-Services (39.63%) can be accessed online.

This category of "e-Services" includes both fully automated electronic public services, which allow electronic self-service (services for which providers ensure the formalization and complete programming of the process of their provision), and partially automated electronic public services, i.e. services for which it is not possible to carry out activities and controls in a fully automated manner and for making decisions regarding the provision of which physical interaction between representatives of the provider and beneficiaries is inevitable.

Of the 283 e-Services, 126 are services related to the issuance of permissive acts and 157 are services for citizens and businesses. Of the 157 public services that can be requested online, 36 (22.92%) are provided in digital format (services for which providers ensure the formalization and complete scheduling of the provision process): 12 cadastral services and 19 services for issuing civil status documents, apostille, extract from the state register of legal units, lack of debts to the state budget, status of the personal social insurance account, criminal record,

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detailed record and contravention available in digital format, including the option of apostille and home delivery (https://www.asp.gov.md/ro/servicii/servicii-electronice).

Recently, MDED has developed an interactive platform that aims to monitor and inform the general public about public services for entrepreneurs in the Republic of Moldova. The platform indicates how many of these services are digitized and the degree of their use. According to MDED data, in the Republic of Moldova there are 523 public services offered by 42 public institutions (ministries, agencies, inspectorates, specialized services and centers, etc.), 226 of them are already digitized, which represents 43.2% of the total number (https://midr.gov.md/noutati/97-de-proiecte-de-dezvoltare-urbana-vor-fi-incluse-pentru-finantare-in-documentul-unic-de-program-2025-2027).

In this context, we can highlight three distinct categories of institutions according to the indicator of the number of digitized services in their area of competence, it being easy to notice a different approach to the digitization processes from one institution to another:

Institutions that have digitized all or most of their services offered (in a proportion of 75% and more): National Road Transport Agency, National Agency for the Regulation of Nuclear and Radiological Activities, Environmental Agency, National Bureau of Statistics, Land Relations and Cadastre Agency, Public Property Agency .

Institutions that have partially digitized their services (in a proportion of 25-75%): Public Services Agency, Medicines and Medical Devices Agency, Civil Aeronautics Authority, National Agency for Regulation in Electronic Communications and Information Technology, State Agency for Intellectual Property, State Tax Service, State Inspectorate for Public Security, MDED, Information Technology Service of the Ministry of Internal Affairs, National Institute of Metrology, Chamber of Commerce and Industry, National Accreditation Center, National Health Insurance Company (https://servicii.gov.md/ro/organization/STI) .

Institutions that have digitized only some public services (in proportion of 25% and less) or that have not digitized any service: Naval Agency, National Food Safety Agency, National Agency for Public Health, National Inspectorate for Technical Supervision, National Radio Frequency Management Service, Customs Service, Ministry of Infrastructure and Regional Development, State Chamber for Marking Supervision. At the same time, several important public institutions have not digitized any service in their portfolio, including the Ministry of Education and Research, the Ministry of Justice, the Ministry of Culture, the Ministry of Labor and Social Protection, the Agency for Geology and Mineral Resources, the Agency for Investment and Payments for Agriculture, the Transplant Agency, the National Archives Agency, the Agency for Energy Efficiency, the National Agency for Quality Assurance in Education and Research, and the National Health Insurance House (https://servicii.gov.md/ro/organization/STI).

2. Degree of Use of Digital Services

The development of digital solutions by responsible institutions is a continuous process, requiring permanent improvements, including to increase their penetration and use by citizens. The launch of a digital public service will not necessarily lead to its massive use by beneficiaries. As part of the analysis, we systematized statistical data reflecting the degree of use of existing public services, selecting services that have a large number of potential users, including those that can be provided based on both online requests and at the counters of the respective institutions. From this perspective, we highlight four distinct categories that reflect the degree of use of existing digitized public services:

Digitized public services, used massively and predominantly compared to the option of the service offered at the counters of the institution (50% and more of the total requests for the respective service). For the most part, these services are offered only in online format or are easily accessible digital services, which have a very high penetration rate: authorization for the import of medicines, medicine registration certificate (Agency for Medicines and Medical Devices), authorization for road transport of goods/INTERBUS carnet (National Road Transport Agency), partial radiological authorization (National Agency for the Regulation of Nuclear and Radiological Activities), waste management authorization (Environmental Agency), statistical/financial reporting (National Bureau of Statistics), registration of taxable objects/standardized forms of primary documents under special regime (State Fiscal Service), customs warehouse authorization (Customs Service), provision of topographic and geodetic materials (Land Relations and Cadastre Agency), initiation/termination of employment relationships (National Health Insurance Company), criminal record for individuals and legal entities (Information Technology Service of the Ministry of Internal Affairs) (www.statistica.gov.md) .

Public services that are offered both in digital format and through requests at counters and that have an average usage rate of the digital option of 25-50%: dangerous goods transport route coordination act (National Road Transport Agency), certificate regarding the value of the real estate asset/extract from the state register of legal entities (Public Services Agency), pollutant emission authorization/forest cutting authorization (Environment Agency).

Digitalized public services that have a low usage rate of 1-25%: authorization of irregular flights (Civil Aeronautical Authority), sanitary-veterinary authorization of means of transport (National Food Safety Agency), sanitary authorization for the operation of objectives (National Public Health Agency), non-preferential origin certificate of goods (Chamber of Commerce and Industry), nuclear/radiological safety certificate (National Agency for the Regulation of Nuclear and Radiological Activities).

Digitalized public services that have a negligible or non-existent usage rate (less than 1%): authorization for the manufacture of medicines (Medicines and Medical Devices Agency), individual authorization for the export/import of strategic goods, information about goods belonging to a natural/legal person (Public Services Agency), authorization for the installation and operation of radio transmitters (Civil Aeronautical Authority), export/re-export phytosanitary certificate (Agency National Agency for Food Safety), environmental impact assessment/cross-border waste transport notification (Environmental Agency), generalized data presentation (National Bureau of Statistics), certificate regarding the absence of budget arrears/tax code assignment/online registration of taxpayers (State Fiscal Service), provisional weapon permit/special car category permit (National Inspectorate of PUBLIC Health), technical-professional construction attestation certificate (Ministry of Infrastructure and Regional Development), detailed criminal record certificate/contravention record (Information Technology Service of the Ministry of Internal Affairs), all services of the National Institute of Metrology. A distinct category of these services is represented by digital solutions reported to MDED as being developed and functional, but which were not used by any beneficiary (zero users) during the reporting period (2022). The total number of such services is 128 or 56.63% of all digital services reported. Thus, according to the analysis, of the 226 digital services reported to MDED, 77 services (34.07%), for which you can make a request both in digital format and at the institutions' counters, did not have any digital requests in 2022, but they had requests at the counters of institutions with a physical presence. Additionally, another 51 digital public services (22.56%) were reported by public institutions to MDED with a figure of zero requests, both in formal online format and at the institutions' counters (https://www.asp.gov.md/ro/servicii/servicii-electronice).

3. Causes of the Low Degree of Use of Digital Services

The low-scale use of digital services is influenced by several factors, which target the elements related to the digital transformation process, but also the way in which society relates to digital innovations:

The small number of users of the advanced qualified electronic signature, an element that represents the fundamental interface for accessing digital services. According to STISC data from September 2022, the number of active public key certificates for advanced qualified electronic signature was 129384 units, of which 97633 (75.45% of the total) were USB tokens, 18400 Mobile ID certificates issued by Orange Moldova, 17725 Mobile ID certificates issued by Moldcell and 66 eID bulletins issued by the Public Services Agency. It should be noted that, with 97,633 STISC certificates issued, the number of unique users was much lower – 45,870, with many citizens holding two (13,086), three (1,631) and more (345) certificates, even though it is not necessary to hold multiple certificates. (www.statistica.gov.md)

Insufficient information of users and beneficiaries about the existence of developed digital solutions, their functionalities, advantages and benefits. Many functional digital services are little known to the final beneficiaries, there are no clear and accessible communication channels through which users can obtain additional information about their use or technical assistance, if necessary. This is also important from the perspective of the connection between users and developers of digital public solutions, so that they are continuously improved, based on suggestions from users.

Complexity, ambiguity and unintuitive interface of digital solutions. If an application or electronic service is characterized by a complex or confusing user interface, beneficiaries of public services may encounter difficulties in the navigation process and in completing the steps necessary to access and benefit from those services. This lack of intuitiveness in the user interface can generate feelings of frustration and can reduce the motivation of beneficiaries of public services to resort to that service. When electronic public services are perceived as complicated or unclear, users may be discouraged from using them. People need to see the clear value of using a digital solution compared to traditional methods. If they do not understand the significant benefits of the transition to a digital solution, they are unlikely to take this step. Also, some electronic public services may experience performance issues, such as slow page loading, delays in providing answers or frequent errors. These issues can create significant barriers or, in some cases, completely prevent beneficiaries from accessing public services and using them effectively.

People's resistance to change and preference for traditional methods. People develop routines and habits over time, and these become a comfortable part of their lives. Transitioning to digital solutions may require learning new skills or procedures, which can be perceived as additional effort and, at times, discomfort. Some people may have fear or anxiety about technology. They may feel insecure about using electronic applications or devices and may avoid using them because of these fears. For some people, digital services may not be as accessible as traditional methods. The change brought about by technology can affect social and cultural relationships. People may have strong ties to their traditions or communities, and adopting digital solutions may seem like a violation of these ties.

Previous negative experiences with digital services. When users repeatedly encounter errors or delays in the processing of digital services, their trust in these platforms can be seriously affected. This decrease in trust can make users more reluctant to use or rely on these services in the future and stick to traditional methods or other options that they are familiar with and consider more reliable. Negative experiences with digital services can affect not only the perception of these services, but also the image of the organization that provides them. Users may associate errors and delays with the incompetence or negligence of the organization, which can affect their relationship and trust in this organization. Negative experiences can lead to the abandonment of digital services in favor of other existing alternatives. Users may look for more reliable or convenient alternatives.

Limited access to technologies and internet connection. In certain circumstances, citizens face major difficulties in adopting digital solutions, mainly due to limited access to technologies and the internet. This limitation may consist of the unavailability of smart devices or the inability to connect to the internet. This problem becomes more pressing in rural areas or among people with limited financial resources. In rural areas, internet infrastructure may be underdeveloped or even non-existent, making access to services difficult digital services to be practically impossible. This not only limits the possibility of citizens to access information or benefit from government services online, but can also create a significant digital gap between urban and rural areas. For people with limited financial resources, purchasing electronic devices or contracting an internet subscription can be financially prohibitive. This financial barrier can exclude a significant part of the population from the benefits of electronic public services and can contribute to the perpetuation of social and economic inequalities.

Insufficient information security. Weak information security of an electronic public service can serve as a barrier against unauthorized access to the personal data of beneficiaries and can constitute a significant impediment to its adoption and use. The lack of confidentiality and protection of personal data can generate consequences of considerable gravity and can act as a deterrent for citizens to resort to that public service.

Relatively low level of use of online payments and e-commerce. Many functional digital services require mechanisms for making electronic payments. If these are not provided, it is not possible to provide the entire digital service. Another related cause is the distrust or fear of making online payments and, as a result, the reluctance or abandonment of using a digital service. Finally, the use of digital services and online payments are interdependent factors: the higher the level of use of online payments, the higher the probability that a user will want to use more digital services and vice versa.

4. Recommendations for Increasing the Use of Digital Services

Digital solutions do not work effectively if they are too complex, difficult to understand and have an unclear or ambiguous design. Finally, developers of digital solutions must understand that these solutions are not intended only for officials with narrow specialization. They are intended for all users and, to the extent possible, must be developed in a manner that is as simple and intuitive as possible. It is essential that public service providers be receptive to the suggestions of public service beneficiaries and continuously improve their electronic public services, in order to meet the needs and expectations of citizens and the business environment. In this context, IPRE proposes a series of recommendations for decision-makers:

Increase the number of users of digital signature certificates available in the Republic of Moldova, including by organizing information campaigns on the functionalities of the digital signature, the advantages it offers as an access key for all existing and prospective digital services. Actions are needed that would simplify the procedures for issuing digital signatures and renewing the respective certificates.

The monetization of the use of digital signatures is a factor that hinders the widespread use of these tools, and it is necessary to identify possibilities for minimizing the costs of obtaining and renewing digital signature certificates, as well as their use, including by excluding the clause limiting the number of digital signatures that a citizen can apply.

The development of digital signature certificates based on the MobiSign smartphone application, which is in the process of implementation and launch, can serve as a huge catalyst for the widespread use of digital services. It is necessary to complete the audit procedures and launch MobiSign, accompanied by a broad information campaign on how the solution works, but also how the security of processes and data is ensured. The most telling example in this regard is the Estonian SmartID application, which, being very intuitive, within reach of every citizen (on a smartphone) and free of charge, very quickly surpassed the other existing digital signature options (eID and MobileID).

Developing digital solutions without taking into account the opinions of direct beneficiaries is a wrong perspective, which directly affects the degree of penetration and use of these solutions. This refers both to consulting in detail the users of specialized solutions (for example, doctors should be consulted directly when developing solutions in the healthcare system, teachers - in the field of education, etc.), and to consulting the final beneficiaries about how they should look and what functionalities the respective solutions should have. As an analogy, patients should be consulted in the case of digital solutions in the medical system, or students and parents in the case of those in the field of education.

Increasing the number of digital ambassadors, who can provide relevant information to any citizen, is vital. From this perspective, the establishment by the Electronic Government Agency, in cooperation with local public authorities, of 100 single service delivery centers (CUPS) by the end of 2023 in the regions is welcome rural areas of the Republic of Moldova. It is essential that CUPS specialists prioritize informing citizens about digital solutions and how they can be used. In larger cities, specialists from the Multifunctional Centers of the Public Services Agency can play a fundamental role in this regard. Other institutions that can be involved in this educational process are libraries, schools, universities and non-governmental organizations.

Promoting digital leadership. Specialists from a ministry, agency, city hall or district council will not use digital solutions if the administration of the respective entities refuses or boycotts their use. It is necessary to adopt much clearer administrative protocols, which would limit the possibility of decision-makers to stop or boycott the widespread implementation of digital solutions. At the same time, it is necessary to improve the digital skills of employees in the public sector and local public authorities, including to deal with the digital divide between urban and rural areas.

Informing citizens about the security of personal data that is used in the context of the development of digital solutions, who and why accesses their data and what are the existing limitations. The goal of cybersecurity should be not only the direct responsibility of the national specialized institution (STISC), but also of basic cyber hygiene programs within all state and educational institutions in the country.

Development of digital education programs in educational institutions, according to the age specifics and current trends. Closer cooperation is needed in this regard between educational institutions, the IT and telecommunications industry. Educational institutions should have greater freedom and flexibility in the process of selecting specialized digital programs. The concept of lifelong digital education must become a component part of the educational system.

Increasing internet coverage at the national level. Despite the fact that the Republic of Moldova has a solid internet connection network, internet accessibility remains a topical issue, especially in rural regions, those far from major infrastructure and road networks, or those with lower incomes. Increasing the accessibility of fast internet access, the development of free internet points following the European Union's "WiFi4EU" model, but also the accessibility of connection devices in public places (schools, libraries, town halls), can minimize the exclusion of certain categories of citizens from among the beneficiaries of digital solutions.

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Economic Activities and CO_2 Emissions: Evaluating the Impacts of Renewable Energy, Industrial Growth, and Financial Development in CO_2-intensive Economies

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Abstract

Contemporary discourse increasingly underscores environmental degradation as a paramount concern. Numerous scholars actively scrutinize various ecological indicators and their impacts within this discourse. Notably, economic activities wield significant influence over ecological deterioration, with the industrial sector emerging as a pivotal contributor. This study investigates the effects of economic growth (GDP), renewable and non-renewable energy utilization (RE, NRE), financial development (FDI), and value-added industry (IVA) on CO2 emissions across a panel of ten countries emitting CO2, covering 1990-2021. Employing the pooled mean group-panel autoregressive distributive lag (PMG-ARDL) method and Granger causality tests, the study discerns several key insights. Firstly, it establishes the independence of residuals across different sections and the long-term co-movement of variables. The validity of the Environmental Kuznets Curve (EKC) hypothesis has been examined. Long-run PMG-ARDL estimations reveal that GDP and NRE exacerbate pollution levels, whereas RE, FDI, and IVA serve to mitigate emissions. Granger causality analysis revealed strong causal links between all the variables. Industrial growth is found to mitigate emission rates, while clean energy generation exhibits a long-term increase in CO2 emissions. Consequently, investment in clean technologies emerges as imperative to foster industrial sector growth and subsequently curtail emission rates.

Keywords: CO2 emissions, renewable energy, industry value-add, PMG-ARDL, emitter countries.

1. Introduction

The topics of environmental degradation and carbon dioxide CO2 emissions (CO2em) have drawn considerable interest from researchers and policymakers across the globe (Adebayo and Kirikkaleli, 2021; Adeneye et al., 2021). Particularly noteworthy is the substantial increase in atmospheric CO2 levels, which rose by approximately 30% between the 19th and 20th centuries (Erdoğan et al., 2022).

The International Energy Agency (IEA, 2017) has estimated that the energy sector is responsible for a substantial 69% of global carbon equivalent CO2em, with fuel-based energy sources, including coal, gas, and petrol, contributing to approximately 44% of this total. Furthermore, intensive industrialization, manufacturing, transportation, and refrigeration practices have engendered a notable increase in other greenhouse gas (GHG) emissions, adversely affecting environmental quality, as corroborated by Verma et al. (2021). Moreover, research findings have indicated that heightened GHG emissions are closely associated with increased levels of economic growth, as evidenced in the study by Wang et al. (2022). On a global scale, the escalation in CO2em is predominantly attributed to the upsurge in industrial activities and elevated energy consumption, an assertion substantiated by the work of Callan et al. (2009).

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The global challenge of global warming is intricately linked to the emission of CO2, a predominant GHG. As industrial activities and energy consumption accelerate, certain countries emerge as major contributors to global CO2em. Currently, the top ten emitter countries account for a significant portion of worldwide CO2em (IEA, 2023; Global Carbon Atlas, 2023). These countries' economic activities, industrial demands, and energy policies critically influence the global carbon footprint. For instance, China, as the largest emitter, is responsible for nearly 30% of global emissions, driven by its rapid industrialization and coal dependency. The United States follows, with substantial emissions from transportation and energy sectors, despite recent strides in renewable energy adoption. Meanwhile, India's emissions continue to rise alongside its economic growth and reliance on fossil fuels. Addressing the carbon emissions of these key countries is essential for global emissions reduction targets, highlighting the need for international collaboration and sustainable policy strategies (United Nations Framework Convention on Climate Change, UNFCCC, 2023).

To adverse impacts of climate change, it is essential to adopt sustainable energy solutions, which entail the application of strategic measures aimed at managing and decreasing human-induced greenhouse gas emissions. These approaches include investing in environmentally friendly technologies, enhancing energy efficiency and conservation efforts, promoting transportation options that minimise carbon emissions, enacting policies and regulations that support sustainable energy use, and raising public awareness and education on these issues (Marunda et al., 2013).

This research focuses on identifying the factors that lead to the rise in CO2 em and assessing the helpfulness of decisions targeted at reducing these emissions and promoting sustainable development in the ten countries with the highest emissions. It specifically examines how economic growth, different types of energy sources (RE, NRE), industrial expansion and financial development influence the reduction of emissions. The study uses the PMG-ARDL methodology and Granger causality tests to explore the short-term and long-term interactions among these variables. Moreover, it explores the EKC hypothesis by assessing the relationship between GDP and CO2 within the selected countries. The top ten CO2-emitting countries were chosen because of their substantial role in global emissions, making them essential for understanding environmental challenges and climate policies.

2. Literature Review

The literature review explores the intricate relationships between economic systems and environmental outcomes, focusing on several key areas. It examines the EKC hypothesis, which suggests an inverted U-shaped relationship between economic growth and environmental degradation, indicating that prosperity can lead to improved ecological quality (Arouri et al., 2012; Akbostanci et al., 2009). The impact of energy consumption on pollution is another focal point, with non-renewable energy negatively affecting CO2em and renewable energy offering the potential for sustainable development (Adedoyin et al., 2020a; Apergis et al., 2018). The industrial sector is studied for its dual role in economic advancement and environmental harm, highlighting the need for cleaner industrial practices (Rauf et al., 2018). Financial development is seen as a driver for environmental improvements through investments in sustainable technologies, as suggested by previous analyses indirectly connected to financial impacts on green innovations. Lastly, the transition to renewable energy is emphasized as crucial for reducing emissions while sustaining economic growth (Bhattacharya et al., 2017; Ito, 2017). Together, these areas provide a comprehensive understanding of how diverse factors contribute to or mitigate climate change impacts, with implications for policy and sustainable economic strategies.

Global warming and climate change are critical issues at the intersection of environmental and economic spheres. Sari and Soytas (2009) highlight that greenhouse gases, notably CO2em, are the primary drivers of global warming and its effects. This realization has led scholars and policymakers to explore the complex relationship between climate change, energy production, and sustainable economic development. Various analytical methods have been applied to study these relationships. One area of economic literature examines the link between economic growth and environmental pollution, focusing on the EKC hypothesis, as explored by Arouri et al. (2012). This hypothesis proposes an inverted U-shaped relationship between different pollutants and per capita income, suggesting that environmental degradation worsens with initial economic growth but begins to improve as a country continues to prosper, thereby outlining a specific correlation between economic growth and environmental quality.

Previous studies have primarily focused on the environmental impacts of large-scale fossil fuel consumption, which result from the intensive use of these fuels in various sectors driving economic growth. In related economic literature, the connection between economic development, energy consumption, and pollution has been examined. For example, Adedoyin et al. (2020a, b) studied the impact of coal consumption, coal rent, and economic growth on CO2 emissions in the BRICS countries (Brazil, Russia, India, China, and South Africa). Using time series analysis, they emphasized the necessity of implementing environment-related regulations to achieve green and sustainable growth. Similarly, Apergis et al. (2018) found that renewable energy use and healthcare expenditures led to a decrease in CO2em, while real GDP was linked to increased CO2em in African countries from 1995 to 2011. Mitić et al. (2017) used cointegration analysis to study the relationship between GDP and CO2em in transitioning countries. Numerous other studies, such as those by Akbostanci et al. (2009), Jaunky (2011), and Narayan and Narayan (2010), have explored the complex dynamics between economic growth and environmental pollutants. Additionally, various researchers, including Ang (2008), Soytas et al. (2007), and Sadorsky (2009), have investigated the interplay between economic growth, energy consumption, and environmental pollutants. Tugcu et al. (2012) conducted a comparative analysis of renewable and non-renewable energy in the G7 countries, revealing a bidirectional causality between economic growth and both types of energy consumption within a classical production function framework. Lastly, Ocal and Aslan (2013) examined the causal relationship between renewable energy consumption and output in Turkey.

3. Data and Method

To test the Porter hypothesis in the BRICS countries, we obtained data from the data service of World Bank from 1990 to 2019 / 2020. We employ two different models to measure the influence of EPS. In first model we consider Trade (% of GDP) and in the second model the study employs TFP as the dependent variables.

Models:

$$Trade\ (\%\ of\ GDP) = \beta_0 + Environmental\ Policy\ Stringency\ Index\ (EPS) + u_i$$

$$TFP = \beta_0 + Environmental\ Policy\ Stringency\ Index\ (EPS) + u_i$$

4. Methodology

The empirical assessment of the interconnections under examination within this research proceeds via a bifurcated econometric methodology. The initial stage involves an evaluation of the stochastic properties of each variable, specifically their stationarity, through the application of the Augmented Dickey-Fuller (ADF) unit root test. Subsequently, the Autoregressive Distributed Lag (ARDL) bounds testing framework is leveraged to ascertain the presence of enduring equilibrium associations, or cointegration, among the series.

As a preliminary step to investigating cointegration, establishing the order of integration for each time series is imperative. Although the ARDL methodology is robust to mixed orders of integration, it is crucial to confirm through unit root diagnostics that no series is integrated of order two, I(2), as this would compromise the validity of the F-statistics derived from the bounds test (Duasa, 2007; Ozturk & Acaravci, 2011). For this purpose, the research utilizes the Augmented Dickey-Fuller (ADF) test. This test, an advancement of the original Dickey-Fuller (1979) procedure, mitigates potential serial correlation in the residuals through the incorporation of lagged differences of the dependent variable (Said & Dickey, 1984; Xiao & Phillips, 1998). The ADF procedure tests the null postulate that a given time series contains a unit root (exhibiting non-stationary behavior) against the alternative postulate of stationarity. The standard specification for the ADF test regression is formulated as follows:

$$\Delta Y_t = \alpha + \beta_t + \rho Y_{t-1} + \Sigma\delta_i \Delta Y_{t-i} + \varepsilon_t$$

where Δ is the first difference operator, Y_t is the variable under investigation, α is the intercept, t is a time trend, ρ is the coefficient of interest, and ε_t is the white noise error term. The number of lagged difference terms ($\Sigma\delta_i \Delta Y_{t-i}$) is typically determined by an information criterion such as the Schwarz Bayesian Criterion (SBC) or Akaike Information Criterion (AIC) to ensure that the residuals are serially uncorrelated.

Subsequent to the verification of the integration order for each time series and the exclusion of any variables found to be integrated of order two (I(2)), the research proceeds to examine potential long-run equilibrium relationships. This is achieved through the application of the Autoregressive Distributed Lag (ARDL) bounds testing approach, a methodology pioneered by Pesaran and Shin (1995) and further developed by Pesaran et al. (2001). The ARDL technique presents several distinct advantages over conventional cointegration analysis methods, such as the Engle-Granger or Johansen procedures. A key strength lies in its applicability to variables irrespective of whether they are integrated of order zero (I(0)), order one (I(1)), or a combination thereof (Odhiambo, 2009; Duasa, 2007). Moreover, this framework is recognized for its robust performance even with limited sample observations (Duasa, 2007; Ali et al., 2017) and offers the flexibility to accommodate distinct optimal lag structures for individual variables within the specified model (Duasa, 2007).

The core of the ARDL bounds testing framework involves the estimation of an Unrestricted Error Correction Model (UECM), which is specified as follows:

$$\Delta Y_t = \alpha + \lambda Y_{t-1} + \delta X_{t-1} + \sum_{i=1}^{p} \phi_i \Delta Y_{t-i} + \sum_{j=0}^{q} \theta_j \Delta X_{t-j} + \varepsilon_t$$

where Y_t is the dependent variable, X_t is a vector of independent variables, Δ is the first difference operator, α is the intercept, and ε_t is the white noise error term. The terms $\sum_{i=1}^{p} \phi_i \Delta Y_{t-i}$ and $\sum_{j=0}^{q} \theta_j \Delta X_{t-j}$ represent the short-run dynamics, while λ and δ represent the long-run coefficients.

The determination of an enduring equilibrium association among the variables is accomplished by performing an F-test, or alternatively a Wald test, on the collective statistical significance of the coefficients associated with the lagged level variables. Specifically, the null hypothesis (H_0), stipulating no cointegration. The computed F-statistic is then evaluated against two distinct sets of asymptotic critical values, as proposed by Pesaran et al. (2001). These comprise a lower critical bound, predicated on the assumption that all regressors are integrated of order zero (I(0)), and an upper critical bound, assuming all regressors are integrated of order one (I(1)). Rejection of the null hypothesis, and thus inference of cointegration, occurs if the F-statistic surpasses the upper critical value. Conversely, if the F-statistic is less than the lower critical value, the null hypothesis of no cointegration is not rejected. An F-statistic falling within the corridor between the lower and upper bounds renders the test inconclusive regarding the presence of cointegration. It is pertinent to note that for analyses constrained by limited sample sizes, the critical values developed by Narayan (2005) are frequently employed as they are considered more appropriate under such conditions (Duasa, 2007; Ali et al., 2017).

Upon confirmation of a cointegrating relationship, the estimation of the conditional ARDL long-run model for Y_t is undertaken. Following this, the short-run adjustment dynamics are elucidated through the specification and estimation of an Error Correction Model (ECM):

$$\Delta Yt = \alpha_0 + \sum_{i=1}^{p-1} \lambda_i \Delta Y_{t-i} + \sum_{j=0}^{q-1} \omega_j \Delta X_{t-j} + \psi ECM_{t-1} + \nu_t$$

where ψ is the coefficient of the error correction term (ECM_{t-1}). This coefficient indicates the speed of adjustment back to long-run equilibrium after a short-run shock. For convergence to equilibrium, the coefficient ψ is expected to be negative and statistically significant (Odhiambo, 2009; Ali et al., 2017).

5. Empirical Results

As a first step of the study, we first apply the ADF unit root test to determine the integration levels of the variables and provide the findings in the following:

Table 1. The Findings of ADF Unit Root Test

Series	t-Stat	Prob.	Lag
EPS_BRAZIL	-1.1337	0.6891	0
EPS_CHINA	0.7569	0.9915	0
EPS_INDIA	1.4268	0.9986	3
EPS_RUSSIA	-1.0486	0.7225	0
EPS_SAFRICA	-1.1016	0.7008	2
TFP_BRAZIL	0.2455	0.9709	0
TFP_CHINA	-1.4497	0.5437	1
TFP_INDIA	1.3086	0.9981	0
TFP_RUSSIA	-0.9872	0.7417	0
TFP_SAFRICA	-0.7254	0.8248	0
TRADE_BRAZIL	-1.9094	0.3226	6
TRADE_CHINA	-1.888	0.333	1
TRADE_INDIA	-1.92	0.318	6
TRADE_RUSSIA	-0.0023	0.9494	6
TRADE_SAFRICA	-1.8009	0.3729	0

The results in Table 1 indicate that all variables exhibit a unit root, I(1), hence we analyse the long-run link among the variables using the ARDL Bounds Test which has good sample properties in the small-samples. We consider EPS as the independent variable and TFP or Trade as the dependent variable. We tabulate the findings in Table 2:

Table 2. The Findings of the ARDL Test

Country	Depentent Variable	Test Statistics

Brazil	TFP	3.063667
	TRADE	1.971041
China	TFP	1.148626
	TRADE	1.660739
India	TFP	6.191011*
	TRADE	1.323831
Russia	TFP	3.125708
	TRADE	18.85906*
South Africa	TFP	0.987839
	TRADE	1.103602

The critical values at the 5% levels are 3.62 and 4.16.

Since the test statistic for the ARDL test exceeds the upper critical value, it is ponted that there is a long-run link for India for the relationship between TFP and EPS, and for Russia for the relationship between TRADE and EPS.

We, next, forecast the long-run and present the findings in the following:

Table 3. Long-run coefficients

Country	Dependent Variable	Regressors	t-stat	p-values
India	TFP	EPS_INDIA	0.166774	0
		C	0.584069	0
Russia	Trade	Russia EPS_RUSSIA	-15.49574	0.0002
		C	65.40527	0

The findings in Table 3 show that the EPS has a positive effect on TFP for India, while it has a negative effect on Trade for Russia in the long run.

6. Conclusion

This paper embarked on an empirical investigation into the legitimacy of the PH within the distinct economic and ecologic context of the BRICS nations, thanks to panel data from 1990 to 2019. By examining the relationship between EPS, proxied by the OECD's EPS Index, and two key economic performance indicators—Total Factor Productivity (TFP) and trade openness (Trade as % of GDP)—our research aimed to shed light on whether stringent environmental regulations can foster productivity and competitiveness in these pivotal emerging economies.

The empirical results, derived from ARDL bounds testing and long-run coefficient estimation, present a nuanced and heterogeneous picture across the BRICS bloc, underscoring the country-specific nature of the environment-economy nexus. For India, evidence of a statistically significant positive long-run linkage was identified among EPS and TFP. This finding lends credence to the 'solid' type of the PH, proposing that, in the Indian context, more stringent environmental policies may indeed stimulate innovation and efficiency improvements that ultimately enhance overall productivity. This implies that well-designed environmental regulations could be a strategic tool for fostering sustainable economic development in India.

Conversely, for Russia, the analysis revealed a statistically significant negative long-run relationship between EPS and trade. This outcome appears to contradict the strong PH's assertion that stringent regulations enhance international competitiveness. It suggests that, for Russia, during the period under review, the costs associated with stricter environmental compliance may have outweighed any innovation-induced benefits, thereby potentially hindering its international trade performance. For the residual BRICS countries—Brazil, China, and South Africa—the ARDL bounds tests did not establish a significant long-run cointegrating relationship between EPS and either TFP or trade with the employed model specifications. This lack of a discernible consistent impact across the entire bloc highlights the complexity of the PH and suggests that its tenets may not be universally applicable without considering specific national characteristics, industrial structures, and the precise nature and enforcement of environmental policies.

This study, while providing valuable insights, has certain limitations. The use of aggregate country-level data for TFP and trade, and a composite EPS index, may mask significant sectoral, firm-level, and policy-instrument-specific heterogeneities. Future research could delve deeper by:

- Employing firm-level or industry-specific data to provide a more granular understanding of the processes through which ecological regulations affect fertility and competitiveness.
- Disaggregating the EPS index to examine the heterogeneous outcomes stemming from multiple types of ecological policy mechanisms (e.g., market-based vs. command-and-control).
- Exploring the influence of other contextual factors, such as institutional quality, level of economic development, technological capabilities, and natural resource dependence, in moderating the PH.
- Expanding the timeframe and incorporating more sophisticated dynamic panel data techniques to capture lagged effects and address potential endogeneity more comprehensively.

In conclusion, while the Porter Hypothesis offers a compelling vision of a "win-win" scenario regarding the objectives of ecological care and economic performance, its applicability in the BRICS context is conditional and varies significantly by country and by the specific economic outcome considered. Our findings underscore the need for nuanced, context-specific policy design and further research to fully understand and harness the potential synergies between environmental sustainability and economic prosperity in these globally significant emerging economies.

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Micromobility, Open Data, and Sustainability: A Global and Türkiye-Focused Analysis

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Abstract

This paper examines the role of micromobility systems—such as bike-sharing and e-scooters—in promoting urban sustainability, with a focus on the integration of open data for policy and research. Through a review of recent academic literature and analysis of open datasets from Türkiye and global sources, we assess the environmental, social, and economic impacts of micromobility. The study highlights how open data can enhance transparency, support evidence-based planning, and contribute to sustainable urban mobility transitions. Findings suggest that while micromobility adoption is growing globally, its sustainability benefits are maximized when supported by robust data infrastructure and inclusive policies.

Keywords: Micromobility, open data, sustainability, bike-sharing, urban mobility

JEL Classification: O18, Q56, R41, L92

1. Introductionş

Micromobility has emerged as a key component of sustainable urban transport, offering low-carbon alternatives to private car use. The proliferation of shared bicycles, e-scooters, and other small-scale mobility devices has been accelerated by digital platforms and increasing environmental awareness. This paper explores the intersection of micromobility, open data, and sustainability, with a particular focus on global trends and case studies from Türkiye. The availability of open data from public and private sources provides unprecedented opportunities to analyze usage patterns, evaluate impacts, and inform policy. While shared e-scooter systems offer significant promises for sustainable urban transport (Schellong et al., 2019), they have also introduced new challenges such as sidewalk clutter and safety concerns. This study aims to examine this balance of opportunities and challenges in the Turkish context through the lens of open data.

2. Literature Review

Recent literature emphasizes the potential of micromobility to reduce greenhouse gas emissions, alleviate traffic congestion, and improve public health (Kopplin et al., 2021). However, challenges related to safety, regulation, and equity remain (Gössling, 2020). City-scale studies on shared e-scooter usage indicate that this mode is typically preferred for short-distance (1-3 km) and short-duration (10-15 minute) trips (Jiao & Bai, 2020).

The effectiveness of micromobility systems can be enhanced by understanding the heterogeneous nature of user behaviors. Degele et al. (2018) used cluster analysis to segment e-scooter users into distinct groups and discussed policy implications for each segment. The role of data transparency and accessibility in optimizing micromobility systems is increasingly recognized (Nikiforiadis et al., 2021).

Recent systematic literature reviews on the role of micromobility in shaping sustainable cities (Abduljabbar et al., 2021) indicate that research is still largely focused on developed Western contexts and that the role of open data in planning remains an underexplored area. This study aims to fill this gap by utilizing open datasets from Türkiye.

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2.1 Open Data in Mobility Research

Open data platforms enable researchers and policymakers to monitor system performance, identify demand patterns, and assess sustainability metrics (Nikiforiadis et al., 2021). Studies leveraging open data have demonstrated improvements in service planning and user engagement (Song et al., 2022).

3. Data and Method

This study employs a mixed-methods approach, combining a systematic review of academic literature (2019–2024) with quantitative analysis of open datasets from Türkiye and international sources. Data were collected from academic databases, public data portals, and industry reports.

3.1 Data Sources

We utilize three primary open data sources:
1. NABSA 2024 Report – Provides global benchmarks and time-series data on shared micromobility usage (NABSA, 2025).
2. "Konya Metropolitan Municipality Bike-Sharing Data" – CSV datasets detailing trip records, duration, and station-level usage (KBB, 2025).
3. "İzmir Metropolitan Municipality 2020 Bicycle and Pedestrian Count Data" – Sensor-based counts from monitoring stations (İzBB, 2025).

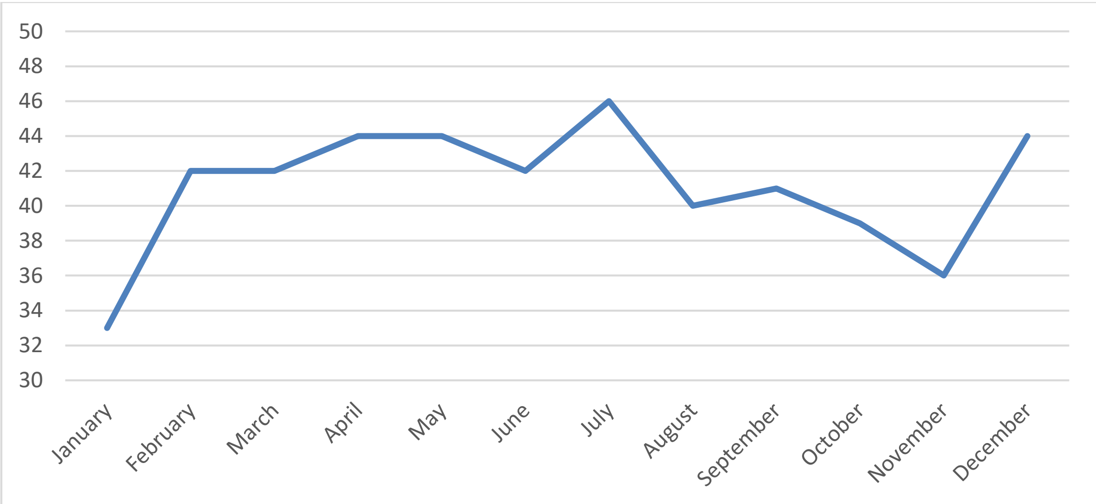

Figure 1: Monthly Average Bike Rental Durations in Konya (2024)
Source: Konya Open Data Portal, processed by authors.

Similarly with Degele et al. (2018) the bike-sharing data from Konya reveals different user patterns. Analysis of Konya's bike-sharing data reveals peak usage on weekdays during commuting hours. Weekends show more recreational use, with longer average trips. By own calculations via Konya 2024 Rental Bike Usage Data, average travel duration is nearly 41 minutes and average trip distance is about 2 kilometres. Jiao & Bai's (2020) finding of 10-15 minute average shared e-scooters travel time, when compared to the average 41-minute bicycle trip duration in Konya, the data supports the range-vehicle selection by Schellong et al. (2019). These patterns align with global trends where micromobility serves both utilitarian and leisure purposes.

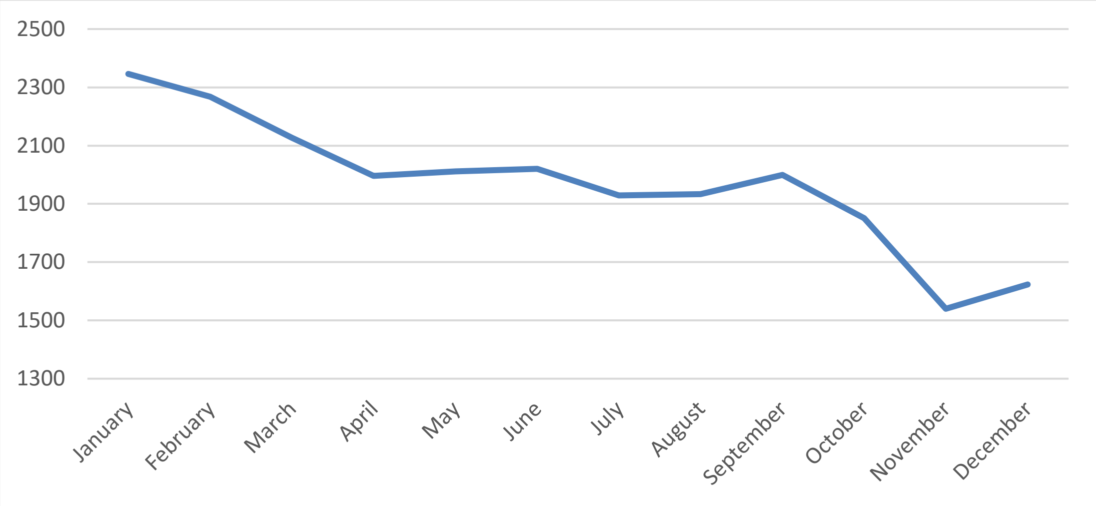

Figure 2: Monthly Average Bike Travel Distances in Konya (2024)
Source: Konya Open Data Portal, processed by authors.

Table 1: Konya Bike Rental Monthly Average Values

Month	Record Count	Average Duration (min.)	Average Distance (m)
January	1629	33	2346
February	2443	42	2268
March	3967	42	2127
April	6500	44	1996
May	8247	44	2012
June	7028	42	2020
July	5767	46	1929
August	4399	40	1933
September	4165	41	1999
October	4596	39	1851
November	2054	36	1540
December	1472	44	1623
Average	4356	41	1970

Source: Konya Open Data Portal, processed by authors.

4. Empirical Analysis

Our review of recent studies indicates strong evidence that micromobility can reduce per-capita transport emissions, especially when integrated with public transit (Reck et al., 2021). Data from Konya and İzmir illustrate the potential for local governments to use open data for infrastructure planning—for instance, identifying demand hotspots for new bike lanes or parking zones. Prediction on micromobility has an attracting intense interest in recent literature (Durmaz & Türkan, 2025). Understanding the spatial distribution of micromobility trips is critical for infrastructure planning. Hosseinzadeh et al. (2021) demonstrated how shared e-scooter trips tend to cluster in urban areas in terms of density and distance. This study methodologically supports why the spatial analysis of bicycle and pedestrian count data in İzmir is important.

Usage in micromobility systems tends to show distinct peaks during morning and evening commute hours, indicating their function as a complement to public transit (Liu et al., 2019). The weekday peak usage pattern observed in Konya dataset confirms this universal urban phenomenon.

The NABSA (2024) report highlights those cities with open data policies see higher user satisfaction and more efficient system rebalancing. In Türkiye, the availability of granular, machine-readable data from municipalities like Konya and İzmir represents a significant step toward data-driven urban mobility management.

5. Conclusion

Micromobility, supported by open data, offers a viable pathway toward sustainable urban transport. This study underscores the importance of accessible, high-quality data for evaluating and scaling micromobility solutions. For Türkiye, expanding open data initiatives and fostering public–private data partnerships can enhance the sustainability impact of micromobility systems. Future research should focus on longitudinal data analysis and equity assessments to ensure inclusive mobility transitions.

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Examining Sustainable Tourist Behavior: A Perspective on Travel Motivation and Perceived Value

Betül Garda[1]

Abstract

This study conceptually examines sustainable tourist behavior within the framework of travel motivation and perceived value and proposes a conceptual model to explain the relationships between these variables. While existing studies on sustainable tourist behavior in the tourism literature mostly focus on variables such as attitude, awareness, and behavioral intention, this study evaluates the formation process of behavior from a motivation and experience-based perspective. Accordingly, travel motivations, which express the reasons for tourists' participation in travel, and perceived value, encompassing the economic, emotional, social, and experiential dimensions of the travel experience, are considered together. Conceptual evaluations show that travel motivations influence how tourists make sense of their experience, and perceived value plays an explanatory role in reflecting these experiences in sustainable behaviors. By considering sustainable tourist behavior not as a one-dimensional outcome, but as a process shaped by the interaction of motivation and experience, the study offers a holistic conceptual perspective to the literature. Furthermore, it is considered that the proposed model can provide a theoretical foundation for future empirical studies.

Keywords: Sustainable tourist behavior, Travel motivation, Perceived value

1. Introduction

The tourism sector is at the center of sustainability discussions due to its environmental, social, and cultural impacts, in addition to its economic contributions. In this context, the success of sustainable tourism depends not only on the practices of destinations or businesses but also on the behaviors exhibited by tourists during their travels. In recent years, the literature has emphasized that tourist behavior plays a decisive role in achieving sustainability goals and that these behaviors need to be examined in greater depth (Becken and Simmons, 2002; Gühnemann et al., 2021; Li et al., 2024).

Sustainable tourist behavior refers to tourists making choices during their travels that are sensitive to environmental resources, respectful of local communities, and attentive to cultural values. However, it is observed that in the literature, this behavior is often addressed only at the level of intention, awareness, or attitude; holistic conceptual frameworks explaining the formation process of the behavior remain limited (Li et al., 2024). This situation increases the need for theoretical models that focus on the antecedents of behavior in explaining sustainable tourist behavior.

In studies aimed at understanding tourist behavior, travel motivation is considered a fundamental concept explaining the reasons why individuals travel and their expectations from travel. The literature shows that travel motivations are examined in different dimensions such as rest and relaxation, entertainment, culture, health, social relationships, and personal development (Yousaf et al., 2018; Chi & Phuong, 2022; Kim et al., 2019). It is accepted that these motivations directly influence tourists' preferences and behavioral patterns during the travel process. However, explaining tourist behavior solely through motivations is not considered sufficient; the concept of perceived value, which expresses how tourists evaluate their travel experiences, is gaining increasing importance. Perceived value refers to tourists

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evaluating their travel experience beyond economic benefit, considering its experiential, emotional, and social dimensions (Pearce and Wu, 2018; Villamediana-Pedrosa et al., 2020). Perceived value is found to have an impact on tourist satisfaction and behavioral tendencies; It is emphasized that this effect can also be decisive in the context of sustainability (Toubes et al., 2021).

When the existing literature is examined, it is noteworthy that the concepts of travel motivation and perceived value are mostly dealt with separately; and that holistic conceptual models on how these two elements together shape sustainable tourist behavior are limited. However, evaluating sustainable tourist behavior within the framework of the interaction between the motivational meanings that tourists attribute to the travel process and the value perceptions formed as a result of the experience can allow for a more comprehensive understanding of the behavior (Li et al., 2024).

The aim of this study is to propose a conceptual model for sustainable tourist behavior that explains the relationships between these concepts by addressing sustainable tourist behavior from the perspective of travel motivation and perceived value. In this respect, the study aims to provide a conceptual basis for future empirical research and to contribute to the sustainable tourism literature at a theoretical level.

2. Conceptual Framework

2.1. Sustainable Tourist Behavior

The consideration of tourist behavior in the context of sustainability is based on early studies on the environmental impacts of tourism. Becken and Simmons (2002), by examining the effects of tourist activities on energy consumption and resource use, revealed that the sustainability of tourism is directly related not only to supply-side policies but also to the individual behaviors of tourists. This approach is considered one of the pioneering studies emphasizing that tourist behavior should be at the center of sustainability discussions.

From this perspective, sustainable tourist behavior refers to the shaping of tourists' choices and actions during their travel process with an awareness of their environmental, social, and cultural consequences. Tourists' transportation preferences, accommodation types, consumption habits, and intra-destination mobility are among the key behavioral areas that determine their impact on sustainability (Becken & Simmons, 2002; Kellerman, 2016). Therefore, achieving sustainable tourism goals is closely related to tourists' preferences in these behavioral areas.

Over time, the concept of sustainable tourist behavior has evolved to encompass not only environmental awareness but also; Sustainable tourist behavior has begun to be addressed within a broader framework, encompassing interaction with local communities, respect for cultural heritage, and responsible consumption (Richards, 2018; Gühnemann, Kurzweil & Mailer, 2021). This demonstrates that tourist behavior exhibits a multidimensional structure and that sustainability includes not only environmental but also social and cultural dimensions. However, the literature often examines sustainable tourist behavior through the concepts of attitude, awareness, and behavioral intention; holistic theoretical frameworks explaining how behavior is formed remain limited. Li et al. (2024), in their systematic literature review on sustainable tourist behavior, emphasize that a significant portion of existing studies focus on the intention-behavior distinction, but that the motivational and experiential processes shaping tourist behavior are not addressed holistically enough. Sustainable tourist behavior is not a static characteristic, but rather a dynamic process shaped by tourists' pre-travel expectations, in-travel experiences, and post-travel evaluations. Kirillova et al. (2018) argue that tourist behavior should be evaluated in conjunction with the meanings individuals attribute to experiences and the social context. This approach suggests that sustainable behavior should be considered not only within the framework of normative expectations or ethical responsibilities, but also within the context of individual evaluation and meaning-making processes.

Furthermore, the literature frequently emphasizes that tourist behavior does not exhibit a homogeneous structure; different travel purposes and types of experiences produce different behavioral patterns. It is stated that special purpose travel, such as cultural, health, recreational, or social visits, shapes tourists' relationship with the destination and their behavior in the context of sustainability in different ways (Backer, 2012; Yousuf & Backer, 2015; Özdemir & Yolal, 2017).

In this context, sustainable tourist behavior needs to be considered together with the motivational meanings tourists attribute to travel and the value perceptions formed as a result of the experience. Indeed, Li et al. (2024) emphasize that future studies aimed at explaining sustainable tourist behavior should address motivation and experience-based variables within the framework of holistic conceptual models.

2.2. Travel Motivation Perspective

Travel motivation is one of the fundamental concepts explaining why individuals travel and what they expect from the travel process. In studies aimed at understanding tourist behavior, motivation is considered a decisive element in the formation of travel decisions and the shaping of behavioral patterns exhibited during the travel process. In this context, travel motivation is considered a precursor to tourist behavior and plays a critical role in understanding sustainable tourist behavior (Yousaf et al., 2018).

In the literature, travel motivations are classified under different dimensions in line with individuals' physical, psychological, and social needs. It is stated that types of motivation such as rest and relaxation, entertainment, cultural exploration, health, social relationships, and personal development affect tourists' travel preferences and the relationship they establish with the destination in different ways (Kim et al., 2019; Chi & Phuong, 2022). These motivations determine the meaning that tourists attribute to the travel process and shape the direction of behavioral tendencies.

It is emphasized that travel motivations influence not only the decision to participate in travel but also the behavioral patterns exhibited during the trip. Yousaf et al. (2018) state that tourist motivations directly affect the activities tourists perform in the destination, their consumption habits, and the satisfaction they derive from the experience. Similarly, Chi and Phuong (2022) reveal that travel motivations play a decisive role in tourists' behavioral tendencies. Behavioral reflections of motivations become more pronounced, especially in special-purpose travel such as recreation, health, culture, and social visits. While Blešić et al. (2019) emphasize that rest and rejuvenation motivation shapes tourist behavior in wellness and health-based travel; Backer (2012) and Yousuf and Backer (2015) state that the motivation of visiting relatives and friends (VFR) differentiates tourists' consumption and mobility patterns. These findings show that travel motivations do not exhibit a homogeneous structure and can produce different behavioral patterns. When considered in the context of sustainability, travel motivations are not limited solely to individual satisfaction It is also seen to be related to tourists' perceptions of environmental and social responsibility. The literature emphasizes that meaning-based motivations such as culture and health can strengthen tourists' tendency to exhibit more sensitive and responsible behaviors towards the destination (Richards, 2018; Kim et al., 2020). This shows that travel motivations are an important precursor in the formation of sustainable tourist behavior. However, Li et al. (2024) argue that motivation-based approaches in the literature on sustainable tourist behavior should be integrated with experiential and perceptual elements.

In this study, travel motivation is considered as one of the fundamental antecedents of sustainable tourist behavior; it is assumed that motivations, how tourists make sense of their travel experience, and how this process is transformed into behavioral outcomes should be evaluated within the framework of the concept of perceived value. This approach forms the first building block of the proposed conceptual model.

2.3. Perceived Value and Tourist Experience

Perceived value is one of the fundamental concepts that expresses how tourists evaluate their travel experience and what meanings they attribute to this experience. In tourism literature, perceived value is not limited only to economic benefit or price-performance ratio. It is considered as a multifaceted structure including experiential, emotional, social, and symbolic dimensions (Pearce & Wu, 2018; Villamediana-Pedrosa, et al., 2020). In this respect, perceived value is considered a critical intermediary concept in explaining tourist behavior.

Tourist experience is a holistic process consisting of pre-travel expectations, interactions during travel, and post-travel evaluations. In this process, tourists make sense of their experience through subjective evaluations, and these evaluations are decisive in the formation of behavioral tendencies (Kirillova, et al., 2018). Perceived value is at the center of this meaning-making process and shapes tourists' overall attitudes towards destinations, services, and experiences. It is widely accepted in the literature that perceived value has a significant impact on tourist satisfaction, commitment, and behavioral tendencies. Villamediana-Pedrosa et al. (2020) demonstrate that perceived value directly affects tourists' interaction with the destination and their level of behavioral engagement. Similarly, Pearce and Wu (2018) emphasize that the perceived value of tourists in entertainment and experience-oriented activities guides their behavior patterns and destination experience evaluation processes.

When considered in the context of sustainability, perceived value is seen to be associated not only with individual satisfaction but also with perceptions of environmental and social responsibility. Toubes et al. (2021) state that the value tourists perceive from their travel experience is effective in the formation of sustainable consumption patterns. In this context, perceived value is considered an important psychological and experiential mechanism in guiding tourists towards sustainable behaviors.

The literature also emphasizes that travel motivations play a decisive role in the formation of perceived value. The motivations behind tourists' travel influence how they evaluate their experience and the elements they value (Chi & Phuong, 2022; Kim et al., 2019). For example, it is stated that tourists traveling with cultural or health-based motivations place more importance on the meaning dimension of the experience; these shapes perceived value and related behaviors (Richards, 2018; Kim, et al., 2020).

However, in the current literature, perceived value is mostly associated with outcome variables such as tourist satisfaction or revisit intention. Its explanatory role in the formation process of sustainable tourist behavior is addressed to a limited extent. Li et al. (2024) emphasize that studies on sustainable tourist behavior should move towards holistic frameworks that consider experience-based concepts such as perceived value together with the antecedents of behavior.

In this study, perceived value is considered as a critical conceptual component explaining the relationship between travel motivations and sustainable tourist behavior. How tourists evaluate their travel experience and how these evaluations translate into sustainable behaviors constitutes one of the key explanatory mechanisms of the proposed conceptual model.

2.4. Holistic Assessment of Sustainable Tourist Behavior in the Context of Motivation and Perceived Value

A review of the literature on sustainable tourist behavior reveals that the behaviors exhibited by tourists during their travels have a multi-dimensional structure that cannot be explained by a single variable. While travel motivation stands out as a fundamental antecedent in the formation of tourist behavior, perceived value is considered a critical mechanism explaining how tourists evaluate their experience and how these evaluations translate into behavior (Yousaf et al., 2018). Considering these two concepts together allows for a more holistic understanding of sustainable tourist behavior. In the literature, travel motivation and perceived value are often addressed within different research lines. While motivation-based studies focus on the reasons why tourists travel and the behavioral consequences of these reasons (Yousaf et al., 2018; Chi & Phuong, 2022), perceived value-oriented studies examine outcomes such as the evaluation of the tourist experience, satisfaction, and commitment (Pearce & Wu, 2018; Villamediana-Pedrosa et al., 2020). However, the emergence process of sustainable tourist behavior makes it difficult to consider these two approaches independently.

In the context of sustainability, tourist behavior is closely related not only to the question of "why one travels" but also to the question of "how the travel experience is interpreted." The motivations that tourists possess determine which elements they value in the experience process; perceived value, on the other hand, can mediate the transformation of this experience into behavioral outcomes (Kim et al., 2019; Toubes et al., 2021). In this context, perceived value stands out as an integrative concept explaining the relationship between motivation and sustainable behavior. Li et al. (2024), in their comprehensive review of the literature on sustainable tourist behavior, emphasize that studies explaining the antecedents of behavior are mostly fragmented and that motivational and experiential processes are not considered within the same framework. This clearly reveals the need for more holistic conceptual models to explain sustainable tourist behavior. Similarly, Gühnemann et al. (2021) state that the effects of tourist behavior on sustainability cannot be adequately understood without considering individual evaluation processes. Furthermore, it is noted that different travel purposes have different effects on tourists' motivational structures and perceived value types; this also diversifies sustainable behavior tendencies (Backer, 2012; Richards, 2018; Kim et al., 2020). These findings show that sustainable tourist behavior has a context-sensitive structure and should be considered within the framework of motivation-value interaction.

This study assumes that travel motivation and perceived value should be evaluated together in understanding sustainable tourist behavior. Accordingly, the aim is to develop a holistic conceptual framework to explain sustainable tourist behavior.

3. Proposed Conceptual Model

This study assumes that sustainable tourist behavior is shaped by the motivational meanings tourists attribute to the travel process and the value perceptions resulting from their experiences. Evaluations within the theoretical framework reveal that sustainable tourist behavior cannot be explained by a single variable; individual evaluation processes such as motivation and perceived value must be considered together (Becken and Simmons, 2002; Yousaf et al., 2018; Li et al., 2024). Accordingly, this study proposes a holistic conceptual model to explain sustainable tourist behavior.

3.1. Theoretical Basis of the Model

The proposed conceptual model is based on the assumption that tourist behavior has a dynamic and process-based structure. Tourists' travel motivations determine the reasons why individuals travel and their expectations from travel; while perceived value explains how the travel experience is evaluated and how this evaluation is transformed into behavioral outcomes. While motivation is emphasized in the literature as an important antecedent of tourist behavior (Chi and Phuong, 2022; Kim et al., 2019), perceived value is also accepted as a critical mechanism shaping behavioral tendencies (Pearce and Wu, 2018; Villamediana-Pedrosa et al., 2020).

When considered in the context of sustainability, it is seen that tourists' evaluations of the travel process are not limited only to individual satisfaction; environmental and social impacts are also included in this evaluation process. Toubes et al. (2021) state that the perceived value of tourists plays a decisive role in the formation of sustainable consumption and behavior patterns. This shows that perceived value is directly related to sustainable tourist behavior.

3.2. Components of the Model

The proposed conceptual model consists of three main components. These are travel motivation, perceived value, and sustainable tourist behavior.

Travel Motivation

Travel motivation refers to the reasons why tourists participate in travel and their expectations from travel. The literature emphasizes that different types of motivation, such as relaxation, entertainment, culture, health, and social interaction, guide tourists' behavior in different ways during their travels (Yousaf et al., 2018; Blešić et al., 2019). In this context, travel motivation is positioned as a fundamental antecedent of sustainable tourist behavior in the model.

Perceived Value

Perceived value refers to tourists' evaluation of their travel experience in economic, experiential, emotional, and social dimensions. The level of value that tourists perceive as a result of their experience is considered an important factor determining the direction of behavioral tendencies (Villamediana-Pedrosa et al., 2020; Pearce and Wu, 2018). In the model, perceived value is considered as an integrative component explaining the relationship between travel motivation and sustainable tourist behavior.

Sustainable Tourist Behavior

Sustainable tourist behavior refers to tourists exhibiting behaviors that are sensitive to environmental resources, respectful of local communities, and attentive to cultural values during their travels. This behavioral pattern is shaped by tourists' individual evaluation processes and emerges as a result of the interaction between travel motivation and perceived value (Becken and Simmons, 2002; Li et al., 2024).

3.3. Proposed Conceptual Relationships

The proposed conceptual model includes the following relationships:

Travel motivation → Perceived value:

The motivations with which tourists participate in travel affect how they evaluate the experience and which elements they attribute value to (Chi and Phuong, 2022; Kim et al., 2019).

Perceived value → Sustainable tourist behavior:

Increased perceived value from the travel experience strengthens tourists' tendency to exhibit more responsible and sustainable behaviors (Toubes et al., 2021; Li et al., 2024).

Travel Motivation → Sustainable Tourist Behavior:

It is assumed that meaning-based motivations (culture, health, learning) are more strongly related to sustainable behavior tendencies (Richards, 2018; Kim et al., 2020).

These relationships form the basis of the conceptual model that predicts that sustainable tourist behavior can be explained within the framework of the interaction between travel motivation and perceived value.

3.4. Theoretical Contribution of the Model

The proposed conceptual model offers a theoretical contribution to the literature by addressing sustainable tourist behavior from a motivation and experience-based perspective. Responding to the need for a holistic and behavior-oriented framework for sustainable tourist behavior, as highlighted by Li et al. (2024), this model serves as a conceptual roadmap for future empirical studies.

4. Conclusion

This study proposes a holistic conceptual model for sustainable tourist behavior, addressing it from the perspectives of travel motivation and perceived value. The conceptual framework presented in this study, reveals that understanding sustainable tourist behavior through one-dimensional explanations is limited. Therefore, the motivational meanings tourists attribute to the travel process and their perceptions of value resulting from the experience must be evaluated together. This conceptual evaluation aligns with the need for a holistic model emphasized in the literature on sustainable tourist behavior (Li et al., 2024).

The proposed model treats tourist behavior not as a static characteristic, but as a mobility and experience-based process. This approach is consistent with Kellerman's (2016) assessments, which emphasize that increasing mobility and multiple travel purposes in tourism are making tourist behavior increasingly complex. The increase in tourist mobility increases the pressure on sustainability; this makes it even more important to address behavior within the framework of motivation and perceived value.

The results of the discussion also align with segmentation-based approaches that reveal that tourist behavior does not exhibit a homogeneous structure. Mumuni and Mansour (2014) emphasize that tourists develop different behavioral patterns according to their motivations and activity preferences. The model proposed in this study, without excluding segmentation approaches, offers a higher-level conceptual framework based on motivation and perceived value, creating a theoretical foundation for how sustainable tourist behavior can be shaped in the context of different tourist profiles. The role of perceived value in explaining sustainable tourist behavior constitutes another important dimension of the discussion findings. Villamediana-Pedrosa et al. (2020) reveal that perceived value has a decisive influence on tourist participation and behavioral tendencies. In this study, perceived value is considered not only as a result of post-experience satisfaction, but also as an integrative mechanism explaining the relationship between motivation and sustainable behavior. This approach shows that sustainable behavior is shaped not only by normative expectations, but also by the meaningful interpretation of the experience.

The proposed conceptual model also offers meaningful implications in the context of different types of tourism. Studies demonstrating that motivation and perceived value influence behavioral outcomes in health and wellness-based tourism (Seow et al., 2022; Zhao et al., 2025) support the testability of the model in different contexts. Similarly, studies emphasizing that motivational structures shape tourist behavior in cultural tourism and social interaction-focused travel (Marlina et al., 2024; Richards, 2018) show that the proposed model offers a context-sensitive framework. In this respect, the study also aligns with approaches that argue that tourism demand should be evaluated not only with quantitative indicators but also with behavioral and experiential dimensions (Song and Witt, 2012). Furthermore, studies highlighting the transformative potential of tourist sites and experience areas in tourist behavior (Sagalyn and Ashley, 2014) support the role of perceived value on sustainable behavior.

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Carbon Pricing Mechanisms and Corporate ESG Outcomes: An Empirical Analysis of Turkish BIST all Share index Listed Companies

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Abstract

This study investigates the comparative impact of carbon taxes and carbon emission trading systems (ETS) on the Environmental, Social, and Governance (ESG) performance of Turkish firms listed on the BIST All Shares index from 2015 to 2025. Using a multi-model approach, we analyze how these carbon pricing mechanisms influence ESG scores, CO_2 emissions, renewable energy adoption, and the cost of capital. Our findings reveal that while both carbon taxes and ETS are effective in reducing emissions, ETS is more successful in enhancing overall ESG performance, particularly by stimulating green innovation and easing financial constraints. Carbon taxes, on the other hand, may penalize firms financially without providing sufficient incentives for broader ESG improvements, though they do encourage investment in renewables. The results highlight the complex and sometimes paradoxical effects of carbon pricing on corporate sustainability, emphasizing the need for integrated policy design to achieve genuine environmental and financial benefits.

Keywords: Carbon Pricing Mechanisms, ESG, Borsa Istanbul.

1. Introduction and Literature

In this paper, we focus on the carbon tax and its environmental effects, comparing it with carbon emission trading. Over the past decade, research and practical experience have shown that carbon taxes and carbon trading are both key policy tools for reducing emissions, but their impacts on economic and environmental outcomes differ. Recent studies indicate that while both mechanisms can effectively reduce carbon emissions, carbon emission trading systems (ETS) tend to generate lower economic costs compared to carbon taxes, making them more attractive for policymakers seeking to balance environmental and economic objectives (Xu et al., 2023). However, carbon taxes may achieve greater total emission reductions over time, especially in energy-intensive industries (Xu et al., 2023).

With the development of financial markets in the 1990s, investors became increasingly motivated by stock market returns rather than tax incentives. This shift led environmental authorities to propose replacing carbon taxes with tradable carbon securities, allowing investors to purchase the right to emit carbon rather than paying a direct tax. These carbon securities, known as carbon emission trading certificates, were first issued by environmental authorities on primary financial markets at their nominal value. Investors wishing to emit carbon can buy these securities and either use them or engage in arbitrage to benefit from speculation on these certificates.

Empirical evidence from recent literature demonstrates that the implementation of carbon emission trading policies significantly improves the ESG performance of participating firms, particularly in heavy-polluting sectors (Dai & He, 2025; Zhang et al., 2023; Yu et al., 2025; Zhou et al., 2025; Tang et al., 2024; Han et al., 2024; Lin et al., 2024; Tian et al., 2024). The positive impact of ETS on ESG performance is primarily driven by the alleviation of financing constraints, stimulation of green technological innovation, and improved internal controls (Dai

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& He, 2025; Zhang et al., 2023; Yu et al., 2025; Zhou et al., 2025; Tang et al., 2024; Lin et al., 2024; Tian et al., 2024). These effects are especially pronounced in larger companies, state-owned enterprises, and firms with higher levels of digital transformation or government support (Zhang et al., 2023; Yu et al., 2025; Tang et al., 2024; Tian et al., 2024). In contrast, the effect of carbon taxes on ESG performance appears to be less significant, particularly in sectors such as real estate, where ETS-driven regulations more effectively promote environmental responsibility and participation in green initiatives (Lee & Liang, 2024).

In our empirical analysis, we test the effects of arbitrage between the carbon tax and carbon trading system, using a set of fundamental financial ratios to assess environmental factors such as the carbon emission rate, renewable production intensity, and the overall ESG score. The findings from recent literature suggest that carbon emission trading systems are more effective than carbon taxes in enhancing ESG performance, especially through mechanisms that encourage green innovation and responsible corporate behavior (Dai & He, 2025; Zhang et al., 2023; Yu et al., 2025; Zhou et al., 2025; Tang et al., 2024; Lin et al., 2024; Tian et al., 2024; Lee & Liang, 2024; Xu et al., 2023).

2. Methodology : Model design & Results

Our study focus on Turkish firms belonging to BIST all Shares of Istanbul Bursa. The number of theses firms is 563 and the period is from 2015 to 2025.

We have used 5 models: We start with broad sustainability outcomes and analyse how carbon pricing mechanisms impact ESG performance (Model 1). We then test whether such policies lead to real environmental outcomes in the case of corporate CO2 emissions (Model 2). From there we study the underlying mechanism of emissions reduction - that is, firms' use of renewable energy sources (Model 3). The last two models focus on financial implications: In Model 4 we examine how carbon pricing affects firms 'cost of equity, and in Model 5 how it affects the cost of debt. In combination, these models present a holistic picture of operational and financial responses to climate policy.

After estimation and checking test of theses models, we have found theses results summarized in Table 1.

Table 1: Estimation of models

	ESG	**Co2**	**Renewable energy**	**Equity Cost**	**Equity Debt**
Carbon Taxe	-2,127***	+0,401**	+0,137	+0,01	+1,660
Carbon Trading	+2,311**	+0,699***	-2,356	-0,02	-2,589
capital cost	+251,82 **	-7,290*	+2,547		
ESG				+0,003	+0,003

Recent research provides nuanced insights into the paradoxical effects of carbon taxes and carbon trading systems (ETS) on corporate ESG performance, supporting and clarifying the results observed in Table 1.

Theoretically, carbon taxes are intended to incentivize firms to reduce emissions by imposing a direct cost on carbon output. However, empirical studies show that carbon taxes can financially penalize companies without necessarily providing the resources or incentives needed to improve their overall ESG performance, especially in the social and governance dimensions (Xu et al., 2023; Jia & Lin, 2020). This aligns with findings that, while carbon taxes may achieve greater total emission reductions over time, they can also increase operational costs, leading firms to focus on short-term financial survival rather than holistic ESG improvements (Xu et al., 2023).

Despite this, the observed increase in renewable energy production suggests that firms are seeking to mitigate future carbon cost exposure by investing in sustainable alternatives. Guo et al. (2020) confirm that firms facing higher carbon cost burdens tend to improve their environmental ESG scores through renewable investments, though these may come at the expense of social or governance aspects.

In contrast, carbon trading systems (ETS) have been shown to significantly improve ESG performance, particularly by alleviating financing constraints and stimulating green innovation (Dai & He, 2025; Zhang et al., 2023; Yu et al., 2025; Zhou et al., 2025; Tang et al., 2024; Han et al., 2024; Lin et al., 2024; Tian et al., 2024). However, the ability to purchase emission allowances can allow some firms to maintain or even increase emissions within regulatory limits, sometimes reducing the incentive for real green investment (Han et al., 2024; Lee & Liang, 2024).

Moreover, the improvement in ESG scores under ETS is often driven by formal compliance and financial market perceptions rather than substantive environmental action, potentially leading to "greenwashing" or misleading signals to investors (Lin et al., 2024). When firms make genuine green investments, such as increasing renewable energy production, the immediate financial returns and ESG scores may actually decrease, as shareholders demand higher returns to compensate for increased costs, while creditors may lower interest rates in recognition of reduced risk (Xu et al., 2023; Lin et al., 2024).

Finally, price increases resulting from carbon regulation can enable firms to adjust profit margins and allocate more resources to social and governance improvements, mechanically boosting ESG scores even if environmental impact remains limited (Tian et al., 2024). This effect is more pronounced under ETS than under carbon tax regimes.

In summary, recent literature supports the complex and sometimes counterintuitive effects of carbon taxes and carbon trading on ESG performance, highlighting the importance of policy design and the need for integrated approaches to achieve genuine sustainability outcomes.

3. Conclusion

The analysis demonstrates that carbon emission trading systems (ETS) outperform carbon taxes in promoting ESG performance among Turkish listed firms, primarily by fostering innovation and improving access to finance. While carbon taxes can drive emission reductions and encourage renewable energy investments, they may also increase operational costs and limit improvements in social and governance dimensions. ETS, however, can sometimes lead to superficial ESG gains through compliance and market perceptions rather than substantive environmental action. These findings underscore the importance of carefully designed carbon pricing policies that balance environmental objectives with financial realities, ensuring that improvements in ESG performance are both meaningful and sustainable. Integrated approaches that combine the strengths of both mechanisms may offer the most effective path toward corporate sustainability and climate goals.

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Redefining Marketing Strategies through Artificial Intelligence Applications

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Abstract

The area of marketing is undergoing a significant transformation with the integration of artificial intelligence (AI), which is introducing innovative approaches to strategy development, customer engagement and value creation. In an era of rapid technological advances and changing consumer expectations, companies are harnessing AI to meet the demand for personalised, meaningful and value-driven interactions.

The technologies underpinning this transformation include natural language processing, machine learning, predictive analytics and computer vision. The synergy of these technologies enables organisations to gain in-depth knowledge of their audience, thus facilitating the creation of more authentic and impactful connections with them. As an example, recommendation engines use AI to generate tailored offers, enhancing the user experience and optimising conversion rates. By examining Internet usage, purchasing inclinations and demographic data, companies can devise marketing strategies that specifically address individual needs and predilections. This degree of customisation, once unthinkable, can be achieved thanks to advances in computing power and machine learning algorithms, which convert raw data into useful information.

In the context of marketing, AI therefore transcends the passive role of analysis and becomes an active agent that actively influences consumer behaviour. Moreover, the integration of AI systems with techniques derived from Nudge Theory (Thaler & Sunstein, 2008) facilitates the creation of subtle messages and incentives that steer consumer choices towards specific goals, such as the adoption of sustainable products or healthy habits. This allows companies to align their business strategies with emerging social values. AI enables marketers to design interactions that not only meet but exceed customer expectations, making them memorable and distinctive. At the same time, there is a need to allocate resources for ongoing staff training to ensure that staff are equipped to harness AI technologies and adapt in a dynamic competitive environment. However, the incorporation of AI technologies into the marketing industry is not without its complexities. Issues such as privacy, transparency and bias are key to building consumer trust and ensuring that marketing practices are ethical. Compliance with regulations such as GDPR is fundamental to avoid legal problems and damage to the company's reputation.

The primary objective of this research is to examine the transformative impact of artificial intelligence (AI) on marketing strategies. In this regard, the research will focus on three key aspects of the impact of AI on marketing strategies: firstly, on the formulation of business approaches in the context of AI; secondly, on the enhanced interactions with consumers facilitated by AI; and thirdly, on the promotion of value creation in a context of rapid technological advancement and changing consumer needs.

Furthermore, it is imperative to explore the potential of AI in improving the integration of marketing strategies, with the aim of addressing emerging challenges. These may include adapting to cross-cultural preferences, promoting human-machine collaboration in creative processes and using progressively sophisticated nudging algorithms. Thus, it can be argued that the integration of AI into marketing strategies will improve their efficiency and effectiveness. Achieving these objectives, the research seeks to illuminate the opportunities and strategic challenges of AI in marketing, providing a comprehensive and nuanced understanding of how AI can improve efficiency, innovation and consumer centricity in a highly competitive global marketplace.

Keywords: Marketing strategies, Artificial Intelligence (AI), Value creation, KM, Business approaches

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1. Introduction

Over the past two decades, Artificial Intelligence (AI) has transformed from a niche research area into a central element of digital transformation in both business and academia (Russell & Norvig, 2021; Nag et al., 2024). Its integration with Knowledge Management (KM) has redefined the way organisations collect, process and exploit knowledge to drive innovation, optimise operations and improve customer engagement (Magableh et al., 2025; Babatunde et al., 2024; Sharma et al., 2023; Liebowitz, 2001). This synergy between AI and KM is promoting a new marketing paradigm, based on data-driven decision-making, real-time adaptability and systematic refinement of value creation processes (Leone et al., 2021). In marketing operations, AI optimises processes such as customer segmentation, lead scoring and campaign management. Predictive analytics identify high-potential leads and predict customer behaviour, enabling proactive marketing strategies (Zaman et al., 2025; Hofacker et al., 2020; Onyijen et al., 2024; Alon et al., 2020). Artificial intelligence-driven automation tools handle repetitive tasks, freeing marketers to focus on strategic initiatives.

Artificial intelligence also supports dynamic pricing strategies by analysing market conditions, competitors' prices and consumer demand in real time. This agility allows companies the resilience needed to maintain competitiveness and profitability (Chatterjee et al., 2021; Chintalapati & Pandey, 2022; Kliestik et al., 2022; Yang et al., 2022).

AI technologies, such as machine learning, deep learning and natural language processing, allow companies to move beyond traditional data analysis, enabling predictive modelling, sentiment analysis and intelligent automation (Dwivedi et al., 2021; Prasetyo et al., 2025). This analysis informs marketing strategies and content creation, ensuring relevance and resonance with target audiences (Hauser et al., 2023; Alon et al., 2020;).

These capabilities significantly improve organisational agility, enabling companies to anticipate market trends and consumer needs more accurately. When integrated into robust knowledge management systems (KMSs), AI acts as a catalyst for continuous learning, transforming raw data into actionable strategic intelligence (et al., 2024; Maier & Hadrich, 2011).

The strategic importance of AI in marketing thus lies not simply in automation, but in the elevation of analytical and relational capabilities. Companies are increasingly using AI to support dynamic segmentation, targeted communication and adaptive content strategies, all of which are key to delivering personalised value (Bashir et al., 2024; Gupta & Prusty, 2024; Ren, 2024). This technological evolution enables a shift from static campaign models to responsive ecosystems that learn and evolve in step with customer behaviour.

An emerging area of research concerns the intersection of AI with behavioural sciences, particularly through the application of Nudge theory (Thaler & Sunstein, 2008). AI-driven choice architectures can be used to guide consumer behaviour in subtle but impactful ways, promoting decisions aligned with health, environmental or ethical considerations (Sadeghian & Otarkhani, 2024). Such approaches are particularly relevant as organisations increasingly align marketing strategies with the Sustainable Development Goals (SDGs) and corporate social responsibility initiatives (Cezarino et al., 2023).

Despite its transformative potential, the integration of AI into organisational processes is fraught with challenges. Ethical dilemmas related to algorithm transparency, data governance and bias mitigation are central to the concerns of both academics and practitioners (Hermann, 2022; Du & Xie, 2021; Tsamados et al., 2021). Furthermore, the successful implementation of AI-KM systems requires a parallel investment in organisational culture and capabilities, particularly in overcoming resistance to change, bridging the digital skills gap and ensuring collaboration across departments (Kinkel et al., 2022).

Case studies of leading digital native companies such as Amazon, Uber and IBM demonstrate how AI, integrated into a mature KM, facilitates rapid innovation cycles and highly responsive customer strategies (Zaman et al., 2025; Umamaheswari, 2024; Fu & Soman, 2021; Jarek & Mazurek, 2019). These companies exemplify how real-time processing of feedback and preference data can optimise not only marketing effectiveness, but also product development and service design.

In conclusion, the AI-MKTG nexus represents a critical strategic asset in today's marketplace. To fully exploit its potential, organisations need to develop an ecosystem that supports continuous knowledge flows, fosters a culture of innovation and supports strong ethical standards. Future research should further explore the role of AI in industry-specific contexts, the development of collaborative human-IA models and the socio-technical implications of algorithmic decision-making in marketing.

Research Objectives

This study aims to explore how Artificial Intelligence (AI) is transforming key marketing functions by analysing its most relevant applications in various sectors. The objectives are:

1. Study the integration of AI in digital marketing strategies, particularly in mobile-first and content-driven environments.
2. Examine how artificial intelligence enhances the customer experience through automation tools such as chatbots and recommendation systems.
3. Assess the impact of AI on marketing operations and decision-making, with a focus on data-driven insights and ethical considerations.

Research questions

RQ1. *How is Artificial Intelligence currently incorporated into the different functional domains of marketing and what does the evolution of the discipline's structure and priorities reveal?*
RQ2. *How do AI-based tools such as recommendation engines, chatbots and personalisation algorithms contribute to improving the customer experience and how can they be strategically leveraged in digital marketing strategies?*
RQ3. *What are the critical operational and ethical implications of integrating AI into marketing decision-making and how can these insights inform both academic theory and managerial practice in shaping the future of marketing?*

Research design

This study takes a secondary data-driven approach, exploiting relevant publications to investigate the evolving relationship between artificial intelligence (AI) and marketing practices in different organisational contexts. Rather than undertaking an original empirical analysis, the study synthesises insights from previously published academic articles, industry reports and other credible sources. The comprehensive overview offered by these sources provides valuable insight into the integration of AI into marketing strategies over time.

The selection of publications was guided by purposive sampling criteria, with the aim of identifying studies and reports that highlight the application of AI tools in marketing in different sectors. The selection of these sources was based on criteria that assessed the visibility, relevance and impact of their AI-based marketing initiatives. A review of peer-reviewed journal articles, conference papers and other authoritative publications related to AI and marketing was conducted, with a focus on those published in the last 5-10 years to capture the latest trends and developments.

The analysis of these secondary sources aims to provide a comprehensive understanding of the influence of AI technologies, including machine learning, natural language processing and predictive analytics, on decision-making processes, customer engagement and value creation in marketing. This methodological approach offers the opportunity to examine the long-term strategic transformations resulting from the adoption of AI, based on a series of case studies and theoretical insights.

The longitudinal nature of the study is maintained by a review of publications documenting the evolution of AI in marketing over time. This review highlights both short-term impacts and lasting changes in marketing practices. This methodological approach ensures an in-depth analysis of the context and facilitates the identification of emerging trends and managerial implications for the future of AI-driven marketing.

2. Literature review

Over the past decade, Artificial Intelligence (AI) has emerged as a transformative element in the marketing landscape, sparking growing academic and managerial interest. Researchers and practitioners have begun to examine how AI-driven technologies are reconfiguring conventional marketing functions. The findings of this study indicate that these technologies are facilitating more precise targeting, automation and personalisation. This evolution has led to a reconfiguration of strategic priorities, operational processes and customer engagement models across all sectors.

This literature review explores the current state of knowledge on the integration of AI in key marketing domains. In particular, it examines how AI supports digital marketing in mobile-first and content-intensive environments, enhances the customer experience through tools such as chatbots and recommendation systems, and influences marketing operations through data-driven decision-making (Varadarajan et al., 2022). By synthesising key theoretical contributions and empirical findings, the review aims to map the existing research landscape, highlight key areas of application and identify gaps that require further exploration.

Given the interdisciplinary nature of the topic, the literature spans several topics, including marketing strategy, consumer behaviour, service automation and ethics in AI implementation. This review provides an overview of key studies and emerging trends and also lays the groundwork for understanding the broader managerial implications and future research directions related to AI-enabled marketing practices

2.1. Theoretical Foundations of Value Creation and Competitive Advantage

In the context of a rapidly changing business environment characterised by technological advances and intensifying competition, the creation of value and the achievement of competitive advantage are of paramount importance for organisations aspiring to sustainable success. These goals are intrinsically linked to the way companies organise their activities, interact with consumers and adapt to changing market demands (Kotler at al, 2022; Porter, 2008; Barney, 1991; Porter, 1985).

The advent of artificial intelligence (AI) has had a profound impact on business strategies and the development of competitive advantage, profoundly changing the way companies interact with data, customers and markets (Haenlein & Kaplan, 2019). Machine learning (ML), deep learning and natural language processing (NLP) are technologies that facilitate the analysis of vast datasets in real time, thus providing insights into consumer behaviour and preferences (Fitzmaurice et al., 2021). This knowledge enables companies to predict trends, customise products and improve processes, thereby increasing efficiency and customer satisfaction (Joseph et al., 2025) and, simultaneously, their own advantage.

Artificial intelligence has a significant impact on content marketing by automating content creation and curation processes. Natural language processing (NLP) and machine learning algorithms generate customised content at scale, responding to different audience segments (Kumar et al., 2020). These technologies also optimise content distribution, predicting the most effective channels and timing for engagement.

In addition, artificial intelligence improves the analysis of content performance by providing real-time feedback on audience interactions. This feedback loop allows marketers to continuously refine content strategies, improving effectiveness and ROI (Ramachandran, 2023).

A significant application of AI is evident in the recommendation systems used by major platforms such as Amazon, Uber and IBM. These systems employ sophisticated algorithms to analyse user data, generating personalised recommendations that have the potential to improve conversion rates, engagement and customer loyalty (Rust & Huang, 2014). The effectiveness of these systems depends on their ability to amalgamate historical data with real-time behaviour, thus generating highly personalised experiences.

Another significant example concerns the use of predictive analytics for refining advertising campaigns (Vlačić et al., 2021). Research has indicated that companies implementing AI-based marketing strategies have observed a significant increase in revenues, with average increases between 20 and 30 per cent compared to those using traditional approaches (Lamarre et al., 2023; Onyijen et al., 2024).

Furthermore, AI plays a key role in automating repetitive tasks and improving decision-making processes in operational contexts (Lamarre et al., 2023). For example, sentiment analysis algorithms enable companies to monitor customer opinions on social media, facilitating timely brand reputation management (Kaplan & Haenlein, 2010).

In the manufacturing sector, artificial intelligence-based tools have been instrumental in optimising inventory management, resulting in lower costs and better responsiveness to market demands (Jones et al., 2019; Rosa et al., 2022; Schwaeke et al., 2024).

Furthermore, the integration of intelligent chatbots, sophisticated search platforms and continuous learning systems has made critical information more accessible, supporting faster and more informed decision-making processes (Romanovska et al., 2024; Sigala et al., 2024).

Despite the many benefits of AI, its implementation poses significant challenges. The implementation of AI requires significant investment in infrastructure, the possession of advanced technical expertise and the establishment of robust governance frameworks (Letheren et al., 2024; Brynjolfsson & McAfee, 2017). Ethical considerations, including data privacy management, transparency of algorithms and risk of bias, require special attention. Furthermore, companies need to devise strategies to balance automation with the imperative to maintain a human touch in customer interactions.

A critical aspect of this integration is, in fact, the collaborative synergy between humans and intelligent systems, in which AI is not seen as replacing human capabilities, but as augmenting them (Salem et al., 2024). Human attributes such as creativity, critical thinking and interpersonal skills remain unique, while AI excels at processing large data sets and identifying patterns (Davenport et al., 2020). To optimise this balance, organisations should prioritise the ongoing training of employees, equipping them with the necessary skills to collaborate effectively with emerging technologies

AI is set to become an increasingly central component of economic and social transformation, with value-generating potential beyond improving business performance to address global challenges such as environmental sustainability and equitable access to resources (Vial, 2019). However, the success of this integration will depend on the ability of companies to adopt responsible and inclusive approaches that consider both economic benefits and ethical and social implications.

2.2. The Transformative Role of Artificial Intelligence in Contemporary Marketing

In recent years, artificial intelligence (AI) has become a key driver of innovation in marketing, redefining the way companies engage with consumers, make decisions and create value. AI-based systems enable marketers to predict market developments, identify emerging customer segments and design highly personalised offers with a level of precision previously unattainable with traditional methods (Davenport et al., 2020). By harnessing these capabilities, organisations not only improve strategic efficiency, but also radically reshape the consumer experience.

A notable manifestation of AI in marketing is evident in the use of recommendation engines, which have become central to the operation of major e-commerce and streaming platforms.These technologies rely on complex machine learning models that interpret user behaviour to generate personalised product or content suggestions. The resulting increase in engagement, satisfaction and ultimately conversion rates is concretely quantifiable (Rust & Huang, 2014). Furthermore, the implementation of predictive analytics, another application of AI, allows for the precise targeting of advertising campaigns. By examining historical and real-time data, marketers can identify the most effective times and channels to distribute promotional content, thereby substantially improving return on investment (Ramachandran, 2023; Chui et al., 2023).

In addition to improving operational results, AI also paves the way for the discovery of new business opportunities. By applying sophisticated data mining techniques, companies can extract valuable insights from large volumes of unstructured data, including those generated by users on social media platforms. These insights can be turned into strategic intelligence. This capability fosters a more agile and responsive market presence, enabling companies to align their offerings with rapidly changing consumer expectations (Fitzmaurice et al., 2021).

The implementation of artificial intelligence-driven virtual assistants and chatbots has led to a paradigm shift in customer care and service delivery. These tools use natural language processing (NLP) to interact with users in real time, offering 24/7 assistance and drastically reducing response times (Fitzmaurice et al., 2021; Huang & Rust, 2021). According to Chung et al. (2020), such systems are now integral to maintaining continuous customer engagement and improving satisfaction levels. Radziwill and Benton (2017) further state that AI-based agents play multiple roles, from task assistance to empathetic companionship, offering users a dynamic and personalised interaction experience. Moreover, when integrated with social media analytics, these tools enable companies to track audience sentiment and identify emerging issues or preferences, thus enriching their strategic responsiveness and enabling marketers to adapt content and strategies to the behaviour and preferences of individual consumers (Chatterjee et al., 2021¸ Onyijen et al., 2024). Programmatic advertising, powered by artificial intelligence, automates ad buying and placement, optimising targeting and efficiency. Artificial intelligence algorithms analyse vast data sets to determine the most effective ad placements, thus maximising return on investment (Chandra, 2020).

A particularly important area of application of AI is the nexus between algorithmic design and behavioural economics, which manifests itself particularly in digital nudging. This approach uses artificial intelligence and machine learning to subtly influence consumer decisions, guiding them towards socially responsible and sustainable outcomes, such as saving energy or buying environmentally friendly products. Using personalised behavioural data allows companies to devise tailored nudges that respond to individual motivations, improving the effectiveness and ethics of their interventions (Thaler & Sunstein, 2008; Mirsch et al., 2018).

A key principle of participatory nudging is the involvement of stakeholders, including consumers, in the design and execution of these behavioural suggestions. Integrating users into the co-creation process has been shown to improve the acceptance and perceived legitimacy of interventions, ultimately leading to greater behavioural compliance and long-term impact (Marchiori et al., 2017). This participatory dimension is consistent with the broader imperative to ensure that AI applications respect user autonomy while providing commercial value.

Despite the many opportunities offered by AI, its integration into marketing practices must be approached with caution and ethical rigour (Haleem et al. 2022).

Another notable advance is the emergence of artificial intelligence-enabled platforms for customer experience management (CEM). These systems analyse behavioural patterns across customer touchpoints, identifying moments of friction and opportunities for delight. By dynamically optimising the customer journey, these tools help companies strengthen the brand-consumer relationship and deliver value at every stage of the interaction (Romanovska et al., 2024; Cutiva Manios, 2018). In conclusion, it can be said that AI is not just a technical improvement of marketing processes; rather, it can be seen as a transformative force that has the ability to redefine the way organisations understand, influence and engage consumers. If implemented carefully and ethically, AI has the potential to enable companies to cultivate meaningful and lasting relationships while contributing to broader social and environmental goals. The evolution of this technology will depend on a balanced approach that integrates innovation, inclusion and integrity.

3. Business Case: The Role of AI in the Transformation of Marketing and Personalisation

Artificial Intelligence (AI) is rapidly reshaping marketing strategies in various sectors such as finance, media, entertainment and retail (Tan et al., 2016). The ability of AI to drive personalisation, optimise content curation and automate consumer engagement processes has significantly transformed the way companies create value and sustain competitive advantage (Jarek & Mazurek, 2019). This section introduces a critical exploration of real-world case studies that demonstrate the power of AI in contemporary marketing practices, setting the stage for a deeper examination of the role of AI in value creation and competitive advantage (Dyche, 2015).

In sectors such as retail and media, AI technologies, including machine learning and predictive analytics, are increasingly being used to provide personalised experiences to consumers. AI-based recommendation systems, such as those used by Uber, Amazon and IBM, are prime examples of how companies use data-driven insights to predict and influence consumer behaviour (Gentsch, 2018; Kumar & Rajan, 2024; Lyndyuk et al., 2024). These applications not only improve personalisation, but also contribute to a deeper understanding of customer preferences, thereby optimising marketing strategies (Joseph et al., 2025).

Furthermore, the integration of AI in marketing is vital to gain a competitive advantage. Through the automation of marketing functions and the ability to generate data-driven insights, AI enables organisations to optimise decision-making processes and gain a nuanced understanding of customer needs (Huang & Rust, 2021). These technologies enable companies to create highly relevant and targeted marketing strategies, resulting in increased customer satisfaction, engagement and loyalty (Mikalef et al., 2020).

Artificial intelligence (AI) has become a transformative force in marketing, enabling companies to improve customer engagement, optimise campaigns and drive business growth (Labib, 2024). Below are some notable business cases that illustrate the relationship between AI and marketing.

3.1. The Integration of Artificial Intelligence in Amazon's Marketing

Amazon exemplifies the strategic integration of Artificial Intelligence (AI) in digital marketing, with a focus on advanced personalisation capabilities (Gupta & Agarwal, 2024). Using sophisticated machine learning algorithms, Amazon is able to analyse a wide range of user behavioural data, including browsing patterns, purchase history and demographic indicators, in order to offer highly personalised product recommendations. This AI-powered system is continuously refined through real-time data processing, enabling highly personalised interactions with consumers that enhance the overall shopping experience (Xu et al., 2024; Shang et al., 2024; Elittan et al., 2024; Pawar & Dhumal, 2024; Arshad et al., 2023; Almahmood & Tekerek, 2022).

Recent advances have further refined Amazon's recommendation system. Shen et al. (2023) identified an innovative approach that identifies high-level purchase intentions, such as preparing for a camping trip or birthday party, by analysing user behaviour. This intention-based recommendation system, implemented in multiple countries and languages, has been shown to improve key business metrics, emphasising the effectiveness of aligning recommendations with users' underlying goals (Shen et al., 2023).

Gomez-Uribe and Hunt (2015) pointed out that a significant part of Amazon's sales can be attributed to its recommendation engine, emphasising the central role of the system in improving customer engagement and revenue. Furthermore, studies have shown that the accuracy and diversity of recommendations positively influence customer satisfaction, particularly when using deep learning-based systems (Kim et al., 2021).

However, it is important to note that although recommendation systems contribute significantly to user engagement, some of this activity may have occurred through other means, such as direct search. Sharma et al. (2015) found that at least 75% of clicks on recommendations can be attributed to user behaviour that would have occurred even in the absence of the recommendations. This finding underlines the need for a comprehensive evaluation of the causal impact of recommendation systems on user behaviour.

By integrating artificial intelligence with knowledge management, Amazon is able to manage and explore large amounts of data, ensuring continuous updates. The knowledge management system used by Amazon is designed to collect and update data from multiple sources, including purchase history, customer feedback and interactions, with the aim of ensuring the accuracy and precision of recommendations (Umamaheswari, 2024). Information extracted from the data is shared between the various business teams (marketing, logistics, product development) to optimise operations through efficient sharing. (Amazon Annual Report, 2024)

In other words, Amazon's approach to customer satisfaction is not limited to satisfying needs, but aims to create experiences that build loyalty and increase the perceived value of the brand. This strategy is in line with the principles of the experience economy, which emphasises the delivery of value through meaningful and personalised interactions (Pine & Gilmore, 2019). The integration of artificial intelligence (AI) and knowledge management (KM) within Amazon's operations facilitates a distinctive purchase journey, characterised by a deep sense of understanding and appreciation among customers (Ramadan et al., 2021) and the establishment of long-term trusting relationships with consumers (Pine & Gilmore, 2019).

3.2. Strategic Implications of IBM Watson in AI-based Knowledge Management and Decision-making

The advent of Artificial Intelligence (AI), particularly in its cognitive form, has brought about a paradigm shift in the field of human-computer interaction. This is due to the ability of these systems to process, interpret and respond to natural language input in a way that emulates human intelligence. A significant example of this advancement is IBM Watson, a state-of-the-art cognitive platform developed to process unstructured data, generate insights and support complex decision-making processes in various domains (Ferrucci et al., 2010; Shahid & Li, 2019). The IBM Watson assistant, a representative of this technological development, uses AI to facilitate the delivery of sophisticated customer service solutions. The system uses deep learning and natural language processing to understand customer requests, thereby generating accurate and personalised responses. The effectiveness of this implementation has been demonstrated by its ability to improve both customer satisfaction and operational efficiency (Devang et al., 2019).

Watson's architecture is based on a multilevel approach to cognition, reflecting the human ability to observe phenomena, generate hypotheses and select optimal decisions based on probabilistic evidence. Its main processes include question analysis, hypothesis generation, evidence scoring and final classification, each of which is facilitated by advanced natural language processing (NLP), machine learning (ML) and information retrieval technologies (High, 2012; Ferrucci, 2012).

A pivotal moment in Watson's evolution was his 2011 triumph in the quiz show *Jeopardy!,* where he outperformed previous human champions. This feat demonstrated not only Watson's ability to understand intricate and often ambiguous questions in natural language, but also its ability to formulate precise, evidence-based answers in real time (Chintalapati & Pandey, 2022; Ferrucci, 2012). This capability underlines Watson's potential to facilitate decision-making in data-intensive environments (Ferrucci et al., 2010). Unlike traditional rule-based expert systems, which are static and fixed, Watson is able to adapt through the process of learning from new inputs and contextual updates. Its processing capabilities are extensive, with the capacity to handle over 200 million pages of text, supported by a high-capacity computing infrastructure that includes 15 TB of RAM and over 500 GB of curated data. For large-scale data processing, it uses distributed computing frameworks such as Hadoop and Apache UIMA. This infrastructure allows Watson to extract structured information from large amounts of unstructured information, which is estimated to account for 80% of all data generated globally (Günther et al., 2017).

The integration of IBM Watson into business applications has taken place in several sectors, including healthcare, legal services, education, finance and tourism. In the healthcare sector, for example, Watson for Oncology assists doctors by synthesising large volumes of medical literature and patient data to recommend personalised treatment options. Research has shown that these AI-assisted systems increase diagnostic accuracy and reduce the time required to make a decision, ultimately improving patient outcomes (Jiang et al., 2017; Patel & Wright, 2020). From a strategic management perspective, IBM Watson is a paradigm of integrating AI and knowledge management (KM) to create competitive advantage (Patel & Wright, 2020). By automating data collection and insight generation, Watson reduces the cognitive overload of decision makers and improves organisational agility. This ability to respond to environmental changes with greater accuracy and speed is an essential skill in today's volatile, uncertain, complex and ambiguous (VUCA) business environment (Nonaka & Takeuchi, 1995; Brynjolfsson & McAfee, 2017)

Moreover, Watson's ability to continuously learn from interactions and feedback loops ensures the progression of decision support over time. This adaptability is particularly valuable in areas where contextual variables change rapidly, such as public health or financial markets (Strickland, 2019). The development of applications such as chatbots using IBM Watson Assistant further illustrates the accessibility and versatility of the platform in enabling intelligent, conversational interfaces that extend organisations' reach and service capabilities (Norouzi et al., 2025; Ali et al., 2021).

In a nutshell, IBM Watson represents a milestone in the evolution of artificial intelligence-based decision support systems. Its implementation in several industries underlines the strategic potential of cognitive computing, which transcends mere technological innovation, serving as a transformative catalyst for business intelligence and competitive positioning. As organisations continue to grapple with the exponential growth of unstructured data, the adoption of systems such as Watson will be instrumental in fostering data-driven cultures, improving decision quality and increasing stakeholder engagement (IBM Annual report, 2024; Chow et al., 2023).

The strategic use of IBM Watson has been shown to contribute to the development of data-driven marketing strategies with the potential to improve customer engagement, personalisation and brand differentiation. In an information-saturated digital economy, the ability to extract useful information from unstructured data sources gives a distinct competitive advantage. Watson's cognitive computing capabilities enable companies to move from reactive to proactive marketing, positioning themselves not only as providers of products or services but also as orchestrators of personalised experiences.

From a value creation perspective, IBM Watson supports the transition to a customer-centric model, where understanding of individual needs, preferences and behaviour is no longer inferred only through segmentation, but dynamically updated in real time (Ali et al., 2021; Günther et al., 2017). By analysing patterns from different data points, including user reviews, social media sentiment and past purchases, Watson facilitates micro-targeted campaigns that maximise conversion potential (Ali et al., 2021; Zeng & Glaister, 2018; Günther et al., 2017). This high level of personalisation, made possible by natural language processing and machine learning, fosters consumers' perception of relevance, increasing their satisfaction and, consequently, strengthening brand loyalty.

In terms of strategic marketing, Watson integration has been shown to enable organisations to develop predictive models that predict consumer demand and behavioural changes, allowing marketing teams to anticipate market trends and optimise resource allocation (Patel & Wright, 2020; da Silva Oliveira et al., 2019).

Furthermore, the integration of AI-driven chatbots and virtual agents with the ability to communicate in a human-like manner has the potential to automate content generation and customer interaction, thus ensuring consistency, availability and scalability at customer service touchpoints (Petiwala et al., 2021; Hurwitz et al., 2015).

Precision marketing should also be enabled, in which marketing messages are tailored not only to demographic categories but also to individual profiles, improving relevance and return on investment (Brynjolfsson & McAfee, 2017).

The insights generated by artificial intelligence, moreover, allow marketers to design adaptive campaigns, tailoring messages and channels in response to user interactions, thus favouring a form of dynamic segmentation based on behavioural evolution rather than static categories. This paradigm shift is in line with the principles of the experience economy (Pine & Gilmore, 2019), in which value is derived not only from products but from the personalisation and memorability of the experience itself.

A further strategic implication is evident in the field of strategic foresight and innovation management. IBM Watson's ability to process academic publications, patents, news articles and industry reports to identify emerging trends and market white spaces is of particular relevance (Kumar et al., 2022). This capability provides companies with the tools to innovate ahead of the competition. This facilitates the development of adaptive and anticipatory marketing strategies, which are critical in fast-changing sectors such as technology, health and finance (Petiwala et al., 2021). A further strategic implication is evident in the field of strategic foresight and innovation management. IBM Watson's ability to process academic publications, patents, news articles and industry reports to identify emerging trends and market white spaces is of particular relevance (Grover et al., 2018; Guenole & Feinzig, 2018). This capability provides companies with the tools to innovate ahead of the competition. This facilitates the development of adaptive and anticipatory marketing strategies, which are essential in fast-changing sectors such as technology, health and finance (Günther et al., 2017).

3.3. Uber's Use of Artificial Intelligence in Marketing

Uber's adoption of artificial intelligence (AI) represents a seminal example of strategic transformation in the on-demand mobility industry (Yun et al.,2020). The integration of intelligent technologies into the company's marketing processes has enabled it to overcome the limitations of traditional segmentation, leading to dynamic personalisation of user experiences, advanced resource management and greater responsiveness to market signals (Yeng et al., 2019).

A significant impact of AI has been seen in the personalisation of advertising content. The Uber Ads platform uses predictive systems that analyse real-time data on routes, consumption behaviour, past preferences and mobility patterns, enabling the delivery of contextually relevant advertisements integrated into the user experience (Fu & Soman, 2021). This strategy has been shown to result in higher levels of user engagement and increased perception of service value (Davenport et al., 2020; Huang & Rust, 2021). This suggests that intelligent profiling is a key factor in achieving competitive differentiation.

Artificial intelligence also plays a central role in optimising allocative decision-making. Uber, for instance, employs predictive algorithms to efficiently allocate its marketing budget across geographies, time slots and user segments. This continuous adaptive capability, fuelled by real-time data streams, enables agile resource management and more effective responses to unforeseen market fluctuations, such as changes in demand or user feedback on social media platforms (Chatterjee et al., 2021; Ramachandran, 2023; SEHGAL et al., 2025). This approach can be considered evolutionary in the context of media planning, where budget allocation is no longer a static process, but rather an adaptive one, supported by machine learning models (Yunus et al., 2019).

A further strategic element is the company's ability to exploit social media analysis as a tool for open innovation. The analysis of user-generated content on platforms such as Twitter and Reddit is facilitated by Natural Language Processing (NLP) models, which are used to detect emerging needs, anticipate trends and identify weak market signals. This approach has been shown to improve brand reputation and perceived proximity to customers, while providing valuable insights for developing new services or refining existing ones (Lobschat et al., 2021; Floridi et al., 2018).

In the context of communication, Uber has also implemented artificial intelligence-based solutions to improve interactions between users and drivers. One of these is the One-Click Chat (OCC) system, which relies on intelligent automated responses that can handle the most common exchanges between passengers and drivers, significantly reducing response times and simplifying communication (Lobschat et al., 2021; Yeng et al., 2019). This form of automation improves the smoothness of the user experience and simultaneously enhances the perceived value of the service, thereby fostering user trust in the platform (Adam et al., 2021). The functionality of these applications depends on the real-time data infrastructure on which Uber has invested heavily. The ability to process large volumes of data at low latency allows for the generation of almost instantaneous automated decisions (Mitropoulos et al., 2021). This ability to make proactive, rather than reactive, decisions is a key factor in Uber's adaptive management capabilities, as demonstrated by its ability to adapt promotional strategies during extreme weather events or to rebalance mobility supply in response to spikes in demand (Uber Annual report, 2023).

The integration of artificial intelligence into Uber's marketing strategies can be considered a radical rethinking of the operating model, rather than a mere technological evolution (Grewal et al., 2020; Taherdoost & Madanchian, 2023). The adoption of a data-driven logic has enabled the creation of a digital ecosystem capable of continuously learning, adapting and optimising its interactions with stakeholders. This approach has far-reaching strategic implications, including improving the customer experience and increasing the efficiency of marketing expenditures. In addition, artificial intelligence allows Uber to consolidate its competitive advantage in a highly dynamic market where responsiveness and customisation are key to long-term success.

3.4. Comparative Analysis

The comparative analysis of the IBM Watson, Uber and Amazon cases provides a coherent and in-depth framework for understanding the integration of artificial intelligence (AI) in marketing strategies. This analysis highlights not only the operational impact of AI but, more importantly, its long-term strategic implications. Despite the heterogeneity of the approaches and contexts of the three cases, they illustrate a convergence towards an evolutionary marketing model based on the ability of AI to process knowledge in real time, predict consumer behaviour, dynamically adapt and personalise interactions with users.

The IBM Watson case exemplifies the transition from passive information systems to cognitive platforms capable of generating predictive and personalised insights. Watson's multilevel architecture, designed to understand natural language, generate hypotheses and evaluate evidence, enables companies to navigate the complexity of decision-making through intelligent data interaction (Ferrucci et al., 2012; High, 2012). This capability has significant implications for strategic marketing: the integration of Watson into Customer Relationship Management (CRM) systems supports the transition from static to dynamic segmentation based on real-time behavioural analysis (Ali et al., 2021; (Cutiva Manios, 2018 Cutiva Manios, J. S. (2018). Uso de la inteligencia artiificial IA en el diseño de estrategias comerciales mediante el aplicativo IBM Watson Marketing.)). In addition, the platform's ability to process unstructured content, including customer reviews, social media conversations of and chatbot requests, facilitates the anticipation of latent needs and the development of promotional campaigns with a degree of precision that was until recently unattainable (Patel & Wright, 2020). The real strategic innovation lies in the ability to implement predictive marketing models that transform data into competitive advantage, thereby improving the responsiveness and effectiveness of managerial actions in volatile, uncertain, complex and ambiguous (VUCA) environments (Nonaka & Takeuchi, 1995; Brynjolfsson & McAfee, 2017). In the case of Uber, AI plays a more immersive role, directly shaping the user experience and improving the organisation's operational agility. The Uber Ads platform, driven by predictive models, facilitates a level of context-aware personalisation that seamlessly integrates advertising into the user journey. Predictive analysis of mobility patterns enables Uber to profile user needs in real time, influencing decision-making with highly relevant advertising content (Davenport et al., 2020; Huang & Rust, 2021). Simultaneously, the integration of AI into the budgeting process of marketing initiatives allows media planning to be transformed from a scheduled activity to an adaptive process. This adaptability is attributed to the automatic and intelligent reallocation of resources in response to sudden fluctuations in demand (Chatterjee et al., 2021). From a strategic perspective, this allows Uber to optimise its return on advertising investment and, at the same time, improve its competitive resilience through a proactive response to complex environmental stimuli. The use of semantic social media analytics further enhances this adaptive capability by detecting weak signals and emerging trends that inform service innovation (Lobschat et al., 2021; Floridi et al., 2018). Uber's technological infrastructure functions as a continuous learning environment, with artificial intelligence acting as a strategic lever to develop a competitive advantage rooted in responsiveness, personalisation and predictive management of uncertainty (Grewal et al., 2020; Taherdoost & Madanchian, 2023).

The case of Amazon, on the other hand, illustrates an application of AI focused primarily on optimising the purchase path and creating hyper-personalised experiences. The integration of machine learning-based recommendation systems enables a granular understanding of users' purchase intentions, resulting in commercial offers aligned to consumers' latent needs (Xu et al., 2024; Elittan et al., 2024; Shen et al., 2023). The advent of intent-based models capable of interpreting complex purchase scenarios such as life events or personal projects has led to a shift from a product-centred focus to an experience-centred focus, thus promoting a loyalty strategy centred on algorithmic empathy. Although a portion of user interactions could potentially take place without AI intervention, as suggested by some studies (Sharma et al., 2015), it is evident that the personalisation enabled by these systems strengthens customer loyalty and increases brand value (Kim et al., 2021).

Strategically, Amazon has implemented an integrated knowledge management model in which data is shared between different functional areas, from marketing to logistics, thus optimising the value chain in a systemic way (Pine & Gilmore, 2019). The synergy between AI and knowledge management allows Amazon to turn every interaction into a learning opportunity, thus fuelling a process of continuous innovation.

The analysis of these three cases emphasises that the integration of AI in marketing should not only be seen as an operational tool, but rather as a fundamental component of corporate strategy. Indeed, AI enables organisations to move from reactive marketing to anticipatory marketing, capable of detecting and shaping consumer behaviour through intelligent, context-sensitive interactions. The strategic implications of this transformation are profound and include dynamic personalisation, adaptive resource allocation, predictive behavioural analysis and the creation of shared knowledge ecosystems, which fundamentally redefine the notion of competitive advantage. The ability to learn and adapt faster than competitors become the key factor in determining competitive advantage (Kumar et al., 2022; Petiwala et al., 2021).

Analysis indicates that recommendation systems (Amazon), intelligent conversational platforms (IBM Watson) and predictive logic embedded in mobility services (Uber) are central tools for improving the customer experience. The use of these tools has been shown to increase the perception of relevance of messages and offers, thus fostering a sense of consumer loyalty. This is achieved through the implementation of algorithmic empathy and adaptive interaction mechanisms. As a result, personalisation has evolved beyond the boundaries of socio-demographic variables, encompassing weak behavioural signals that are processed in real time (Kim et al., 2021; Huang & Rust, 2021).

This suggests that sustainable competitive advantage derives not so much from the collection of data, but from the ability to transform it into actionable insights, creating consistent and memorable experiential journeys. It is evident that companies that successfully assimilate such tools into a cross-functional ecosystem based on shared knowledge (as exemplified by Amazon) achieve not only increased customer lifetime value, but also a superior capacity for uninterrupted innovation (Pine & Gilmore, 2019; Xu et al., 2024).

A tension between the operational efficiency enabled by AI and related ethical issues is strongly highlighted by a comparison of cases. The use of predictive models to influence consumer choice gives rise to pertinent questions regarding the transparency of algorithms, the safeguarding of personal data and the potential for behavioural manipulation (Floridi et al., 2018; Martin, 2019). The integration of tools such as algorithmic nudges, for instance in the context of personalised offers or timed suggestions, has the potential to promote sustainable choices. However, it is imperative to recognise the potential implications of opaque persuasive dynamics if these tools are not governed by transparent and accountable AI governance structures (Brown, 2022; Letheren & Dootson, 2017).

This reflection has two implications. First, there is a need to develop theoretical marketing models that incorporate the logic of algorithmic accountability. Second, from a managerial perspective, there is a need to adopt hybrid metrics that measure not only the economic return, but also the ethical and reputational impact of AI in decision-making processes (Ramachandran, 2023; Sabourne, 2024).

The integration of artificial intelligence in the cases of IBM, Uber and Amazon provides a comprehensive and articulate answer to the three research questions, offering an evolutionary overview of contemporary marketing. Three fundamental directions emerge from this analysis:

The strategic structuring of marketing must be informed by data.

The construction of hyper-personalised experiences should be based on contextual interactions.

The growing relevance of algorithmic ethics should be recognised as a source of competitive and reputational leverage.

The result is a paradigm shift in which AI is no longer considered a mere operational tool, but rather an enabler of new organisational and decision-making models that require transversal skills, sound governance and a systemic vision. The answers to the RQs support the need for a theoretical reconceptualisation of the marketing discipline, which is progressively intertwined with data analysis, cognitive science and digital ethics.

In the future, the evolution of AI towards more sophisticated forms of generative and conversational intelligence will further expand the transformative potential of these technologies, opening up new avenues for experiential marketing, the co-creation of value for customers and the development of long-term relationships based on trust and relevance (Kumar et al., 2022; Petiwala et al., 2021). In this context, the ability of companies to effectively integrate AI into their strategic architectures will become an increasingly critical factor for their long-term competitiveness and sustainability

4. Conclusions and Implications

In recent years, marketing has undergone a profound transformation, driven by the integration of AI technologies capable of analysing large data sets and providing real-time insights. AI has transformed from a mere auxiliary tool to a strategic resource, facilitating the execution of highly targeted and cost-effective campaigns (Davenport et al., 2020; Chatterjee et al., 2021).

The integration of AI in marketing is not only a simplification of operations, but a transformation of the entire discipline. The use of artificial intelligence (AI) has become prevalent in contemporary marketing practices, particularly in the areas of dynamic segmentation, resource allocation and the development of personalised shopping experiences. This development indicates a structural reorganisation of marketing, with a shift towards cognitive automation and real-time personalisation. The shift from passive information systems to cognitive platforms, as exemplified by IBM Watson, signifies a paradigm shift towards predictive and prescriptive analysis in marketing. The use of artificial intelligence (AI) as a strategic tool has emerged as a facilitator of decision-making in volatile, uncertain, complex and ambiguous environments. This paradigm shift implies a reorganisation of the internal hierarchy of business functions, with marketing becoming a priority in a data-driven decision-making framework. However, it is imperative to emphasise that the ethical implementation of these strategies depends on maintaining transparency and rejecting manipulative dynamics. It is imperative to comply with data protection regulations, such as the General Data Protection Regulation (GDPR - Regulation (EU) 2016/679). Furthermore, biases embedded in algorithms must be systematically addressed to avoid discriminatory results (Mehrabi et al., 2021).

To address these complexities, it is up to companies to develop robust AI governance structures. These structures must ensure ethical alignment, monitor system performance and maintain consumer trust (Letheren & Dootson, 2017). The definition of precise performance metrics that comprehensively assess customer experience and return on investment is fundamental to this process (Sabourne, 2024; Ramachandran, 2023). However, it is imperative to emphasise that the ethical implementation of these strategies depends on maintaining transparency and avoiding manipulation. The importance of adhering to data protection legislation, such as the General Data Protection Regulation (GDPR) (Regulation (EU) 2016/679), is paramount. Furthermore, biases embedded in algorithms must be systematically addressed to avoid discriminatory results (Mehrabi et al., 2021).

These structures must ensure ethical alignment, monitor system performance and maintain consumer trust (Letheren & Dootson, 2017). The development of clear performance metrics that evaluate both customer experience and return on investment is critical to these efforts (Sabourne, 2024; Ramachandran, 2023).

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Foreign Direct Investment and Technological Innovation: Empirical Evidence from G7 Countries

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Abstract

This study examines the relationship between foreign direct investment (FDI) and technological innovation (PAT) in G7 countries over the period 1990–2021. According to the results of the Emirmahmutoğlu–Köse (2011) panel causality test, changes in FDI are found to be the cause of changes in innovation, while no significant causality is detected in the opposite direction. The findings indicate that foreign direct investment is a determining factor for technological innovation in G7 countries, although the strength of this relationship varies across countries.

Keywords: Foreign direct investment, technological innovation; G7 countries

1.Introduction

Foreign direct investment (FDI) has long been recognized as one of the principal channels through which capital, technology, managerial know-how, and organizational practices are transferred across countries. Beyond serving merely as a source of financing that augments domestic capital accumulation, FDI plays a critical role in accelerating technological innovation, enhancing productivity, and supporting structural transformation. In an era characterized by intensified global competition, rapid technological change, and increasingly fragmented value chains, the relationship between FDI and technological innovation has regained prominence in both academic research and policy debates (OECD, 2023; UNCTAD, 2024).

Technological innovation, broadly defined as the development and diffusion of new products, processes, and organizational methods, constitutes one of the fundamental determinants of long-term economic growth and competitiveness. Endogenous growth theories emphasize that innovation outcomes depend not only on domestic research and development (R&D) activities but also on external knowledge spillovers generated through international trade, investment, and the mobility of skilled labor (Romer, 1990; Aghion & Howitt, 1992). Within this theoretical framework, FDI—particularly through multinational enterprises (MNEs)—emerges as a key mechanism facilitating cross-border technology and knowledge transfer.

G7 countries provide a highly suitable sample for analyzing the FDI–innovation nexus. Accounting for a substantial share of global FDI flows, R&D expenditures, and patent applications, G7 economies occupy a pivotal position in shaping global technological trajectories (WIPO, 2024).

The literature frequently emphasizes that the relationship between FDI and technological innovation is neither automatic nor unconditional. A large body of empirical research demonstrates that the positive effects of FDI on innovation depend critically on host-country characteristics, including the level of human capital, institutional quality, financial development, and the maturity of domestic innovation systems (Cohen & Levinthal, 1989; Borensztein et al., 1998).

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In recent years, the structure of FDI has undergone significant transformation alongside globalization and technological change. The fragmentation of global value chains (GVCs) has facilitated the international coordination of innovation activities by multinational enterprises. In this context, FDI has evolved beyond a channel for the transfer of existing technologies to become a mechanism that integrates host countries into global innovation networks (OECD, 2023).

Institutional structure and governance constitute another critical dimension shaping the innovation effects of FDI. Strong intellectual property rights, transparent regulatory frameworks, and effective competition policies can foster collaboration and knowledge exchange between foreign and domestic firms, thereby strengthening innovation spillovers generated by FDI (North, 1990; OECD, 2023).

Human capital represents another key mediating factor in the FDI–innovation relationship. Both theoretical and empirical studies highlight that the absorptive capacity of domestic firms and the workforce—namely their ability to internalize foreign technologies—depends on education levels, skill composition, and learning capabilities (Cohen & Levinthal, 1989). In economies with a highly skilled labor force, FDI is more likely to support innovation through joint R&D activities, labor mobility, and knowledge-intensive linkages. By contrast, skill shortages may constrain the learning and innovation effects of FDI (Borensztein et al., 1998).

Foreign direct investment and technological innovation thus represent intertwined processes that shape growth and competitiveness in the global economy. While FDI offers significant opportunities to enhance innovation capacity, these benefits are neither automatic nor evenly distributed. Accordingly, understanding the conditions under which FDI contributes to technological innovation is crucial for the design of effective investment and innovation policies. This introductory section provides a conceptual and empirical foundation for the panel data analysis conducted in the subsequent sections of the study.

2. Literature Review

Foreign direct investment (FDI) has long been examined in the international economics literature in the context of capital movements, technology transfer, and economic development. Classical approaches viewed FDI primarily as a mechanism facilitating the transfer of capital from capital-abundant countries to capital-scarce economies. Over time, however, this perspective has been broadened to recognize that FDI represents not only a financial flow but also a vehicle for the transmission of technology, managerial expertise, and organizational innovations (Hymer, 1976).

In this transformation, Dunning’s (1988) Ownership–Location–Internalization (OLI) paradigm has played a central role. According to the OLI framework, multinational enterprises make FDI decisions by combining firm-specific ownership advantages with the locational advantages offered by host countries and by internalizing their operations. Within this framework, technology, R&D capacity, and innovative capabilities emerge as key drivers of FDI.

The impact of FDI on technological innovation materializes largely through knowledge spillovers. Blomström and Kokko (1998) identify four main channels through which such spillovers occur: (i) backward and forward linkages, (ii) labor mobility, (iii) competitive pressure, and (iv) imitation and learning processes. Relationships established by foreign firms with local suppliers can contribute to improvements in domestic firms’ production processes and facilitate the adoption of new technologies.

Although the empirical literature on the FDI–innovation nexus is extensive, it exhibits considerable heterogeneity in its findings. Borensztein, De Gregorio, and Lee (1998) demonstrate that the growth-enhancing effects of FDI become significant only when the host country surpasses a minimum threshold of human capital. Their findings suggest that while FDI can support innovation through technology transfer, this process is inherently conditional.

Similarly, Alfaro et al. (2004) find that the effects of FDI on growth and innovation depend critically on the level of financial market development. Well-functioning financial systems facilitate the allocation of foreign investments toward innovative activities and enhance the effectiveness of technology spillovers. By contrast, in countries characterized by severe financial constraints, the innovation-enhancing effects of FDI tend to remain limited.

One of the key channels through which FDI influences innovation is competition. The entry of foreign firms into domestic markets may intensify competitive pressure on local firms, thereby strengthening incentives for productivity improvements and innovation. Aghion et al. (2005) argue that competition stimulates innovation up to a certain threshold; beyond that point, excessive competition may discourage R&D investment by domestic firms.

3. Data

In this study, the causal relationships between foreign direct investment inflows (FDI) and patent applications (PAT) in G7 countries are examined for the period 1990–2021. Due to data limitations, Italy is excluded from the analysis, while the United States, Germany, the United Kingdom, France, Japan, and Canada are included. Only countries with consistent and complete data availability are incorporated into the analysis. The econometric analysis is conducted within a panel data framework, and the Dumitrescu–Hurlin symmetric panel causality test is employed to determine the direction of the relationships between the variables. The variables and data sources used in the analysis are presented in Table 1.

Tablo 1: Variables and Definitions

Variables	**Sembol**	**Source**
Foreign direct investment, net inflows (% of GDP)	FDI	WorldBank (2025a)
Patent applications, residents	PAT	WorldBank (2025b)

4. Econometric Analysis

In the econometric framework, the existence of cross-sectional dependence among the variables was assessed through the LM (Breusch–Pagan, 1980), LM-adjusted, and LM CD (Pesaran, 2004) tests. The corresponding results are displayed in Table 2. According to the probability values, the null hypothesis of cross-sectional independence is rejected for both foreign direct investment (FDI) and patent applications (PAT), confirming the presence of significant cross-sectional dependence among the G7 countries. This finding implies that shocks or changes in one country tend to be transmitted to others, reflecting strong interconnections in investment and innovation dynamics across the panel.

Table 2. Cross-Sectional Dependence Test Results

Variable	**CDLM1 (Breusch-Pagan, 1980)**		**CDLM2 (Pesaran, 2004)**		**CDLM (Pesaran, 2004)**		**Bias-Adjusted CD Test**	
	Test Stat.	**Prob.**	**Test Stat.**	**Prob.**	**Test Stat.**	**Prob.**	**Test Stat.**	**Prob.**
FDI	85.17192	0.0000	12.81158	0.0000	12.71481	0.0000	8.212201	0.0000
PAT	452.4090	0.0000	79.8596	0.0000	79.7628	0.0000	21.2641	0.0000

Table 3 reports the outcomes of the second-generation Pesaran (CIPS) unit root test, which incorporates cross-sectional dependence among the series. The results indicate that the FDI variable is stationary at the 5% significance level in its level form and remains stationary after first differencing at the 1% level. Similarly, the PAT variable is also stationary at the 5% level in levels and achieves stronger stationarity after first differencing. These findings suggest that both variables attain stationarity once their first differences are considered, implying that the series are predominantly integrated of order one [I(1)].

Table 3. Second-Generation Pesaran (CIPS) Unit Root Test Results

Variable	**Constant**			
	Level		**First Difference**	
	Test Stat.	**Prob.**	**Test Stat.**	**Prob.**
FDI	-2.47662	<0.05	-5.56185	<0.01
PAT	-2.54726	<0.05	-2.81190	<0.01

Table 4 presents the results of the Emirmahmutoğlu–Köse panel causality test. The findings indicate that changes in FDI (foreign direct investment) lead to changes in PAT (patent applications) at the panel level (p = 0.031). Conversely, changes in PAT do not have a statistically significant effect on FDI (p = 0.766). This suggests that in G7 countries, variations in foreign direct investment are associated with changes in technological innovation, while changes in innovation do not significantly influence capital inflows.

Table 4. Emirmahmutoğlu–Köse Panel Causality Test Results (FDI and PAT)

Country	**Lag**	**FDI ⇒ PAT**	**p-value**	**PAT ⇒ FDI**	**p-value**
Canada	6	18.547	0.005	8.243	0.221
France	1	0.277	0.599	0.002	0.963
Germany	2	6.594	0.037	4.100	0.129
Japan	1	0.248	0.618	0.005	0.942
United Kingdom	2	1.557	0.459	0.444	0.801
United States	1	0.772	0.380	0.073	0.787
Panel Results		**Fisher Stat.**	**p-value**		
FDI ⇒ PAT		**22.671**	**0.031**		
PAT ⇒ FDI		8.238	0.766		

5. Results and Conclusion

This study investigates the causal relationship between foreign direct investment (FDI) inflows and technological innovation, proxied by resident patent applications (PAT), in G7 countries over the period 1990–2021. Using the Emirmahmutoğlu–Köse (2011) panel causality test, which allows for cross-sectional dependence and heterogeneity across countries, the analysis provides both panel-level and country-specific insights into the FDI–innovation nexus.

At the panel level, the empirical results indicate a weak but statistically meaningful causal relationship running from FDI to technological innovation. The Fisher statistic for the direction FDI → PAT is significant at approximately the 10% level, suggesting that foreign direct investment tends to stimulate innovation activity across G7 economies, albeit modestly. In contrast, the reverse direction—from innovation to FDI—is not statistically significant, implying that higher levels of patenting do not systematically attract additional foreign capital inflows at the panel level. This asymmetry highlights that innovation outcomes alone may not be sufficient to drive FDI decisions in advanced economies, where investment flows are shaped by a broader set of factors, including market size, institutional quality, strategic assets, and global value chain positioning.

The country-level results reveal substantial heterogeneity among G7 members. For at least one country—likely a large and technologically advanced economy such as the United States or Germany—a bidirectional causal relationship between FDI and innovation is observed. This finding suggests the presence of a virtuous cycle in which foreign investment enhances domestic innovation capacity through technology transfer and spillovers, while strong innovation performance simultaneously reinforces the country's attractiveness to multinational enterprises. Such dynamics are consistent with the literature emphasizing absorptive capacity, scale effects, and well-developed innovation ecosystems as key conditions for mutually reinforcing FDI–innovation linkages.

In another country—likely France or Japan—the results indicate a unidirectional causality running from FDI to innovation. This pattern implies that foreign investment contributes to technological upgrading primarily through spillover channels, such as linkages with local suppliers, labor mobility, and competitive pressure, without a corresponding feedback effect from innovation to investment inflows. This outcome aligns with studies suggesting that, even in advanced economies, the innovation benefits of FDI may dominate the investment-attraction effects of domestic R&D performance.

For the remaining countries, no statistically significant causal relationship is detected in either direction. This absence of causality underscores the importance of country-specific characteristics in shaping the effectiveness of FDI as a driver of innovation. Differences in sectoral composition, the nature of FDI (market-seeking versus technology-seeking), the strength of domestic innovation systems, and institutional frameworks may all influence whether foreign investments translate into measurable innovation outcomes.

Overall, the findings suggest that while FDI can act as a catalyst for technological innovation in G7 countries, its impact is neither automatic nor uniform. The weak panel-level causality and heterogeneous country results support the view that FDI-induced innovation depends critically on complementary factors such as human capital, institutional quality, and the maturity of domestic R&D ecosystems. From a policy perspective, these results imply that attracting FDI alone is insufficient to foster innovation. Instead, policies should focus on enhancing absorptive capacity, strengthening innovation systems, and promoting linkages between foreign and domestic firms to maximize the innovation gains from foreign investment.

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WorldBank (2025b), Patent applications, residents, https://data.worldbank.org/indicator/IP.PAT. RESD,

Digitalization and Innovation: An Empirical Analysis on G7 Countries

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Abstract

In this study, the interaction between digitalization and innovation in G7 countries during the period 1990–2021 was examined using the Dumitrescu–Hurlin panel causality test. The analysis employed the variables internet users (INT), mobile cellular subscriptions (MOB), and patent applications (PAT). The findings reveal a mutual and dynamic interaction between digitalization indicators and innovation in G7 countries. This result indicates that digital infrastructure and technological innovation processes mutually reinforce each other, suggesting that digital transformation and innovation policies should be addressed through a holistic and integrated approach.

Keywords: Digitalization, Innovation, G7 Countries

1.Introduction

Digitalization is not merely a technical transformation confined to the diffusion of information and communication technologies (ICT); rather, it represents a multi-layered process of structural change that is redefining production, consumption, public administration, and the organization of global value chains. While this process amplifies the role of data in economic value creation, it simultaneously gives rise to new business models and competitive dynamics through technologies such as platformization, cloud computing, artificial intelligence (AI), the Internet of Things (IoT), and big data analytics. The current phase of digital transformation is characterized by rapid technological change, in which the pace of innovation accelerates alongside the expansion of risk domains (OECD, 2024a; OECD, 2024b). Accordingly, the relationship between digitalization and innovation should be examined not only through traditional indicators such as R&D expenditures or patent counts, but also through a holistic framework encompassing complementary factors including infrastructure, skills, regulation, trust, data governance, and sustainability.

G7 countries constitute a laboratory in which the digitalization–innovation nexus can be observed most clearly, given their global economic weight, technological capabilities, and policy-making scale. The G7 economies are characterized by high income levels and a strong presence in advanced technology production. In this context, the main motivation of this study is to analytically examine how digitalization stimulates innovation at the G7 level, through which channels it reshapes innovation ecosystems, and how these dynamics intersect with objectives related to productivity, competitiveness, inclusiveness, and sustainability.

One of the most critical areas where digitalization intersects with innovation is artificial intelligence. While the OECD highlights the potential of AI to stimulate productivity growth, it also emphasizes that such outcomes are conditional: without appropriate skill sets, competitive markets, access to data, robust security and privacy standards, and institutional adaptation, investments in AI may translate into limited gains in social welfare (OECD, 2024c). Moreover, the effects of AI on income distribution and labor markets remain contested, with

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the distribution of technology-driven gains emerging as a key determinant of inclusiveness (OECD, 2024c).

The impact of digitalization on innovation is increasingly being reassessed through the lens of environmental sustainability. UNCTAD draws attention to the growing environmental footprint of the digital economy, arising from device production, data centers, network infrastructures, and e-commerce logistics, and calls for the integration of sustainability perspectives into digital policy frameworks (UNCTAD, 2024a; UNCTAD, 2024b). The core tension lies in the dual nature of digital technologies: while they may offer efficiency-enhancing solutions that reduce energy and resource use, they can also generate new consumption patterns and waste dynamics driven by expanding data traffic and device turnover. Given their significant role in global production and consumption networks, G7 countries are compelled to manage this tension; the concept of "green digitalization" requires innovation strategies to be designed in a manner that makes environmental costs visible and accountable (UNCTAD, 2024a).

For G7 countries, digitalization and innovation are not merely components of growth strategies but constitute a "multi-objective policy domain" that simultaneously shapes productivity growth, global competitiveness, inclusive development, and climate objectives. Evidence from organizations such as the OECD and UNCTAD indicates that the digital economy is expanding and its influence is spreading across sectors; however, this expansion also generates new policy challenges related to measurement issues, inequality risks, trust and privacy concerns, and environmental footprints (OECD, 2024a; UNCTAD, 2024a).

2. Literature Review

In the literature, digitalization is widely recognized as one of the fundamental structural forces reshaping modern economies. Early studies primarily conceptualized digital technologies as tools that enhance productivity through automation and improved information processing (Brynjolfsson & Hitt, 2000). More recent approaches, however, characterize digitalization as a general purpose technology (GPT) that exhibits broad applicability, continuous improvement, and strong complementarities with organizational and institutional transformations (Bresnahan & Trajtenberg, 1995; OECD, 2024a). Within this framework, digital technologies such as broadband infrastructure, cloud computing, artificial intelligence (AI), and data analytics are viewed not merely as production inputs, but as core building blocks of innovation systems.

Empirical evidence suggests that countries with higher levels of digital adoption tend to perform better, particularly in terms of productivity and innovation outcomes. Nevertheless, the magnitude of these effects varies substantially across countries, with such differences largely attributable to heterogeneity in institutional quality, human capital, and complementary investments (World Bank, 2024). This heterogeneity is of particular relevance for G7 countries, which encompass both advanced digital frontrunners and economies undergoing rapid digital transformation.

Within the literature, digital infrastructure emerges as one of the key determinants of innovation. Infrastructure components such as broadband access, mobile connectivity, and data centers reduce transaction costs, accelerate knowledge diffusion, and facilitate firms' integration into global value chains (Czernich et al., 2011).

Human capital represents one of the most critical mediating variables in the relationship between digitalization and innovation. Endogenous growth theories identify skills and knowledge accumulation as the primary drivers of innovation (Aghion & Howitt, 1992). In the digital economy, this relationship becomes even more pronounced, as advanced digital skills play a decisive role in both the development and effective utilization of new technologies.

Empirical studies indicate that countries with higher levels of digital literacy and STEM education derive greater innovation benefits from digitalization (OECD, 2024c).

At the firm level, digitalization influences innovation through multiple channels. Digital tools enable firms to optimize internal processes, enhance collaboration, and adopt open innovation models (Chesbrough, 2003). Micro-level evidence demonstrates that firms with higher digital intensity—particularly in knowledge-intensive sectors—are more likely to engage in product and process innovation (Brynjolfsson et al., 2021).

At the same time, the literature cautions that digitalization may increase market concentration through network effects and data-driven advantages. In particular, the dominant role of large technology firms within innovation ecosystems can lead to an unequal distribution of innovation gains across firms (Autor et al., 2020). This dynamic is especially relevant for understanding the sectoral distribution of digital innovation across G7 economies.

3. Data

In this study, the causal relationships among internet users (INT), mobile cellular subscriptions (MOB), and patent applications (PAT) in G7 countries are examined for the period 1990–2021. Due to data limitations, Italy is excluded from the analysis, while the United States, Germany, the United Kingdom, France, Japan, and Canada are included. Only countries with consistent and complete data availability are incorporated into the analysis. The econometric analysis is conducted within a panel data framework, and a symmetric causality test is employed to determine the direction of the relationships among the variables. The variables used in the analysis are presented in Table 1.

Table 1. Variables and Definitions

Variables	Sembol	Source
Internet users (% of population)	INT	WorldBank (2025a)
Mobile cellular subscriptions (per 100 people)	MOB	WorldBank (2025b)
Patent applications, residents	PAT	WorldBank (2025c)

4. Econometric Analysis

In the econometric analysis, cross-sectional dependence among the variables is examined using the LM, LM-adjusted, and LM CD tests, and the results are presented in Table 2. Based on the probability values of these tests, the null hypothesis of cross-sectional independence is rejected for internet usage (INT) and mobile cellular subscriptions (MOB), indicating the presence of cross-sectional dependence among the countries. However, for patent applications (PAT), the null hypothesis cannot be rejected according to the Bias-Adjusted CD test, suggesting that patent activities are largely independent across countries.

Table 2. Cross-Sectional Dependence Test Results

Variable	CDLM1 (Breusch-Pagan, 1980)		CDLM2 (Pesaran, 2004)		CDLM (Pesaran, 2004)		Bias-Adjusted CD Test	
	Test Stat.	Prob.	Test Stat.	Prob.	Test Stat.	Prob.	Test Stat.	Prob.
INT	458.6127	0.0000	80.9922	0.0000	80.8955	0.0000	21.4124	0.0000
MOB	452.4090	0.0000	79.8596	0.0000	79.7628	0.0000	21.2641	0.0000
PAT	183.2544	0.0000	30.7189	0.0000	30.6221	0.0000	4.0189	0.0000

Table 3 presents the results of the second-generation Pesaran (CIPS) unit root test, which accounts for cross-sectional dependence. According to the results, the INT variable is stationary at the level, the MOB variable becomes stationary after first differencing, and the PAT variable is stationary both at the level and after first differencing. Overall, all variables become stationary after taking their first differences, indicating that the series are mostly integrated of order one, I(1).

Table 3. Second-Generation Pesaran (CIPS) Unit Root Test Results

Variable	**Constant**			
	Level		**First Difference**	
	Test Stat.	**Prob.**	**Test Stat.**	**Prob.**
INT	-3.42288	<0.01	-4.77728	<0.01
MOB	-2.20938	>=0.10	-3.87877	<0.01
PAT	-2.54726	<0.05	-2.81190	<0.01

Table 4 reports the results of the Dumitrescu–Hurlin panel causality test examining the direction of relationships among the variables. According to the probability values, all causal relationships are statistically significant at conventional levels, indicating the presence of bidirectional causality among mobile cellular data usage (MOB), internet usage (INT), and patent applications (PAT). This implies that changes in one variable are associated with corresponding changes in the others, reflecting a strong and dynamic interdependence between digitalization indicators and technological innovation across countries.

Table 4. Dumitrescu–Hurlin Panel Causality Test Results

Relationship	**Probability**	**Interpretation**
MOB → INT	3.E-09	Changes in mobile cellular data usage lead to changes in internet usage.
INT → MOB	1.E-09	Changes in internet usage result in changes in mobile cellular data usage.
PAT → INT	1.E-11	Changes in patent applications lead to changes in internet usage.
INT → PAT	0.0391	Changes in internet usage result in changes in patent applications.
PAT → MOB	0.0483	Changes in patent applications lead to changes in mobile cellular data usage.
MOB → PAT	0.0017	Changes in mobile cellular data usage lead to changes in patent applications.

5. Results and Discussion

The empirical findings of this study provide strong evidence that digitalization and innovation are mutually reinforcing processes in G7 economies. The panel causality results reveal statistically significant bidirectional causal relationships among internet usage (INT), mobile cellular subscriptions (MOB), and patent applications (PAT). These results suggest that digital infrastructure, digital usage, and innovation outputs are not linked through a linear or unidirectional mechanism; rather, they evolve through a dynamic feedback system.

The presence of bidirectional causality between mobile cellular subscriptions and internet usage (MOB ↔ INT) highlights the complementary nature of digital access technologies. Increases in mobile connectivity facilitate broader internet adoption, while rising internet usage simultaneously stimulates demand for mobile data services. This finding is consistent with the notion that digital infrastructure components reinforce each other, lowering access costs and accelerating digital diffusion. For G7 countries, where mobile and broadband infrastructures are already relatively advanced, this interaction reflects qualitative improvements in usage intensity rather than mere access expansion.

More importantly, the results demonstrate a bidirectional causal relationship between digitalization indicators and innovation output, as proxied by patent applications. The mutual causality between internet usage and patent activity (INT ↔ PAT) indicates that greater digital penetration enhances firms' and individuals' capacity to generate and disseminate knowledge, thereby fostering innovation. At the same time, increases in patenting activity appear to stimulate further digital adoption, likely through the commercialization of new technologies and the diffusion of digitally enabled products and services. This finding supports the characterization of digitalization as a general purpose technology whose innovation effects materialize through complementarities with intangible assets and knowledge creation processes.

Similarly, the bidirectional causality identified between mobile cellular subscriptions and patent applications (MOB ↔ PAT) underscores the role of mobile technologies as both an input to and an outcome of innovation dynamics. Mobile technologies facilitate real-time communication, data collection, and platform-based innovation, particularly in knowledge-intensive and service-oriented sectors. Conversely, innovation activity contributes to the development of new mobile applications, standards, and devices, further expanding mobile usage. This reciprocal relationship aligns with recent micro- and macro-level studies emphasizing the co-evolution of digital infrastructure and innovation ecosystems.

Taken together, these findings have several important implications. First, they suggest that policies aimed at fostering innovation in G7 countries cannot be decoupled from digitalization strategies. Investments in digital infrastructure and efforts to expand digital usage do not merely support innovation indirectly; they actively interact with innovation outputs in a self-reinforcing cycle. Second, the results imply that innovation-led growth strategies may generate stronger returns when accompanied by policies that promote widespread and inclusive digital adoption. Without sufficient digital diffusion, the innovation-enhancing effects of patenting activity may remain localized or unevenly distributed.

Finally, the evidence of mutual causality also helps explain why the innovation impacts of digitalization differ across countries, as emphasized in the literature. Even among G7 economies, variations in digital usage intensity, institutional quality, and complementary investments may shape the strength of these feedback mechanisms. From this perspective, digitalization and innovation should be viewed not as isolated policy domains but as interdependent components of a broader structural transformation process. Policies that recognize and leverage this interdependence are more likely to support sustainable productivity growth and long-term competitiveness in advanced economies.

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Business Transformation Projects-The Roles And Impacts of Artificial Intelligence and Data Sciences (RAIDS)

Antoine Trad[1]

Abstract

The Applied Polymathical/Holistic Mathematical Model for Integrating Artificial Intelligence (AI) and Data Sciences and AI (AHMM4AI) supports Enterprise's transformation projects (simply Project). The AHMM4AI uses various Mathematical Models (MM), that abstract, incorporate, and integrate Data Sciences (DS), AI-Subdomains, Information Communication System (ICS) components with Project's transformed resources. Transformed resources can be services (and artefacts), success factors (or calibration variables), business processes (and scenarios), mixed-methods, AI-Models, and adequate Enterprise Architecture (EA) Principles and Models (EAPM). MMs, mixed-methods' based services, artefacts, and EAPMs can be used to establish set of DS Patterns and Models (DSPM) that include DS technics/capabilities, data-platforms' access (and management), algorithms-functions, mapping concepts, unbundled services; to model and implement Decision Making System's (DMS) Processes' (DMSP) related infrastructure, data-storage(s), components-models, and end-users' integration. The integration of DSPMs enforces and automated DMSPs, Project's validity-checking, and GaP-Analysis (GAP); which all need adapted interfaces to access Enterprise, Project, Data-storage(s), ICS, EAPMs, pool(s) of Artificial Intelligence (AI) services, and other types of resources. On the other hand, DSPMs communicate with other, by using Project's and AI components; and can use also various medias-types formats, like the private, eXtensible Markup Language (XML) format, and many others. Imported (or exported) DSs' contents and structures are combined with other Project's artefacts and components, to deliver DSPMs for various AI-Subdomains.

Keywords: AI-Subdomains, Polymathical mathematical models, Data Sciences, Business and common transformation projects, Enterprise architecture, Artificial intelligence, Qualitative and quantitative research, and Critical success factors/areas.

1. Introduction

AI-Subdomains include Bigdata (BD), Machine Learning (ML), Deep Learning (DL), and other. The AHMM4AI is used for Project's AI-Subsystems' integrity-checking, algorithms' integration, GAP, financial analysis, risk-management, and many other types of strategic DMSP related operations. DSPMs use MMs (where AHMM4AI is a set of MMs) and hence In-memory datasets (IDS) that can be interrelated with mixed-research method(s). These methods are based on mainly qualitative and associated quantitative methods. The RAIDS takes a transformative enterprise-wide view and not just DS' usage in a specific case of statistics; it also promotes DSPMs which support the central reasoning-engine for the qualitative Heuristics Decision-Tree (HDT). Knowing that Projects are complex and have high rates of failure [1]. MMs and hence the AHMM4AI, support AI by aligning AI-Subdomains, Projects, EAPMs, AI-Models (AIM), and other artefacts. In this article the focus is on DS, related DSPMs, and their relations with other AI-Subdomains, services' architectures, interface-variables, adapted mixed-methods, and domain functions, EAPMs, data-platforms… AI-Subdomains like (R)DS, ML, DL, DP, and other, are the fundaments of an efficient DMSP that constitutes the basis of an enterprise DMS. As already mentioned, DSPMs are used for validity-checking, GAP, and optimization activities, and DMS activities. Before reading this article, the valuable reader can consult In-House Implement (IHI) Transformation Framework (IHITF) related guides, and Projects fundamental works, like: 1) The IHITF Guide [2]; 2) The IHITF Glossary [3]; 3) A related syllabus [4]; 4) The AHMM4PROJECT [5]; and 5) The AI based Projects [6]. A Project is a set of Critical Success Areas (CSA) where a CSA corresponds to a DSPM; and the first CSA is the Research and Development Project (RDP).

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2. The RDP Constructs

2.1. The Research Question and Related Hypotheses

This article and RDP's Research Question (RQ) is: "Which RAIDS and related AI-subdomains features, and structural inter-action are needed to support AI-based Projects and Entity's sustainable evolution(s)?" The RDP's Polymathic Resources and Literature Review (PRLR) uses AI literature, IHITF's knowledge DataBase (DB), Conceptual Proof of Concepts (CPoC), and previous articles repository, and gives advantages to the authors' relevant works and professional consulting-projects, like:

- The Polymathic set of MMs or the AHMM4PROJECT(s) [5].
- Deep Learning Integration for Projects (DLI4P) in Projects [22].
- Machine Learning Integration for Projects (MLI4P) [7].
- The Business, Societal, and Enterprise Architecture Framework: An Artificial Intelligence, Data Sciences, and Big Data-Based Approach [8].
- An Applied Mathematical Model for Business Transformation and Enterprise Architecture: The Holistic Organizational Intelligence and Knowledge Management Pattern's Integration … [9].
- Enterprise Transformation Projects: The Polymathic Enterprise Architecture-Based Generic Learning Processes (PEAbGLP) [10].
- The Business Transformation and Enterprise Architecture Framework-The Applied Holistic Mathematical Model's Persistence Concept (AHMMPC) [12].
- An Applied Mathematical Model for Business Transformation and Enterprise Architecture-The Holistic Mathematical Model Integration (HMMI) [13].
- Using Applied Mathematical Models for Business Transformation [14].
- The Polymathic approach for Projects that use a Meta-Model [15].
- Applied Holistic Mathematical Models for Dynamic Systems (AHMM4DS) [16].
- … and others.

2.2. The Set of MMs for RAIDS

The Project, ICS, AIMs, EAPMs, and other, are in fact sets of MMs and IDSs. The RAIDS uses the most relevant MMs which are [5]:

- MM for U4MP (MM4UP) which supports unbundling.
- MM for Factors (MM4FC) which structure and checks Factors.
- MM for GAP (MM4GP) which supports GAP's estimations.
- MM for PRWC (MM4PR) which supports PRWC's estimations.
- MM for Expectations and Constraints (PEC) (MM4PE) which structures PEC.
- MM for Polymathic Enterprise MtM (PEMtM) (MM4PM) which is base for PEMtM.
- MM for Methodologies and ICS (MM4MD) which supports and checks OOM/UM, Archimate, and other.
- MM for MDTCAS (MM4MT) which supports and checks MDTCAS.
- MM for APDs (MM4AD) which supports and checks APDs and its problem-types.
- MM for Intelligence (MM4IN) which supports and checks AI and decision-making.
- MM for AHMM (MM4AH) which constructs the for a specific topic .
- And others.

2.3. The AMM4AI's Implementation

The RAIDS needs holistic organizational intelligence and knowledge management capabilities offered by the AHMM [9]. Which restructures (or transforms) an Entity in the optimal manner, by applying AI/DS modules and DSPMs. That needs a concept that is based on standards, mapping-mechanisms, and interoperability. DSPMs respect standards, and methodologies to support AI based Projects. Transforming Entity's legacy ICS and DMSPs into an AI based atomic service-oriented environment.

2.4. RDP's Hypothesis

This RDP uses hypotheses (or assumptions and even constraints) that are in fact linked to Project's CSAs and the RAIDS corresponds to the main CSA and RQ. RQ's real-scope and feasibility, and RDP's credibility, depend on the perceived hypotheses (and assumptions). Where RQ's main hypotheses depend on the following Project's transformational-activities (and phases) successful finalizations:

- Project's start, budget, contracting, goals, AI/RAIDS vision (and roadmap) developments were hammered and documented.
- There is the needed a sufficient level of political support and AI/DS skills/experiences.
- Disassembling strategies were implemented to offer AI/DS services and The IHI methodology is the Methodology, Domain, and Technology Common Artefacts Standard (MDTCAS) artefacts.
- The Entity and Project have successfully implemented MDTCAS, Factors Management System (FMS), Polymathic Rating and Weighting Concept (PRWC), HDT, and In-House Implement (IHI) Polymathic Transformation Framework (IHITF).
- The Project uses the DB Centric Concept (DBCC) (or DB first) for data operations [17]; and the DB Centric Implementations (DBCI) [18].
- The Entity privileges IHI solutions and AI-Subdomains' integration.
- The Project's team has the needed skills for AI/DS modelling and development.
- The Project (and Entity) has implemented the AHMM or AHMM4AI (and its MMs) fundaments and interactions [5].
- A hypothesis (assumption) corresponds to a CSA, which are selected using the PRLR.

2.5. The PRLR and FMS

This RDP localized an important research-gap that is due to: 1) There isn't anything similar to the RAIDS, AHMM4AI, and MMs, and IHITF; 2) eXtremely High Failure Rates' (XHFR) and their possible identification; 3) There isn't a mixed method similar HDT that includes the Adapted Quantitative-Qualitative Research Mixed Model (AQQRMM); 4) A concrete Weightings-rating (Wgt) based PRWC and FMS that are related to AI/DS, GAP, MMs, ICS and IHITF; 5) The use of CSA Decision-Tables (CSA_DT) to qualify Project's CSAs; and 6) A structures approach to AI-subdomains and the DS' integration. As shown in Figure 1. GAP is applied to all CSAs, but in this article only one GAP/CSA_DT will be presented. The AHMM4AI supports DSs and DSPMs by inter-relating MMs for Factors (MM4FC), where Critical Success Factors (CSF), and Performance Indicators (KPI) are used for Project's and DSs basic-evaluations, and Optimization-Functions (OF). The AHMM (and MMs) support DS' MetaModels (MtM) and a Polymathic Enterprise MtM (PEMtM). The PEMtM perform Entity's validity-checking and also uses the FMS and its underlying Factors that offer [19,20]:

- They can be used in Natural Programming Languages (NLP) scripts.
- The FMS incorporates CSAs, CSFs, KPI, and ICS VARiables (Var) (simply Factor).
- A CSA maps to a set of CSFs (and Project's resources), and a CSF is a set of KPIs.
- The Team manages and tunes the initial-sets of Factors.
- A KPI maps to a unique requirement and problem-type.
- CSFs are used for solving problem-types, in DMS/Knowledge Management System (KMS) (simply Intelligence), and other.

- FMS ensures that: 1) A CSA maps to an Entity APD (or a common functional-domain); 2) A CSF maps to a set of requirements (and directly linked problem-types); and 3) A KPI maps to a ICS' item-variable or Var.

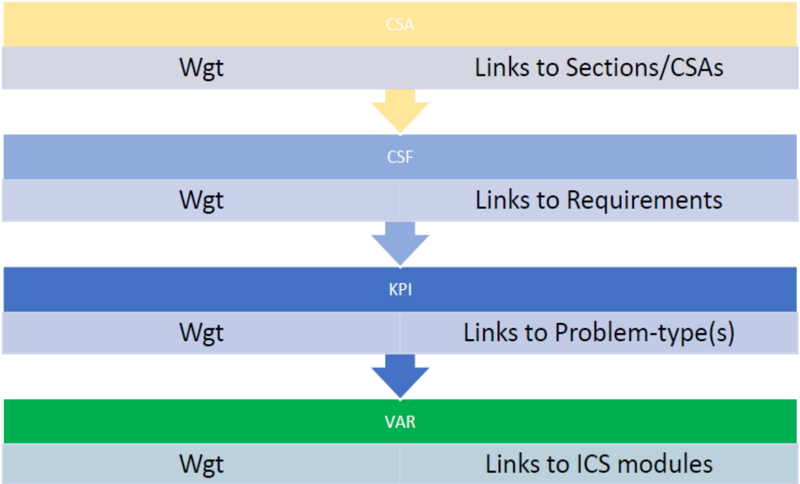

Figure 1: The evaluations for IHITF and AHMM that process CSA_DTs.

2.6. The PRWC, CSA_DT's Evaluation, and GAP

The PRWC interacts with the FMS and Intelligence to offer [21]:

- An Entity standard for CSA-DTs' evaluation method like the Decision-Making Notation (DMN).
- CSAs are evaluated using CSA_DTs, where a CSA corresponds to a Project topic.
- CSA_DTs deliver RDP's Phase's 1 evaluations which constitute Project's DT (Prj_DT).
- The AHMM4AI and MM4PR are supported by the PEMtM.
- Is used to evaluate Project's integrity and used by DSPMs.
- Uses the FMS that includes: Factors like VARs that are accessed by DSPMs.
- GAP evaluates Projects, DS' modules, and other components statuses; by using HDT based Intelligence to eliminate gap(s).
- The PEMtM enables GAP's processing in all Project's phases which are synchronized by the Transformation Development Method (TDM).
- The TDM uses The Open Group's Architecture Framework (TOGAF) and its Architecture Development Method (ADM).
- GAP uses Factors like CSFs which can be: 1) Project's resource; 2) Disassembling outcomes; 3) DSPMs' evolutions; 4) PRWC's outcomes; 4) TDM's synchronization; 6) AI/DS' outcomes; and 7) Use of KPIs to link VARs to concrete components.

3. ICS, EAPMs, Data-DBs, and Other

3.1. Introduction and Distributed ICS

The AI Generic and Basics Artefacts (AI-GBA) is common layer for all AI-Subdomains, where an Entity and a Project can implement an IHI AI-GBA, which is the largest and critical part of AI-Subdomains' integration and/or implementation. Building a robust AI-GBA for transformed ICS (or modern applications) ensures scalability and reliability for AI-Subsystems. The AI-GBA: 1) Includes the hardware, software, data-access mechanisms, and networking components, which are essential for transforming, implementing, deploying, and managing Projects and AI-Subsystems; 2) It is the backbone of AI-Subsystems, that enables AI-

Subdomains like, ML algorithms to process huge data-volumes and to generate data-insights; 3) Supports the integration of patterns like DSPMs; 4) Avoids just using commercial products that cause a hairball; and 5) Offers a robust infra-structure and necessary resources for AI-Subdomains, so Entities can integrate complex algorithms like ML and BD for data-insights and data-driven DMSPs. The different and extensive processing of AI-Subdomains requirements and AIMs, is strongly related to large IDS (used in launching complex computations). The use of various types of massive IDSs is a considerable challenge. Secured and Distributed ICS (SDICS) and related computing-processing, need parallel processing-steps which enables AI-Subdomains and AI-Modules to be scalable and supports the demands for massive data-driven environment [23,26].

3.2. SDICS and High-Performance Processing (HPP) Systems

As shown in Fig. 2, the AI-GBA recommends Graphics Processing Unit (GPUs) and Tensor Processing Units (TPU) usage, [23,24,25] because:

- Graphics based processing technologies have enforced AI-Processing capabilities.
- GPUs offer new possibilities in complex domains like AI and were originally created/designed for graphics and video-rendering.
- But they are also suitable for accelerating AI-Subdomains processing/computations, where their architecture is based on hundreds of cores which can handle thousands of threads simultaneously. That makes it exceptionally capable for parallel-processing requirements of ML algorithms.
- As it is designed for parallel processing/multi-threading, the GPU can used for various types of applications, whereas TPUs are Application-Specific Integrated Circuits (ASIC) used for ML and DS.
- TPUs are designed to support and accelerate the processing of TensorFlow's framework, which is mostly used for DL; and they are optimal for high-throughput used by matrix-operations that are dominant in Nural Networks (NN) processing-calculations, which offers efficient alternative to GPUs for specific AI-Subdomains.
- TPUs are AI-accelerators, which are optimal for large AIMs training, in a variety of use-cases (or APDs), like chatbots, code-generation, media content-generation, synthetic-speech, vision-services, recommendation engines, personalization-models…
- Entities use SDICS (or Clouds) based TPUs for IDSs for real-time DA and DS tasks.
- Clouds' services and APIs enable Entities to adapt to AI-Requests, ensuring optimal-performances and robust Projects.

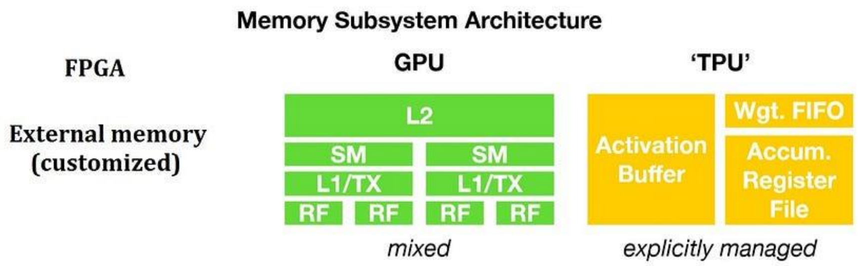

Figure 2: The ICS processing setup.

3.3. The Setup of High-Performance Data Storage Management Systems and Solutions

The AI-GBA recommends high-performances Data Storage Solutions, [23] based on:

- Distributed File Systems (DFS) like the Hadoop Distributed File System (HDFS) and Google Cloud Storage (GCS) are crucial for managing and coordinating large/huge IDSs across ICS' multiple nodes.
- HDFS splits (or breaks) large/huge files into smaller blocks, which are distributed and can be replicated across ICS-nodes, which support scalability, and high-throughput.
- It persists-stores data (or IDSs) near to computation-processing nodes, enhancing performances for various types of tasks like batch-processing.
- High-Speed Solid-State Drives (SSD) are important for data-intensive applications, like in AI-Subdomains, due to extremely fast read/write speeds.
- SSDs have outperformed legacy Hard Disk Drives (HDD) in speed, which is crucial vital for fast data-processing, application-launches, and real-time DS and Data-Analysis (DA) activities.

The AI-GBA recommends Data Management, based on [23]:

- Data-ingestion and preprocessing are important steps in the data-pipeline, which ensure that raw-data is transformed into a request data-format that is ready for AI-Subdomains like DA, DA, ML…
- Extract, Transform, Load (ETL) pipelines, that are shown in Fig. 3, are applied to manage data-flows from multiple data-sources.
- In the extraction-phase, data is gathered from different data-sources like DBs, APIs, and system-files. In this data-transformation phase, the data is formatted, including Quality of Data (QoD) topics like missing values, duplicates, and inconsistencies.
- The loading phase is responsible for storing the processed-data in a Data Warehouses (DW) or DB, to be accessible by DS.
- ETL pipelines ensure data-integrity and efficient DS operations.
- Data labelling tools are used for implementing annotated DataSets, which are important for supervised learning; the mentioned tools enable tagging and categorizing data, like images, text, or audio, providing la-bels for training ML models.

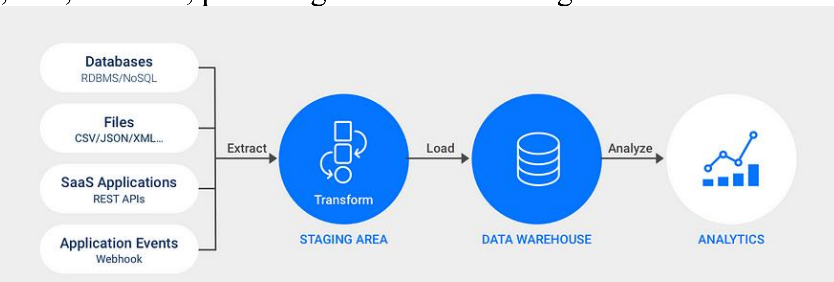

Figure 3: The ETL pipelines [23].

3.4. The DB Centric Strategy and Use of IDSs

In AI there are various streams and probably the most important ones are:

- A DBCC and DBCI are Data (or DB) oriented approach which is the most popular concept in AI-Subdomains, especially in APDs like business, marketing, logistics [17, 18]… Such an approach is known Quantitative methods and statistics.
- A heuristics approach (like the proposed HDT) uses an Actions-Research (AR) engine is and experiences oriented, which is adapted to PEAbGLPs.

- Enterprise oriented which a mixture, which is combination of the two previous approaches, and is represented by the AHMM4AI, AQQRMM, IHITF, and Entity AI Concept (EAIC); which need an AI generic and basic constructs strategy.

3.5. Design for AIMs and AI-Subdomains Architectures

AIMs and AI-Subdomains that define a specific AI-Architecture and related EAMs are considered in the context of the Entity's EA-Models and has the following characteristics [39]:

- EA or Unified modelling language can be used for these purposes.
- Based on the Project's requirements and problems, specific algorithms can be selected to design AI-Architecture integration and interactions.
- The selected algorithms can include rule-based learning, DL, and NLP.
- AI-Architecture affects performance in an important manner, so there is the need to tweak different AI-Platform configurations to find the most effective one.
- Various learning technics are very efficient for different APDs.
- NLP models like transformers would be better for managing complex contextual relationships.

4. AI-GBA Advanced Topics

4.1. The Setup and Use of IDSs

IDS is the basis of using data artefacts and IDSs' main characteristics/features, parts, components, or modules are [27]:

1. They enable AIMs setup, training, and learning.
2. They can have different and formats depending on the applications of AI-Subdomains, which can range from images, binary, text, complex sensor-io...
3. The QoD and quantity of IDSs are important CSFs in estimating AIMs.
4. QoD must ensure that used data is errors-free, otherwise IDSs will be full of biases, or irrelevant information; which will cause the AIM to deliver erroneous predictions.
5. QoD needs: 1) Data cleaning of inaccuracies and inconsistencies; 2) Data labelling and tagging with correct-labels for supervised learning; and 3) Data augmentation helps AIMs and EAPMs to improve generalization.
6. Quantity of data improves predictions (and prediction-accuracies), because, more data/IDSs means better AIMs, but that can prove itself wrong… Data quantity has to correspond to the AIM's problem-space, which means that it should have enough variation and samples of different classes/outcomes needed for AIM's PEAbGLPs.
7. IDSs preparations are important for AI-Subdomains like ML includes: 1) Irrelevant-data identifying and discarding; 2) Duplicated data detection; 3) Noise data filtering; 4) Incorrect data-types correction; 5) Missing-values corrections; 6) Multi-collinearity improvements; 7) Outliers are managed; and 8) Unacceptable format are discarded.

4.2. The Preparations and Use of AIMs

An AIM is a program (or logic) that autonomously supports specific business tasks, in an automated manner. Like HB, it learns, solves problems, and makes predictions. It does learn from experience like the HB, but it acquires knowledge from massive IDSs and applies mathematical-techniques and algorithms to derive insights. An example case, is an AIM that is used to compare pictures of tele-phones and PCs/laptops, using training on labelled images of both. To find differences, the AIM analyses the inputted images to detect patterns, like size, key-board, used building materials, and screen's design. When the AIM is highly trained, it can be used for decision making for new objects, as shown in Figure 4. AIMs can be used for different Apart from this image recognition task, you can apply AI models to different workflows; that includes Apart from this image recognition task, you can apply AI models to several workflows; that include NLP, anomaly-detection, predictive-modelling, and forecasting… These include natural language processing (NLP), anomaly detection, predictive modelling and forecasting, and robotics. to several workflows. These include natural language processing (NLP), anomaly detection, predictive modelling and forecasting, and robotics [39].

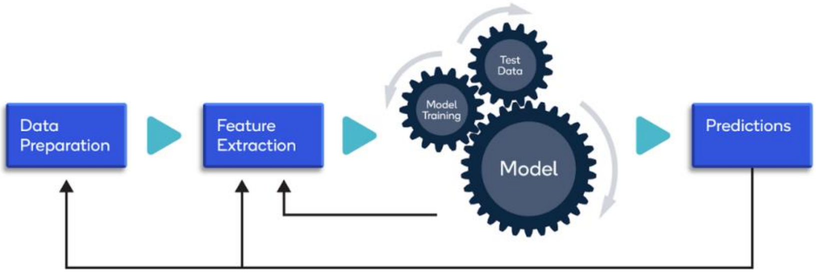

Figure 4: An AIM [39].

As shown in Figure 5, supporting an AIM needs [39]:

- Identifying the problem to be solved and defining goals to be achieved.
- Data preparation and gathering DataSets that reflect the workflows. Where data can be structured, unstructured, static, or streaming, and inconsistencies must be removed.
- Execute AI-Architecture tasks.
- Training, validation, and testing data splitting into three DataSets as follows:
- Training DataSet, which can be up to 70% of the total DataSet.
- Validation IDSs use 15% of remaining data for validation, and AIM's enhancements.
- Testing DataSet, reserves the final 15% to evaluate the AIM performances.
- AIM training uses backpropagation to incrementally tune its internal parameters; and requires important ICS-resources and efficient frameworks.
- Hyperparameter tuning of batch-size, learning-rate, and regularization methods keeps the balance between underfitting and overfitting.
- Model assessment by using validation DataSets, to evaluate the AIM's effectiveness.
- Testing and deployment use testing DataSets and the AIM has to to meet defined use cases; and if the results are satisfactorily, then deployment processes are initiated.
- Continuous evaluation and enhancements are supported by the applied AIMs to adapt to the transformation of data-patterns. Received reports helps in understanding AIM's performances and how to make needed adjustments to keep it relevant.

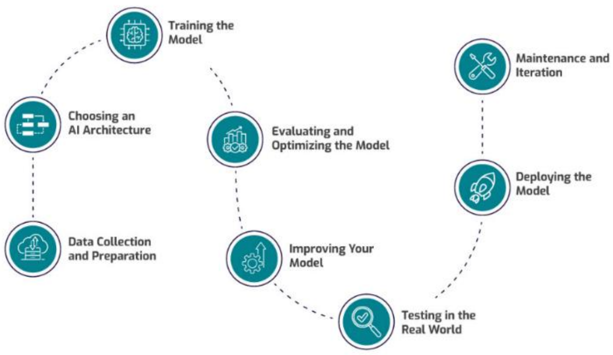

Figure 5: The creation of an AIM [39].

4.3. Needed Support

Supporting an AIM needs [27]:

- AIM's training process includes improve PEAbGLPs to offer predictions or decisions based on inputted IDS, that includes various steps.
- The selection of the Right-Model step, offers an algorithm that corresponds to the IDS and the problem to be solved.
- The Preparation step, splits the IDS into training, validation, and test sets of data.
- The Feeding step, inputs IDSs into the AIM in batches, during the training-phase.
- The Backpropagation step, adjusts AIMs by PRWC (weightings) that is based on predictions' errors.
- Validation steps, use validation IDSs to tune AIMs' hyperparameters.
- Testing steps, evaluate AIMs' performances on unseen IDSs to ensure generalization.
- AIMs' training faces many challenges, and overfitting, underfitting, and ensuring AIM's interpretability are barriers that AI-Engineers face [27]:
- Overfitting is the case AIM learns too much, from the training IDS too well, which results in including noise and outliers, and causes poor performances on new IDSs.
- Underfitting is the case when the AIM is very simple to capture the underlying-trend(s) in the IDSs.
- Interpretability refers to the ability to understand AIMs' made decisions, which is determinant.

To overcome these challenges, AIMs can use best practices [27]:

- Regularization: Techniques like dropout or L1/L2 regularization can prevent overfitting.
- Cross-Validation: Using different parts of the data to train and validate the model helps in assessing its performance.
- Feature Engineering: Selecting and transforming the right features can improve the model's learning ability.
- Model Explainability: Tools and techniques that help explain the mod-el's decisions can build trust and aid in debugging.

4.4. The Setup and Use of Services/API

AI-Subdomains use specialized services, APIs, and AI As A Service (AIaaS) which cover a wide-spectrum of required AI-Functions, like understanding hu-man-language(s), recognizing objects in images and videos, learning from data, understanding speech, analysing sentiments, suggesting personalized advices-recommendations, and other. The AIaaS offers [11,28,29,30]:

- The AIaaS platform ecosystem is optimal for fast commoditization in cloud-services. Cloud-vendors offer a range of standardized, pre-configured AI-Services. Like AI-services that supports the deployment of chatbots; financial-services, fraud-detection…
- Services-Oriented Architecture (SOA) and MSA which accompanied the decline of legacy monolithic ICS architectures. The emergence of SOA and MSA enable the implementation of cloud-services, like AIaaS.
- Legacy monolithic ICS architectures, an application is a set of unit, whereas, SOA and MSA support applications composed of atomic Blocks, which supports the implementation of AIaaS-Functions.
- Commoditization of AI-Functions in AIaaS offers: 1) Optimizing ICS-infrastructure costs; 2) 'pay as you go' model; 3) Reduction of special-ists' costs; 4) 'out of the box' pre-trained AI models can be used; and 5) Integration with other SDICSs.

- Supports various APDs like image-recognition as shown in Figure xxxx that enables a user to identify objects by taking a photo.
- There are many AI-Frameworks that deliver AI-Services and for various subdomains like Machine Learning as a Service (MLaaS).

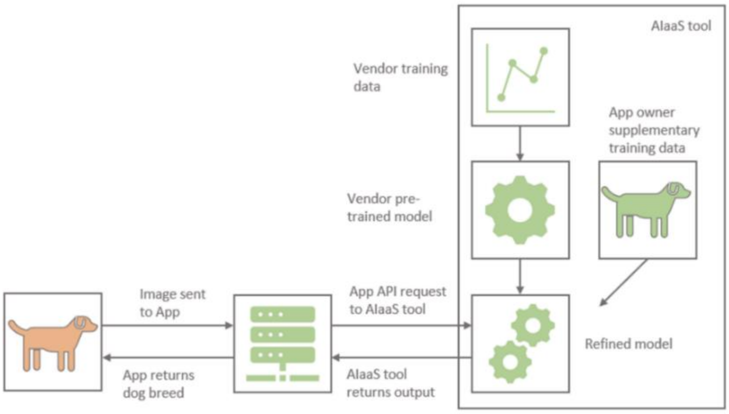

Figure 6: An AIaaS based application that recognizes objects [28].

5. Learning Approach

5.1. Generic Learning Approaches

There is a strong interaction between Projects, AI-Subdomains implementation and Entity PEAbGLPs (ELP), and therefore the Entity has to implement a Polymathic Enterprise Architecture-Based Generic Learning Processes (PEAbGLP). The PEAbGLP manages all ELPs' that includes ML, DL, DS, traditional-legacy LPs and other. The PEAbGLP proposes an IHI concept for a generic and transcendent EAIC. EAIC generic approach means that it supports and interfaces with all AI-Subdomains. The EAIC uses a Polymathic transformation framework that is specialized in Projects. Projects have XHFRs, and added to this complexity, AI-Subdomains implementations and related products can force a siloed-integration implementation approaches, which are the main reason for XHFRs. The EAIC ensures Entity's sustainability, just-in-time decision-making, and operational efficiencies [10].

5.2. AI-Learning Subdomains

There various types of AI-LPs types: 1) Artificial Narrow Intelligence (ANI); 2) Artificial General Intelligence (AGI), and Artificial Super Intelligence (ASI). Where AI-LPs can be classified to its ability to function like the HB; and the main differences are [8,31]:

- ANI is used for simple AI-Subdomains and applies algorithms implemented by developers, which is equivalent to the implementation of a predefined-task, and it does not include autonomous-reasoning; like the AI for Voice (AI4Voice) commands, offer users appropriate responses, used in APDs such as fraud-detection, machine-translation…
- AGI is the case where AI can reason and offer decisions like the Human Brain (HB), where the level of precision is still to be defined. AI based problem-solving which HBs cannot solve like scientific research or mathematical-reasoning.
- ASI is in initial phases, and it is supposed to mimic HB's intelligence but for the moment AI is much more an enhanced statistics field.

In AI related ELPs and more specifically the author's PEAbGLP supports various AI-Subdomains by offering like [7,31]:

- AI-Machines are today are the base of ELPs, where machines which SDICS based, interpret, process, and analyse IDSs to diagnose or solve problems. It is mainly a Quantitative approach in which massive IDSs are inputted to SDICSs to be processed.
- ML has different types of LPs, which are to: 1) Supervised; 2) Unsupervised; and 3) Reinforcement LPs.
- Supervised ML (SML) LPs are based on labelled data-samples; where machines executed specialized tasks on samples that have been labelled, such samples are known as Training-Data for AI (TD4AI), like for example in on image-recognition.
- SML's image-recognition the main concept is based on idea that a machine determines if the image belongs to a specific category and object. Once the machine learned to recognize object's image from TD4AIs, then it will be fed with new images to tune the knowledge related to the object; and at the end used to make predictions.
- Unsupervised ML (UML) LPs are based learning by comparing objects. UML is different from SML, because the machine will not use labelled samples to execute tasks like analysis. By using comparison, that depend on the characteristics of the objects' different elements, like in the case of image-segmentation. Image-segmentation's goal is to classify-group similar image-objects depending on their attributes, without having pre-defined solutions, like online products' search.
- Reinforcement ML (RML) LPs are based learning from concrete user-experiences and interactions with the concerned environment(s) and APDs, where LPs correspond to HBs' way of reasoning. In this case the machine explores DMS options and offers feasible recommendations (or rewards) or penalties, depending on the selected Factors. And the objective is that the machine improves and persists LPs with the most rewards and therefore, improves its future DMS performances.
- DL LPs are based on NN, which is a subcategory of ML that in-turn uses Artificial NNs (ANN) to solve-process more complex IDSs and deeper (more aggregated) AIMs. DL efficiency exceeds ML, because it is capable of analysing more complex DataSets using deeper with sophisticated NNs based processing. Like in the case of an image-recognition the DL LP analyses the shapes.
- And afterwards iteratively, it tries to understand object's constructions from various viewpoints. So, DL LPs, develop a Virtual NN (VNN) from large IDSs to offer solutions.
- The VNN explores a number of layers, and data becomes hard to analyse.
- NLP based AI (NLP) is founded on scientific methods related to learning from NLP to implement machines capable of communicating, and developing businesses and their Business Processes (BP).
- Other Subdomains based AI (OS) like robotics, expert systems, fuzzy logic (and other) LPs include: 1) Robotics that uses AI on robots; 2) Expert systems that offers HB expertise to develop a well-defined reasoning-thinking capacity; 3) Fuzzy logic-based AI for machines/computers to understand topics, problems, and solution which are not just binary 0 or 1 ("true" or "false"). They are applied for machines to offer decisions that are close to HB's decisions made in complex situations, like in medical systems.
- ML LPs support the evolution of ML oriented Projects. ML supports DMS, AI-Subdomains (like DS, BD…).
- AI-Subdomains like DS, BD, and other need a Project and Entity strategic roadmaps which defined AI based transformation processes to implement an Entity DMS where the role of DS and DS and the needed AI-Roadmap and DSPMs [8,32].

6. AI-Roadmap and DSPMs

6.1. AI-Roadmap

AI-Roadmap needs to define the real relations and interactions between various SDICS and AI-Subdomains, and related AI-Components, ML, DS, and DL. The mentioned AI-Subdomains are inter-connected to analyse large IDSs. AI-Components, ML, DS, and DL are related, but they are applied for different goals and have different methods of practical operation [6,8,32]:

- AI-Subdomains need a generic concept to support the DMS.
- A generic concept thar needs a Project to transform the traditional business environment into an automated one.
- AI-based business environment control and monitoring.
- The role of BD, DS, and data-modelling techniques are essential for the DMS.
- ELPs for DL and ML are based action research approach can unify all AI-Subdomains.
- As already mentioned, DS deals with IDSs using environments, and technics to extract hidden-patterns, meaningful-insights, and to offer optimal decisions.
- DS automated processes includes: gathering, organizing, and analysing IDSs. And can be considered a Polymathic (interdisciplinary approach) which merges different fields of SDICS, scientific processes (and methods), and statistics.
- For mining BD (associated with DS), DS uses various techniques, tools, and algorithms.
- DS uses mathematical statistics and ML to handle voluminous IDSs.
- In ML, statistical-methods are used by DCIS to enhance their LPs, without being implemented by software packages. And it focuses on making algorithms learn from the imputed-data, collected-insights, and persisted predictions/decisions on data.

As already mentioned, ML have 3 LP types: Supervised; Unsupervised; and reinforced; and can be related by [32]:

- The Polymathic RAIDS can put together capabilities from various APDs and AI-Subdomains ML, quantitative statistics, and visualization; to deliver APD-valuable insights from voluminous IDSs, supporting robust DMS' processes in various areas, like SDICS/technology, scientific-research, and usual business oriented APDs.
- ML is a subset of both DS, and AI, which utilizes algorithms and statistical models to process IDSs, that in turn support ELPs to be enriched without hard-coding.
- AI is a wider concept, and it focuses on creating DCISs which execute operations which are commonly done by the HB which has intelligence, reasoning, learning, and problem-solving capabilities.
- DS is the foundation for ML and AI that incorporate IDSs for applied AIMs, and to learn from them. It integrates algorithms from ML and includes concepts from legacy traditional APDs' expertise, statistics, and mathematics to implement solutions.
- AI is a valuable resource for DS related fields, because it generates data-insights. The main difference with AI, lies in DS's comprehensive approach to data-collection, preparation, and analysis, transcending only algorithmic or statistical tools-facets. Where ML and AI focuses on algorithms' implementation in Projects.
- An ML case is predictive-maintenance, which is used to predict future results (or outcomes) based on historical-data. Predictive-maintenance includes analysing IDSs from sensors to predict equipment's possible failure(s). ML algorithms are applied to find or identify patterns in IDSs that become problems, and enables maintenance engineers to automate corrective actions before that problems occur.
- NLP is the combination of the mentioned concepts and it involves analysing human language(s) to extract insights and their meaning. DS is used to collect and prepare

DataSets, and ML is used to develop the needed algorithms, and AI is used to support the NLP subsystem.

6.2. Cases of Interactions Between AI and DS

Cases in which AI, DS, and ML interact can be [32]:

- The Recommendation systems, is an AI case, where it represents an algorithm that delivers personalized recommendations based on IDSs. DS participates in the collection and analysis of user IDSs, while ML is used to implement algorithm(s) that supports the mentioned recommendation system. A concrete case of the recommendation system powered by AI, is Amazon's personalized product recommendation-algorithm. The mentioned system applies ML techniques and algorithms to analyse user-behaviours' information, including historical-transactions, product-ratings, and browsing history, to finally provide personalized-recommendations/suggestions to end-clients.
- The Fraud detection system uses DS and ML to analyse large data amounts and to identify (hidden) patterns and errors/anomalies that can include fraudulent actions. ML algorithms identify such patterns and anomalies, while DS collects and prepares IDSs for DA. Like in the case of PayPal which utilizes a ML mixed-methods and DS to analyse huge quantities of transactions' information to find fraudulent-actions. Such a concept identifies patterns and errors/anomalies in IDSs that could indicate fraudulent-actions, like atypical expenditure habits or suspicious Internet Protocol (IP) locations.
- The NLP based chatbots which are designed to simulate conversations with people (clients). AI-Subdomains support chatbots, like ChatGPT, which uses ML algorithms, and NLP techniques, to understand Natural Language Queries (NLQ), to provide personalized responses. The implementation of chatbots, forces AI-Developers to start with collecting and preparing large training IDSs. These IDSs are used to train ML models that can analyse and interpret Natural Language Text (NLT). When the models were trained, then they are integrated into chatbot(s) to provide intelligent and precise answers or solutions.
- General Electric's (GE) predictive maintenance platform which uses ML, which collects sensor IDSs from its equipment and analyses them to predict their statuses. The mentioned platform uses advanced ML's algorithms to detect patterns in sensors' IDSs. It is designed to learn from historical-data, to improve predictions' accuracy.
- The mentioned AI-Subdomains overlap and there are redundancies, which each Subdomain has a unique role in solving problems. The interdependence of Subdomains DS, ML, and AI leads to the use of adapted environments. Where Machine Learning Algorithms (MLA) play a central role.

6.3. MLA Integration

There are different types of MLAs [33,40,41,42]:

- SML Algorithms (SMLA), consists of a target (or outcome) variable (also known as a dependent variable), which is used to predicted from a given set of predictors (independent variables). SMLAs for classification and regression include generating a function/module that maps input-data to corresponding outputs. Training is applied until the AIM achieves the defined or sufficient-enough level of precision. The most popular and used SMLAs are: 1) K-Nearest Neighbours (KNN) is a SMLA classifier, which uses proximity to create classifications (or predictions) on the grouping of individual data-points. It is the common classification/regression classifiers [34]. 2) Regression uses a set of mathematical-methods to predict a continuous outcome (y) based on the value of (1 to n predictor) variables (x). Linear regression is the most common regression analysis method because it is simple to use in predicting and forecasting activities [35]. 3) Logistic regression is a statistical algorithm applied to binary-classifications, used to predict results (or outcomes) that comes from 1 of 2 offered possibilities (yes or no, True or False, Spam or Not spam…). It is used to predict continuous-values for classification problems [36]. 4) Decision Trees (DT) are a non-parametric SML used for classification and regression to create an AIM which predicts the value of the defined target-variable by learning from Decision-Rules (DR) deducted from DataSets. And a DT Classifier (DTC) is a ML prediction mechanism which generates rules, like the "IF Rule THEN…" clause [37,45]. 5) Random Forest is a popular, dynamic and simple ML algorithm that offers, without exaggerated parameter configuration-tuning, optimal results. It is used for classification and regression functionalities [38]. 6) Linear Discriminant Analysis (LDA) is an algorithm for classification and dimensionality reduction; it is used to IDSs that contain large number of features (like image-data). The reduction of the number of useful features is essential to achieve a clear classification process [46]. 7) And other…. Each SMLA uses different types of IDSs, problem-type, or requirement.

- UML Algorithms (UMLA) acts on unstructured and unlabelled data, in which there are no target (or outcome) variable for predicting purposes. UMLAs for clustering and data-mining identify hidden-patterns (or possible structures) in data. Using the mentioned patterns, data-points are grouped by using "similar-characteristics", that auto-generates a function for mapping input-data to clusters (or groups). This iterative process continues until the applied AIM identifies meaningful patterns in IDSs. The most popular SMLAs are:1) K-Means clustering used for clustering-problems used in ML or DS contexts, where it groups unlabelled IDS into different clusters. K defines the number of pre-defined clusters, created and as if K=2, creates 2 clusters, and for K=3, creates 3 clusters…2) Hierarchical Clustering, used to group the unlabelled datasets into a cluster and also known as Hierarchical Cluster Analysis (HCA). It develops the tree-hierarchy of clusters (a dendrogram). Applies two approaches: a) Agglomerative is a bottom-up concept, which starts with defining data-points (as single clusters and merging them until one cluster is left); and b) Divisive is the reverse of the agglomerative algorithm because it is a top-down concept. 3) Principal Component Analysis (PCA), it is a statistical method that transforms observations of correlated-features into s set of linearly uncorrelated features, with the support of orthogonal-transformation process. The new transformed-features are PCAs used for exploratory data analysis and predictive modelling. It is a technique to draw strong patterns from the given dataset by reducing the variances. Each of these UMLAs serves different types of data/IDSs and problem-type, requirements, making these algorithms widely applicable across various APDs, AI-Subdomains, and other fields, such as customer-segmentation, anomaly-detection, and pattern-recognition.
- RML Algorithms (RMLA), consists of reinforcement ELPs' algorithms, where the SDICS supports continuous-training (by trial & error) to offer recommendations and/or decisions. ELPs learn from past-experience and (try) to capture optimal knowledge used to offer precise decisions. RMLA's are: 1) Markov Decision Process (MDP), is a stochastic dynamic process, that originates from Operations Research (OR) and is used to model interactions between ELP's and the Entity's environment, SDICS, BPMs and other. MDPs are divided into two categories: a- Value-based; and b- Policy gradient-based. In this framework, the interaction is characterized by states, actions, and rewards. 2) Value-based algorithms learn from state's value(s) of the Entity's environment (and related artefacts), where the value is given by the expected-rewards to finalize the task. 3) Q-Learning is model-free, off-policy algorithm, which focuses on providing

recommended action(s) to take and in specific APD's contexts to offer optimal solutions. It uses Q-Tables in which possible solutions are persisted (for different state-action pairs in the environment). It also contains Q-Values that are updated after actions' execution. 4) Deep Q-Networks (DQN), are deep Q-Networks, which operate like Q-Learning algorithm, but DQN is based on NNs. 5) State-Action-Reward-State-Action (SARSA) is on-policy algorithm that uses current-actions from the current-policy used to learn and from where the values are deduced. 6) Policy-Based algorithms update the policy to optimize the reward/solution path(s); and there are different policies gradient-based algorithms.

6.4. Secured RAIDS Integration

Secured RAIDS (SRAIDS) needs precise evaluation and measurement technics for: Effectiveness, Cost-efficiency, and User-satisfaction. AI has transformative capabilities in many domains like data-privacy and ESec, but needs a strategy and Qn based analysis of AI-Subdomains based security-measures, which focus on SDICS' effectiveness, and robustness in various APplication Domains (APD) like government departments, finance, education… SRAIDS have the capability mitigating Security-risks like threats, reducing operational costs, and enhancing user experience. Using Factors enable finding valuable data-insights that facilitates the integration of AI in SRAIDS' security-framework. Several AI technologies have proven to be particularly effective in enhancing security measures related to the evaluations of anomaly-detection (and response), automation of threat-identification processes, and predictive-DA. Where RAIDS is very effective in anomaly-detection processes which identify patterns in IDS that deviate from defined norms. It uses MLA because they are able to analyse huge IDSs and to identify deviated-patterns and can also continuously support the IDSs to monitor network-traffic, user-behaviour, and SICS' activities. This approach that ensures quasi-immediate responses, leaves no time and space for attackers, in the case of "unusual login patterns", where a user accesses the SDICS from multiple places. That needs advanced integration technics which is very challenging, especially when using security frameworks. These challenges can be technical human, and organizational. The mentioned challenges endangers the utilization of RAIDS and related AI-Subdomains in security. SRAIDS uses measures and Factors to represent to control Entity's security, and this is done with leveraging AI, to enhance Entity's ability to detect, prevent, and respond to threats [47]. SRAIDS main characteristics are [48]:

- Security-risks' assessments are fairly objective, and are repeatable assessments, which uses IDSs and Factors (frequency and magnitude).
- Provides actionable solutions-results using cost-benefit SRAIDS to enable Security-risks' mitigation modules.
- But it has major limitations like: Needs more time, resource-intensive, the threat-context must be precise and known…

7. Complete Proposition and Prototype-The CPoC

7.1. Preparing SDICS' Platform

The CPoC's first step is to prepare the optimal RAIDS platform that includes:

- An IHI Cloud based SDICS.
- SDICS that offers HPP capabilities for enforced AI-Computing and accelerating AI-Subdomains processing, to support parallel-processing for ML algorithms.
- Support for AI-Accelerators, which are optimal for AIMs' training …
- HPP support for DBs based on DFSs that in turn enable scalability, fault-tolerance…
- Use DB centric concepts and design for AIMs and AI-Subdomains.

- All RQ's hypotheses are fulfilled and the Entity is transformation ready.

7.2. Preparing IDSs

The CPoC is a concept that is based on patterns that support IDSs for this undertaking and the CPoC is mainly based on [44,45]:

- The Iris Flower IDS (or Fisher's Iris IDS, IFIDS), is a multivariate IDS which was used for multiple-measurements in taxonomy related problem-types.
- It uses MLA's LDA to process IFIDSs and to quantify the morphologic variation of Iris flowers (of related "n" species).
- The IFIDS consists of 50 samples for each of 3 species of Iris (Iris setosa, Iris virginica and Iris versicolor), as shown in Figure 7.
- The selected "m" or 4 features were used and were measured for each data-sample: Length and width of sepals and petals, in centimetres.
- The combination of 4 features used by LDA-Model compares the species.
- These IFIDS can be used in AI-Subdomains basic constructs.

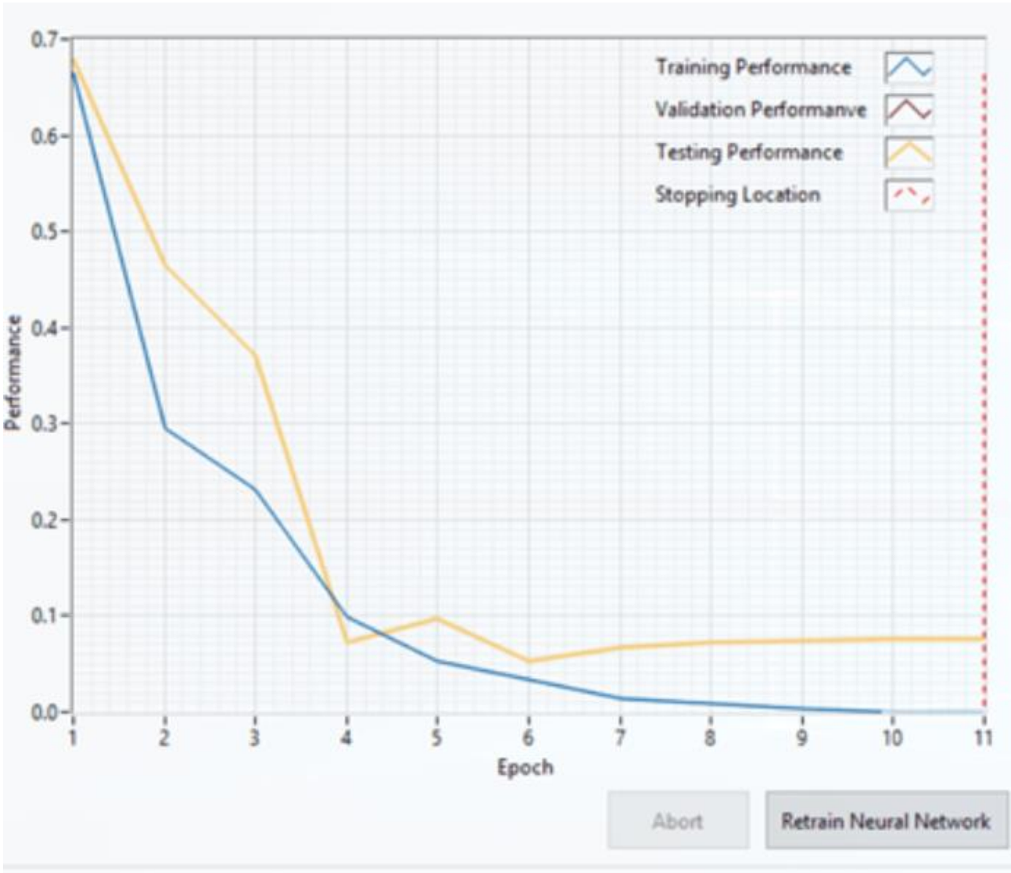

Figure 7: Scatterplot of the IFDS [45].

7.3. Basic Constructs

This prototype's main characteristics are [45]:

- Uses a DT and Working DTC (WDTC) are ML-Prediction system that generates rules.
- Uses an ML-Library which is a customized library for DT, which carries out the following tasks: 1) Implementing functions which split training-data into small DataSets depending on their disorder; and 2) Implementing source-code that calls/uses splitting-functions to create a DT from IFDS and processes/computes a predicted-class.
- Setting-up the CPoC with n=50 data items that are a subset of the data-store.

- The objective is to predict object-types (tagged with 0, 1 or 2).

7.4. The Execution-Setup

This PoC's setup has the following steps [45]:

- There isn't a standard format for WDTC and the Project must define its IHI version as shown in Figure 8 below.
- Each WDTC node contains 6 values defined in a Node class:
  1) The List<int> is the nodes' collection.
  2) The root-node's nodeID has the value: "0". The source-rows are the rows of the entire 30-item dataset with the values: [0, 1, 2. . . 50].
  3) The splitCol and splitVal attributes determine where the source-rows in the node are split in 2 subsets (having small average Gini-impurity). Small-impurity reflects a higher-level of homogeneity that is optimal.
  4) The selected splitCol is set to "2" and splitVal to "3.3", that implies that rows with column [2] has the values strictly-less than "3.3", are shifted (or assigned) to the left-child (or side) of the root-node, and the same with values greater than or equal to "3.3" are shifted/assigned to the right child of the root-node.
  5) The classCounts is an attribute collection that has the numbers of classes related with source-rows in nodes. Root-node's classCounts contains numbers of every class that is associated with source-rows. As all (50) rows are contained in the root-node, and 10 are left of each of the three classes, the classCounts collection that contains [10, 10, 10…].
  6) The predictedClass attribute is used for the prediction which is associated with the actual/current node.
  7) root-node's predictedClass is a class that maps/corresponds to classCounts' highest value. As all 3 class-counts is equal, implies that the predicted class is a tie between classes 0, 1, and 2. In cases of ties, PoC's WDTC randomly selects the 1st of the tied classes, which implies that the predicted class is "0".

```
public class Node
{
  public int nodeID;
  public List<int> rows;
  public int splitCol;
  public double splitVal;
  public int[] classCounts;
  public int predictedClass;
}
```

Figure 8: The class Node structure.

7.5. The Execution-Conditions

This PoC's execution conditions, and constraints [45]:

- The use of splitting (and disorder) scripts creates WDTC.
- The WDTC is ML based and predicts and then generates rules like IF Budget < 10000.0 AND Project_Status >= 2.0 THEN RiskFactors = 10 (which is high).
- The WDTC is ML must be customized and standard-library for DTs offer a huge set of complex functions. Therefore, it is better to use an IHI DWTC.

- For this PoC 30 (training/reference data items) to implement the IHI WDTC which has 7 nodes; which enables 100% accuracy.
- The PoC proves by predicting the class/species of a new (unkown iris-flower with sepal and petal values of (6.0, 2.0, 3.0, 4.0).
- The WDTC predicts that the class is 0, corresponding to the rule: IF (column 2 < 3.1) AND (column 0 >= 5.1) THEN class = 0.

7.6. The Execution-Prediction Process

This PoC's prediction process [45]:

- In the case of external tools or libraries WDTC, and specifically the environments that apply recursions, makes it complex and difficult to define the set of rules that offer predictions.
- PoC's WDTC ignores this complex topic and bypasses using sets of rules (as string-collections) in prediction processes.
- Sets of rules for WDTC's root-node is: IF (any value in all column of the item to be predicted, THEN it is anything.
- The PoC labels this condition using the snippet-string: IF (*) THEN […].
- In some simple cases the root-node is sufficient.
- The prediction_accuracy of a minimal WDTC is the comparison-etalon value; like for a collection of 30 items includes 22 class_1 items, 4 class_0 items, and 4 class_2 items, which means that root-node's class-counts is [4, 22, 4].
- The WDTC predicts class_1 for all items and related prediction_accuracy is 22 / 30 = 0.73 (rounded). The result that corresponds to the prediction_accuracy of a root-node is achieved by simple guessing.
- Therefor a credible WDTC offers prediction_accuracies that is better (>) than its minimal root-node version.

8. Conclusions

DSPMs support reasoning-engines for Projects which are complex. The RAIDS aligns AI-Subdomains, Project components, EAPMs, AIMs, and other artefacts. In this article the focus is on DS, other AI-Subdomains, services' architectures, EAPMs, SDICS-platforms… AI-Subdomains like (R)DS, ML, DL, DP, and other, are the fundaments of a DMS. This articles main RAIDS conclusions are:

- The RAIDS takes a transformative enterprise-wide view and not just DS' or AI views.
- IDSs' contents and structures are combined with AI-Subdomains and SDICS artefacts to deliver DSPMs to be used by a DMS.
- IDSs can be interrelated with mixed-research methods.
- An has to build a performant IHI SDICS Platform to support AI-Computing and ML algorithms, which are optimal for AIMs' building and training.
- Apply a DB, AIaaS, and IDS centric concepts.
- Use ELPs that includes ML, DL, DS, traditional-legacy LPs that results in implementing a transcendent EAIC.
- EAIC generic approach means that it supports and interfaces with all AI-Subdomains.
- An AI-Roadmap defines the relations between various SDICS and AI-Subdomains, AI-Components…
- An RAIDS supports the interaction of AI, DS, and ML components.

Acknowledgements and Future Works

This paper is a part of a series of research works related to AI, Projects, and EAPMs. It is an intersection of the mentioned fields that are interconnected using a Polymathic methodology and framework. The Author will in the future work on finding common AI algorithm that can help AI based transformations.

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(e)Health Transformation Projects-A Polymathic Secured Implementation Strategy (HTP-PSIS)

Antoine Trad[1]

Abstract

This article illustrates the role and how to design and implement an Government Transformation Projects (GTP) in-house E-Health Polymathic Secured Implementation (GTP-PSIS, or simply *e-health*) that use the authors' previous works, like the Enterprise's Holistic Security *e-health* (ETP-HSC) [1,2,3]. In this article the focus is on *e-health* in the context of the comparison of major Governmental Health Systems (GHS) to be adapted for the Kingdom of Saudi Arabia's (KSA) health system. *e-health* includes interfaces to practically all major domains, like Traditional health domains, electronic/web-based health, AI based health modules.... *e-health* uses the author's Polymathic transformation framework and included methodology that supports the GTP-PSIS [7]. Knowing that GTPs (and other types of transformations initiatives) are complex and have very high level of failure rates (at about 95 percent). GTP's main problem is in the acceptance and integration of a GTP-PSIS and *e-health* [7]. *The e-health* shows how an GTP integrates GTP-PSIS and AI based health modules to support GHS' major security breaches. The GTP-PSIS is supported by the author's (today usable) Applied Holistic Mathematical Model (AHMM) for *e-health* (*M-Model*). This article is a Polymathics research and uses an adapted mixed-research method based on the Heuristic Decision Tree (HDT) [8,9]. The *M-Model* based *e-health* supports: 1) A mixed-method empirical Decision-Making System (DMS) and Knowledge Management System (KMS) (simply *Intelligence*); 2) An Action Research (AR) (ideal for GTP-PSISs) method for *e-health*; 3) Portable generic services' approach; and 3) An in-house framework for a successful finalization of secured GTPs. *The e-health* is a new block in the author's Research and Development Project (RDP) and is a natural evolution and the aim is to offer an example of an In-House Implemented (IHI) Transformation Framework (IHITF). *The e-health* for the KSA includes many of the author's research works on the applications of GTPs (simply a Project), global security concepts, Health systems, AI, and Mathematical Models (MM).

Keywords: e-health, Security Processes; Artificial Intelligence; Polymathic; Enterprise Security; Enterprise architecture; Enterprise Transformation Projects; Natural Languages; Mathematical Models; Requirements; Strategic and Critical Business Systems; Performance Indicators; and Strategic Visions.

1. Introduction

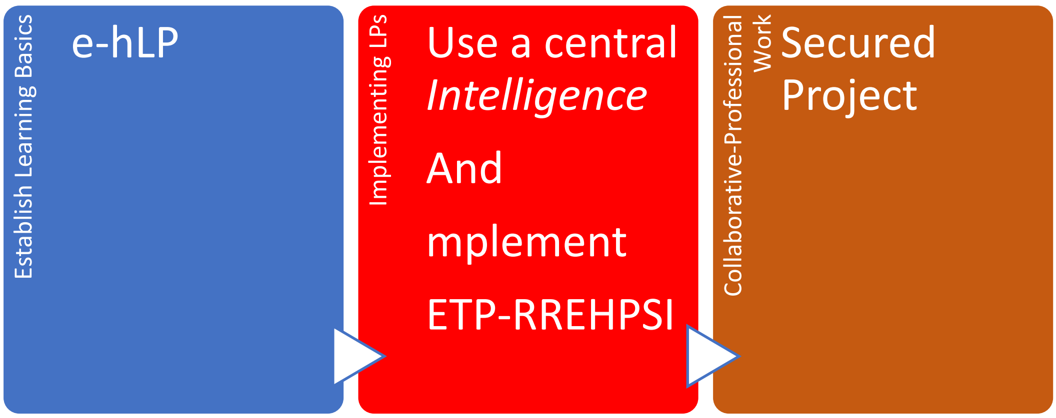

Figure 1: The integration of *e-health* in a Project.

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e-health uses, the GTP-PSIS, specialized global security cases, Council of Cooperative Health Insurance (CCHI), Saudi Health Insurance Bus (SHIB) Project (SHIBP), Enterprise Architecture (EA), and other specialized domains. The AR based HDT solves problems and the solutions (and defines their paths to actions) are persisted in GTP-PSISs; and can be hammered in Project's security strategy. *e-health's* can be used by executive (or Project) managers, security architects/analysts, and infrastructure specialists to enable solutions to transform the legacy system. This RDP is Polymathic and includes existing IHITF modules like ETP-HSC, IHITF, (Re)Organization concepts for Projects, Information and Communication Systems (ICS)/secured ICS (sICS), EA, Health systems' analysis, and other… This article is linked to all the author's works and previous RDP's findings; which implies that previous blocks are reused/included in this article. *e-health* uses the ETP-HSC that includes already analysed security mechanisms like: Managing Passwords, Firewalls, Secure Development and Operations, Antivirus, Wireless Fidelity, Malware, Security Monitoring and Log**s…** [10,11]. And *e-health's* Learning Process (e-hLP) [3] is used to implement, modify, and integrate GTP-PSISs related experiences as shown in Figure 1.

1.1. e-health's and GTP's Viewpoints

A Project can have many Viewpoints, that can include:

- "A" for EA and ICS based transformations.
- "F" for Asset, and financial transformations.
- "G" for Generic transformations.
- "I" for Infrastructural transformations.
- "O" for Organizational, Enterprise and Business transformations.
- "S" for Security based transformations.
- "C" for complete transformations that combines all previously mentioned Viewpoints and where some selected Viewpoints have a priority like "S" in this article (or GTP-PSIS in this article).

1.2. e-health's Characteristics

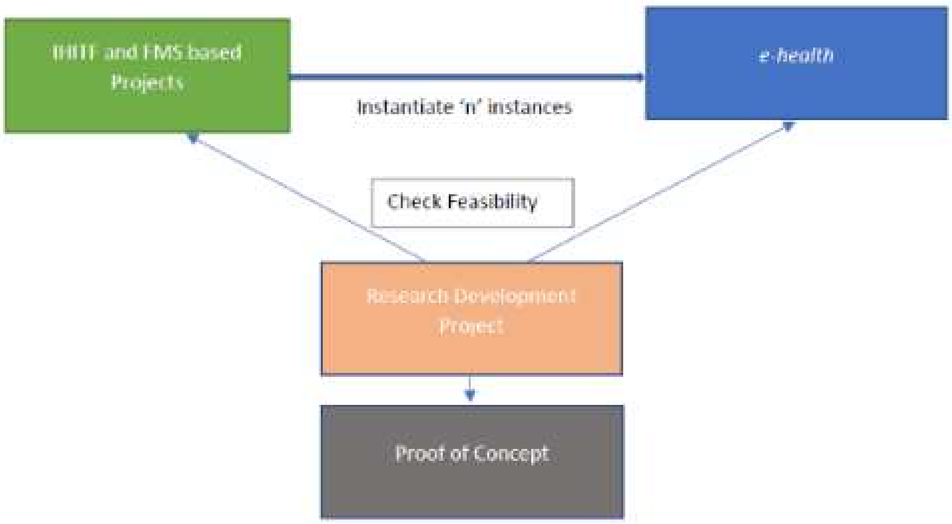

Figure 2: The interaction between the Project, RDP, and GTP-PSIS/*e-health*.

This article uses the Factors' Management System (FMS) and IHITF or the author's Transformation Research Architecture Development framework (*TRADf*) that includes: 1) sICS for *e-health*, and corresponding GTP-PSIS patterns; 2) *Intelligence*; 3) *e-health* generators; and

5) An RDP evolutive strategy, which is the 1st CSA and its heading is in fact the initial set of FMS' CSFs.

1.3. The FMS

The FMS includes and manages the following Project's artifacts:

- Critical Success Areas (CSA), Critical Success Factors (CSF), Key Performance Indicators (KPI), Concrete sICS VARiables (VAR).
- Project's CSAs, CSFs, KPIs, and VARs are known as Factors.
- GTP-PSIS and *e-health* use the FMS based HDT to support *Intelligence* and hence solve security and common problem.
- Uses the Polymathic Rating and Weighting Concept (PRWC) to evaluate Factors.
- A FMS contains sets of CSAs and a CSA contains a set if CSFs.
- A CSF is a set of KPIs.
- A KPI maps (or corresponds) to a unique Project or GTP-PSIS requirement or feature [15].
- For a given requirement (or a problem), TRADf selects initial sets of Factors, to be used by the HDT based *Intelligence*.
- A CSF maps to a requirement(s), GTP-PSIS… [16,17].
- Factors are RDP's main Building Block (BB).

2. The RDP for e-health

2.1. M-Model's Generic Basic Elements

This article (like all author's works) uses generic MM elements that were already defined in the [2,3]. MM's basic elements help in building the Polymathic GHS's Meta-Model (PEMM) and M-Model's elements assess Project common and security risks; some of these basic elements are:

- ***a*** for atomic
- ***m*** mapping operator
- ***….***
- *REQ* *is a GTP or e-health* ***requirement***
- ….
- *GAP* *is a* GTP ***gap*** that results from *e-health*.
- ….

2.2. M-Model's Nomenclature

The e-health uses *M-Model's* basic elements to construct its nomenclature that has two major parts: 1) ICS basics; and 2) The applied security requirements, as shown in Figure 3:

<u>Requirements Viewpoint (R):</u>

mcREQ	= ***m*** KPI	(R1)
mcMapping mcArtefact/mcREQ	= mcArtefact + ***m*** mcREQ	(R2)
FTR	= mcREQ	(R3)
PRB	= ***m*** PRB	(R4)
REQ	= ***m*** CSF = $\underline{\cup}$ mcREQ	(R5)
REQ	= $\underline{\cup}$ FTR + $\underline{\cup}$ RUL + $\underline{\cup}$ CNT + $\underline{\cup}$ DIA + $\underline{\cup}$ REL	(R6)

Figure 3: *M-Model*'s nomenclature.

Where a GTP-PSIS is the choreography of a set of actions that were used to solve a security problem or requirement.

2.3. A Polymathic Projects' and e-health's Approaches

The GTP-PSIS and hence the *e-health* use the secured Unbundling Process (sUP) to disassemble and defragment the legacy organizational units (simply Unit), which in general have heterogenous methodologies/structures, (s)ICSs, Model View Control (MVC) pattern (that includes sets of atomic MVCs-aMVC) and security concepts. As shown in Figure 4, the *e-health* (and the underlying GTP-PSIS) focuses on transforming and securing Unit's resources and applying Viewpoint "C",. Viewpoint "C"'s has the following structure [2,3]:

- sMA = $\sum$ aBB + $\sum$ sBB + $\sum$ aMVC (C1)
- sBB = $\sum$ UP+ $\sum$ sMA + $\sum$ sOPM (C2)
- sCBB = $\sum$ sBB + $\sum$ sABB + $\sum$ SBB (C3)
- sIBB = $\sum$ sCBB (C4)
- Unit = $\sum$ sIBB (C5)
- GTP-PSIS = $\sum$ Unit-modifications' actions (C6)
- …
- sUnit = $\sum$ sSUPL (C10) … secured Unit (sUnit)
- PSIS(i) = $\sum$ sUnit-modifications' actions (C11)
- *GHS*(C) = $\sum$ PSIS(i) (C12)

The e-health supports the refinement and securing secured Unit (sUnit) platform components.

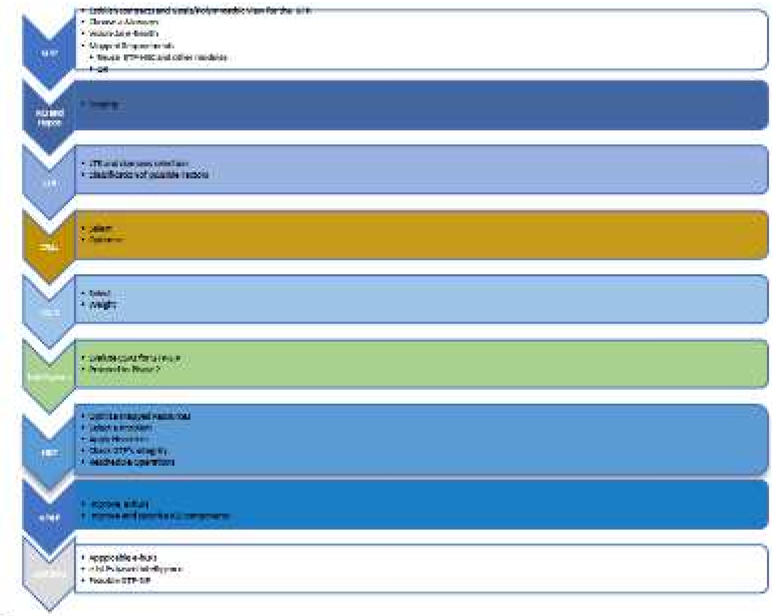

Figure 4: *e-health*'s Polymathic approach.

The RDP presents *TRADf* which relates the selected Applied Case Studies (ACS) and the PoC, which are based on a concrete transformation initiative inspired by a concrete GTP-PSIS, SHIB. Figure 4, shows the Polymathic-holistic approach used by the *e-health*. And the first step established the Research Question (RQ) and initiated an in-depth Polymathic Literature Review Process (PLRP).

2.4. The RQ and PLRP

The RDP's RQ is: "Can the *e-health* support a nation's health system; and thus, apply GTP-PSISs for a secured GHS?". Where this article's auxiliary RQ is: "How can GTP-PSISs accumulate Project's experiences in e-hLPs?". The RDP uses: AI related GTP-PSISs, EA/ADM inspired Transformation Development Method (TDM), *M-Model*, FMS, HDT, and *Intelligence*. PLRP's processing and analysis showed that there are no similar concepts, frameworks, and approaches; and that *TRADf*, has a clear lead in Polymathic Organizational Transformation Research. TRADf is used to show how can an GHS implement an IHITF for *e-health* or any other domain. Unfortunately, today are some non-Polymathic (or siloed) industry and scholar resources on the mentioned topics, like the case of The Open Group Architecture Framework (TOGAF) that can be used as a minor reference, which mentions superficially transformations initiatives. *e-health*, the M-Model, and other author's works), are un-conventional/pioneering, innovative and tries to cover a significative Projects' gap(s) and their eXtremly High Failure Rates (XHFR). XHFR are about 95% and that confirmed by the PLRP [12,13,14]. XHFR are due to siloed approaches and uncapable academic levels that is essentially focuses on immediate tangible or financial goals. The lack of a Polymathic approach to Projects and can endanger *e-health*. The PLRP used the following resources and references: 1) Articles and resources related to AR/GTP-PSISs, Education, ETP-HSC, sICS, GTP-PSIS, generic reengineering, EA/TDM, and various types of Projects; 2) The existing author's RDP/PLRP works, and TRADf; 3) GTP's and *e-health*'s feasibilities, using a concrete ACS or SHIB; 4) Initial sets of Factors and the FMS; 5) The application of the HDT and PRWC; and 6) The RDP uses of the Empirical Engineering Research Model (EERM); and as shown in Figure 5, the next Project's step is to select and classify the sets of Factors in the FMS [15].

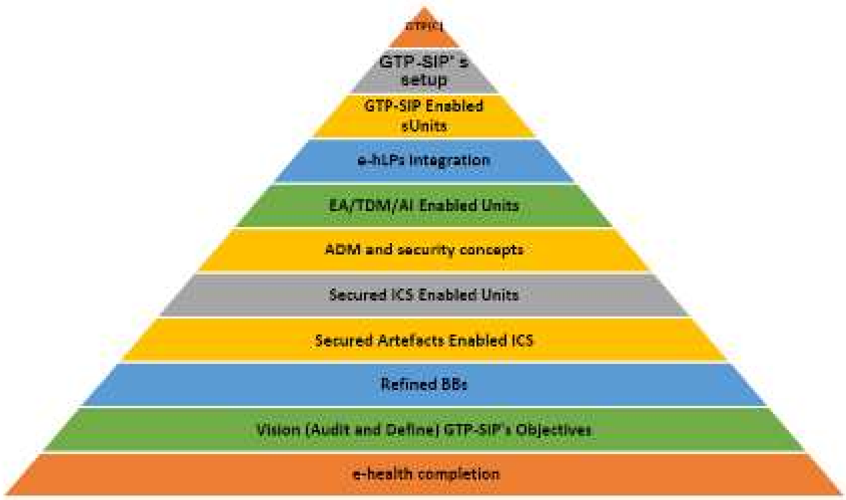

Figure 5: *e-health*'s evolution.

The PRWC evaluates Factors and interfaces *Intelligence;* where *Intelligence's* requests are served by the IHITF as shown in Figure 6. KPIs are linked to concreted VARs [16,17,18,19]. RDPs' phases are: 1) Phase 1 (represented in CSA Decision Tables, CSA_DT), forms the empirical part of the RDP,CSA_ DTs check CSAs; and 2) Phase 2, tries to solve a concrete problem by using the HDT and PRWC.

Figure 6: *The e-health* and FMS' integration with the RDP [20,21].

2.5. The PRWC an IHI Solution

This section explains the internal PRWC and Weightings (WGT) [22] that are a part of TRADf (or any IHITF), knowing that a Project can use also external products or concepts. or it can use an external commercial product. There are various ways on how a Project can use a generic PRWC. An GHS can use a standard PRWC or like in the case of TRADf, it can build its own one. TRADf's PRWC proposes the following rules:

- Sets up and initializes the CSA_DTs.
- The weighting for each CSA is CSA_WGT ϵ { 0.00% … 100.00% } which is a floating-point value/percentage values, which are derived from CSA_DT as one CSA_DT and a set of CSFs).
- The selected corresponding weightings to CSF ϵ { 1 … 10 } are fixed integer values.
- The selected corresponding ratings to CSF ϵ { 0.00% … 100.00% } are floating point percentage values.
- A weighting is defined for each PRWC CSF, and a rating for each KPI.
- The selected corresponding ratings for a KPI is KPI_RAT ϵ { 0.00% … 100.00% } and is derived from: 1) An ICS application/module VARs; 2) Estimated by the IHITF or a domain specialist; or 3) An external concept.
- CSA_WGT = ∑CSF*CSF_WGT.
- CSF_WGT = ∑KPI*KPI_RAT.
- KPI_RAT = ∑VAR*VAR_RAT.

2.6. PRWC Interfacing the System

It interfaces the system by:

- The *M-Model* applies the HDT, which uses the PRWC.
- PRWC (Project-iteration i) = ∑CSA*CSA_WGT.
- The *M-Model* applied a research mixed model, which uses a PRWC.
- *The e-health* uses the HDT which is mainly qualitative method and has specific calls to quantitative methods.
- Can use external solutions.

2.7. PRWC External Solutions

The PRWC can use standard solutions like:

- The Object Management Group's (OMG) [23]: 1) The DMN to support CSA_DTs' evaluations; 2) For implementing business decisions and business rules; and is optimal for Project's status checking; and 3) For HDT's operations.

- The weighted criteria matrix that supports: 1) *Intelligence* to evaluate Projects; and is based on the evaluation criteria (that has weighted by ratings). By evaluating alternatives based on KPIs with respect to defined criteria; and 2) A decision-making module that evaluates projects based on defined evaluation criteria weighted by ratings. By evaluating alternatives based on KPIs with respect to individual criteria [24].

And such complex PRWC needs the EERM as central research methodology.

2.8. EERM's Integration

The EERM is optimal for Projects' oriented RDPs and the HDT (which is a mixed-research) [16,17,18,19], and it includes: 1) A heuristics-reasoning approach; 2) Quantitative Analysis for PRWC (QNT4PWRC); 3) Qualitative Analysis for PRWC (QLT4PRWC) that is mainly based on the HDT; and 4) The RDP and GTP-PSIS based *e-health's* feasibility [16,17]. The EERM checks if outcomes are acceptable and in such engineering initiatives (a PoC is a software prototype) tests the RQ by using its Factors (or independent variables) are processed to evaluate returned effects on these dependent variables. *e-health*'s author's related works are:

- A Transformation Framework Proposal for Managers in Business Innovation and Business Transformation Projects-The role of transformation managers in organisational engineering [1].
- Enterprise Transformation Projects-The Role of Enterprise Architecture in Implementing a Holistic Security Refinement *e-health* (ETP-HSC) [2].
- Enterprise Transformation Projects-The Role of The Polymathic Security Learn Processes (ETP-RPSLP) [3].
- The CCHI/ SHIB Project [4].
- The Holistic Brick based Architecture for SHIB [5].
- An Intelligent Microartefact Patterns' based Architecture for SHIB [6].
- Business Transformation Projects-The Role of a Transcendent Software Engineering *e-health* (RoTSEC) [26].
- Business Transformation Projects-The Role of Requirements Engineering (RoRE) [27].
- Business Transformation Projects based on a Holistic Enterprise Architecture Pattern (HEAP)-The Basic Construction [28].
- Integrating Holistic Enterprise Architecture Pattern-A Proof of *e-health* [29].
- A Transformation Framework Proposal for Managers in Business Innovation and Business Transformation Project-Intelligent atomic building block architecture [30].
- Transformation Framework Proposal for Managers in Business Innovation and Business Transformation Projects-An Information System's Atomic Architecture Vision [31].
- Organizational and Digital Transformation Projects-A Mathematical Model for Building Blocks based Organizational Unbundling Process [32].
- Organizational and Digital Transformation Projects-A Mathematical Model for Enterprise Organizational Models [33].
- Organizational Transformation Projects-The Role of Global Cyber Security and Crimes (RoGCSC) [25].
- Using Applied Mathematical Models for Business Transformation [20,21].
- Applied Holistic Mathematical Models for Dynamic Systems (AHMM4DS) [12,13,14].
- Various Polymathic articles that support GTP-PSISs [3,10,11].

A GTP and *e-health* are complex and that causes resistances and hence XHFRs failures, to avoid such XHFR the Project needs to implement Transformation Readiness Checks (TRC).

2.9. The TRC

Project's lack of Polymathic concept and related complexities' management are XHFRs' origins, and many sources confirm such facts, like *The Chaos Report*, edited by the Standish Group assert that: … *only about 29% of transformations come in on time and budget…* [34,35]. IHITF's TRC enables [36]:

- *Business Transformation Readiness Assessment* capacities.
- TDM's management and executions.
- *e-health* capacities and feasibility.
- GTP-PSIS accumulates experiences and persisting in e-hLPs.
- Use an IHI Methodology, Domain, and Technology Common Artefacts Standard (MDTCAS).
- Gap Analysis (GAPA) to avoid Project's deviation.

2.10. PRWC RDP's CSFs

Table 1: This CSA has the average of 9.25.

Critical Success Factors	KPIs	Weightings
CSF_RDP_Polymathic_Approach	Proven	From 1 to 10. 10 Selected
CSF_RDP_Factors_FMS_Integration	Proven	From 1 to 10. 10 Selected
CSF_RDP_PRWC_Integration	Complex	From 1 to 10. 08 Selected
CSF_RDP_EERM	Feasible	From 1 to 10. 09 Selected
CSF_RDP_TRC	Feasible	From 1 to 10. 09 Selected
CSF_RDP_M_Model	Feasible	From 1 to 10. 09 Selected
CSF_RDP_IHITF_TRADf	Possible	From 1 to 10. 09 Selected
CSF_RDP_PLTR	Proven	From 1 to 10. 10 Selected

valuation

Based on the *M-Model*, PLRP, GAPA, and *Intelligence*, this CSA's CSFs/KPI were evaluated with the PRWC and the results are shown in Table 1 (or the 1st CSA_DT). This CSA's result of 9.25, which is high and that is due to the fact that the RDP's and TRADf's maturity [32]. As the RDP's CSA_DT presented positive results, the next CSA to be analyzed is the Project's Overview that is this article's ACS that is based on Automated *e-health* System (AeS).

3. The Project Overview

3.1. The AeS

Figure 7: The fully automated French AeS..

The French GHS is based on a fully AeS, whose national holistic regulatory framework is definitely the best worldwide and that forces similar players to improve their e-services. This fact is based on the comparison of leading global AeS; and France's GHS has an absolute lead in all verified domains. A French citizen has the right on an e-card Vitale as shown in Figure 7, that gives basic rights in the *e-health* system. France's GHS and related social system that is based on humanistic values leaves nobody in desperate situations [37]. Because of France's GHS and *e-health* system, the KSA decided to test its adaption and initiated SHIB project that is this article's CSA. The French GHS has demonstrated its humanistic principles during the latest massive pandemics (COVID-19) which has inflicted immense damages worldwide and especially in Western countries, but also shown some Western countries real values. In the West, France's humanistic and solidary approach was more than evident and had imposed strict confinements, massive spendings, and the mobilizations of its efficient public sector/population; which makes France the best and real Humanistic Democracy (HD). But there were very astonishing and unhuman Materialistic Democracies (MD) or money-first attitudes, sere the so-called Nordic/Swedish, and Swiss approaches, in which very little was done, and has left people to their own fate and especially homeless, poor, migrants/foreigners… Knowing that North-Europe/Sweden and Switzerland praise themselves for a high standard of their GHSs, standards, and equality, but when it comes to finance (or money), then MD's GHSs seem to forget the humanistic part of medicine. In this major crisis Western corporations (except France) have made trillions of USDs in massive profits; and many companies and individuals have multiplied their richness, mainly because they have absorbed the largest part of the public spending. The COVID-19 crisis is a major test for multilateralism and there is a need for a humanistic approach to support the poor. And of avoid that countries (like North Europe/Sweden and Switzerland) and companies (mainly consulting) get richer who gained trillions and avoided to pay taxes. This all comes at the same time with massive immigrations waves, and climate change [37,38,39]. These make the French GHS and its *e-health* approach very credible and even a reference for health transformations, like SHIB.

3.2. The ACS-The SHIB project

The KSA wanted to develop its GHS with CCHI's management and GHS' vision included the design a model of *e-health* which:

- Conforms to the highest international standards for quality and security.
- Strengthened the health care services, which will be patient-centered, and secured.
- Offers interoperability of its e-services, in order that a person's health data is available to GHS' professionals and healthcare establishments.
- Enables the transfer of patients between GHS Units.
- Manages spendings and better financial controls.
- Global e-services inter-action.
- Manages massive health information and flows.
- Offers a secure technical and software infrastructure.
- Supports the evolutions in health e-service.
- Supports the design, integration, and operations of SHIB.
- Implements a Main Data Center & Disaster Recovery site.
- Monitors GHS' insurance industry with high efficiency from the medical and financial perspectives.
- Establishes healthcare statistical reports.
- Professionally manages Project's phases.

3.3. Project's Phases

The Project's and *e-health* phases are:

- Development: includes the design and development of sICS solutions.
- Business Process (BP) Outsourcing: Concerns customer, processing on its behalf its BPs.
- Network: The creation, organization and management of diverse partners (service providers, health professional, publishers, etc.).
- Software as a Service (SaaS): The legacy ICS is unbundled in e-services, which are recomposed in e-health BPs.
- Management of information and associated e-services: To design added value e-services.
- Security infrastructure and digital confidence: To offer rusted security infrastructure to support high volumes of sensitive information in real time.

3.4. GTP-PSIS Main Objectives

GTP-PSIS's main objectives are:

- Physical security, where the main aim was to offer high level of security that includes GHS' physical security and to insure compliance with established references that lay down general security requirements (like the ISO 2700X series of standards…).
- The sICS is managed by an RSSI (Information Systems Security Manager).
- Security and physical safety is managed by the Physical Security Manager (Security Officer).
- Video surveillance and access control by contactless badge or Biometric access control.
- The protection of personal that includes: 1) Respecting Freedoms; 2) Conformity and risk management; 3) Build sICS skills; 4) Enforce legal controls.
- Supporting the Insurance Management Services (IMS) that supports: 1) Send messages over the network; 2) Validate Health Practitioner Status; 3) Claim supporting document services management; 4) Raise Complaint services management; 5) Tracking Complaint Services; 6) Reporting Fraud services; and 7) Detecting Fraud / Misuse service; and 8) Generating Reports Service.

Figure 8: The Evolution of *e-health*.

The evolution of the French GHS care reimbursements in 2012 was € 16 billion, € 900 million as shown in Figure 8. That needs special sICS solutions.

3.5. sICS Solutions' Overview

In *e-health* sICS data and processes grow exponentially both in volume and in quality, and therefore the importance of effective sICS processing, which needs well-designed and managed, mostly in the AeS sector, where the sensitivity of information is a fundamental parameter and the capacity to synchronize information and actions between various players. *e-health's* e-services support: Third-party payments, GHS' Data management, Detecting fraud, Data-flows management, High-level of security, Optimizing costs, Invoices' management, Value-added services. These e-services are integrated in BPs to ensure uninterrupted chain of trust (information, flow, delimiters…).

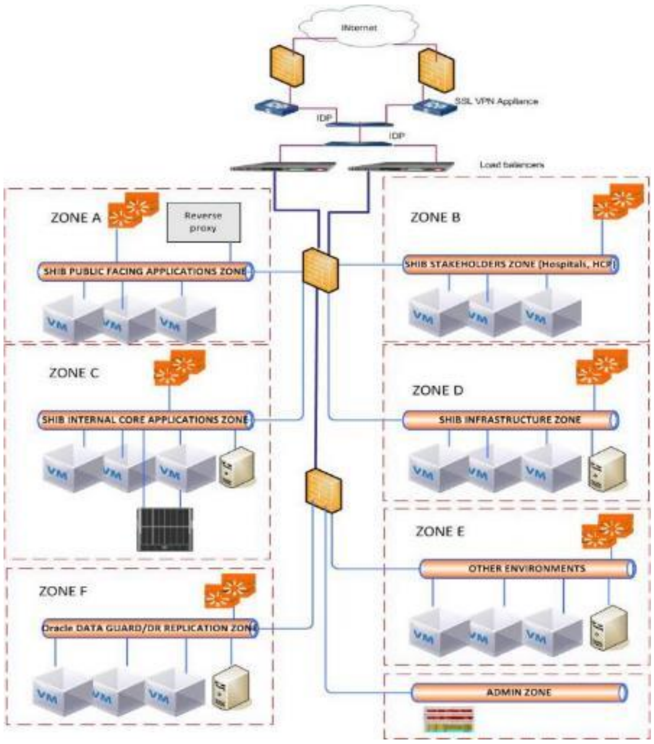

Figure 9: *e-health* sICS security zones.

The GTP-PSIS allows the relevant integration of, in response to the *e-health's* domain developments, to support sICS':

- Connectivity: 1) To federate actors of the global healthcare sector with an enhanced technical flexibility and reliability; 2) Manages a network of partners (healthcare professionals, insurers, health institutions); 3) Interconnects pharmacists, hospitals, insurers, practitioners, health care institutions, specialists, governmental organizations; 4) Manages the identification and authentication of these actors, the access rights to the services and the flow of information including the reimbursement of healthcare costs; 5) Establishes a robust link between health-care professional's and a central sICS; 6) The health-care professional performs medical processes which are precisely defined in the fee structure with a control of the insurance schemes.
- Interoperability: 1) The solution is interoperable and applies data standards; 2) Data processing with remote sICS; 3) Supports HL7 standard based solutions; 4) Offers BBs to interface publishers to support health professionals business needs; and 5) An operations team to support customers in real time.
- Capability, scalability, and Auditing: Implementing control rules requires specific workflows to detect suspicious activities. A suspicion activity is identified by monitoring and will be implemented by Business Process Management (BPM) and supports: Detecting by a user or an operator; Validating the fraud by authorities; Configuring the fraud detection rules; Executing detection rules; and Reporting detections in real-time by the monitoring systems.
- Defines adapted security zones as shown in Figure 9.

3.6. The Security and Operations Concept

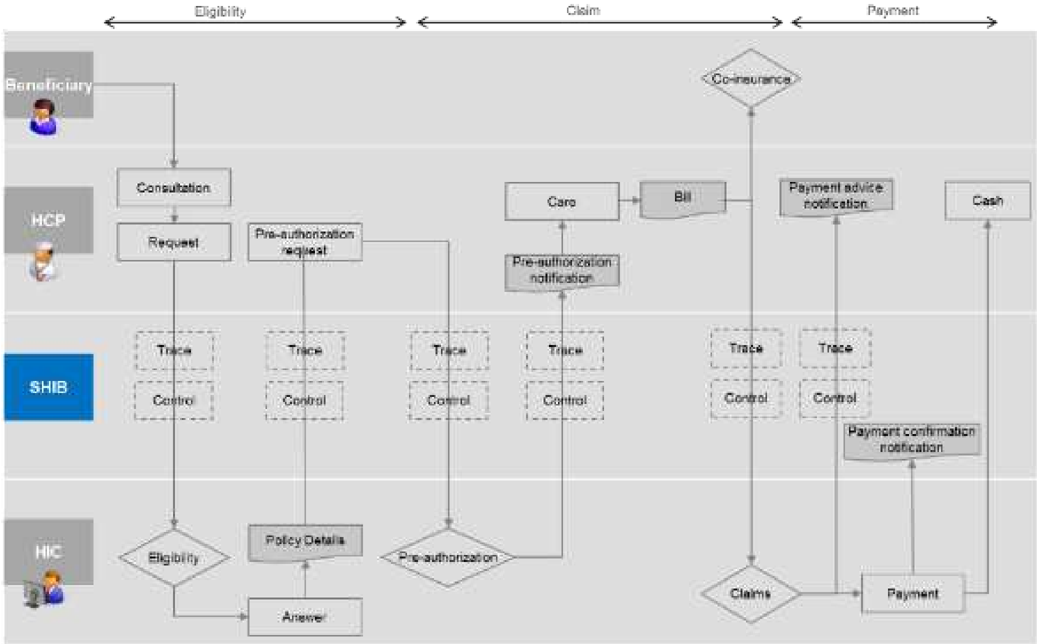

Figure 10: *e-health* main e-services.

e-health security and operation concept includes, as shown in Figure 10:

- A security infrastructure capable of managing huge volumes of sensitive data/information, in real-time, which can be duplicated.
- Has a pool of e-services capable of managing data/information supplier's identity, their traceability and access permissions.
- Guarantees data integrity, confidentiality, retention, and trusted third party.
- Through our expertise in the management of sensitive information, we have developed a remote medicine platform aimed at strengthening the monitoring of patients with chronic diseases…
- An expert system that supports monitoring and the coordination of patients…
- Patients are equiped with sensors connected to the GHS.
- Scalable technical that supports TDM/Business architectures and to respond to massive requests…
- Secured integration of external partners, evolution of users and patients profiles.
- Evolution of spaces like workplace, web-hosting…
- Supports messages exchanging between: GHS and Health Care providers and Health Care financers….
- Messages are HL7 based and can be collected, traced, and processed.
- Control exchanges include: Eligibility, Claim, Payment, messages (associated with same medical treatment/service).
- Infringements (regulatory or fraudulent) are Persisted in specialized stores.
- Security includes the following components: 1) The PKI that handles the lifecycle of the X 509 certificates; 2) The IAM that is used to configure access to all e-health's components; 3) The LDAP responsible for storing of information on individuals, groups or entities; 4) The Security Information and Event Management (SIEM) is for aggregating and correlating security events, used for generalized supervision of security for the project.

Identity and Authorization Management (IAM) manages the lifecycle of users/patients and access control throughout the GHS for any e-service. To support the isolation of roles, *e-health* is based on the principle of the least privilege. Users' management uses authentication that is managed by a central authentication server. Identity is looked-up in the repository to retrieve the user roles and data/information .A user can accesses *e-health* using a personal login/password. In order to give an increased confidence to authentication process, the service can provide for future needs a wide range of authentication method within strong authentication. Business to Business (B2B) partners have certificates and a private key to ensure the confidentiality and the authentication of any exchange with the Project. Non-repudiation is also covered with the digital signature and archiving of every transaction with the Project. We chose to implement a fine grained model of authorization which is built around a Role Based Access Control (RBAC) rather than a Discretionary Access Control which would not fit the required need of traceability and policy enforcement. The chosen IAM service, supported by Oracle Identity and Access Management, is a user centric component which enforces compliance by mandatory logging and auditing of requested authentication and access. The authorization mechanism used allows giving fine grain access to data or functionalities.

3.7. Claim Management Service and Payment Management Service

e-health enable the Heal Care Providers (HCP) to send a claim by using e-services; and the system returns payment notifications service. The payment notification, the claim payment, the pre-authorization as well as the eligibility request will all be grouped into a same insurance claim record to keep e- transactions' coherence. As shown in Figure 11 the BP is designed using a Business Process Management (BPM) environment. The scheme is illustrative to show how the process would be designed in the solution, using BPMN 2.0 standards. The Integration of BPMs is supported by the Services Oriented Architecture (SOA) which allows the mapping of native BPs and e-services. BPMs use Enterprise Service Bus (ESB) for intra GHS communications.

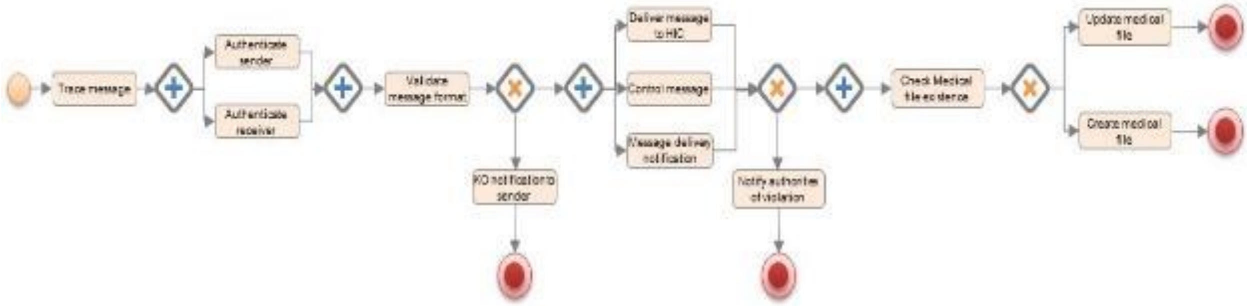

Figure 11: e-service supports BPs.

3.8. The Role of EA

e-health's EA and especially Business Architecture (BA) satisfies Project's requirements using BBs needed for the following BA/functional domains as shown in Figure 12, which is considered a logical view and that includes:

- Operations: Supports the exchange of HL7 messages to manage eligibility, claims, payment monitoring and e-services.
- Configuration: Provides sICS administrators capacities to manage BPMs, BP rules/events, and file-exchange.
- Distribution: Is ensured by a front-end/portal, B2B exchanges supported by web-services, Contact-center, Management of BBs, and Management of authentication/authorization
- Management and auditing offers: Real-time monitoring using Business Activity Monitoring (BAM); Statistical reports and retrospective analyses using Business Intelligence (BI).
- Support: For logging, monitoring and solving requests/complaints.

- BPMs (BPMN2) are heavily used and are related to BAM and BI environments. BPMs are main EA's components; and their topology is based on: 1) GHS' e-services with DataBase (DB) accesses; 2) BA-services which incorporate BPs and data; 3) BP services which stored in the BPM system (BPMS).
- The BAM includes: 1) Monitoring and regulating technical activities on the service-bus; 2) Detecting thresholds (like fraud); and 3) Loss of connectivity.
- e-services registry is a catalogue containing information (like versions and other) on the internal/external services to be used by *e-health*.
- The EA Repository: That is supported by TOGAF, ArchiMate, BPMN… EA's artifacts persisted in a repository with a secured interface that enables: Business analysis; Solution/Application modelling;

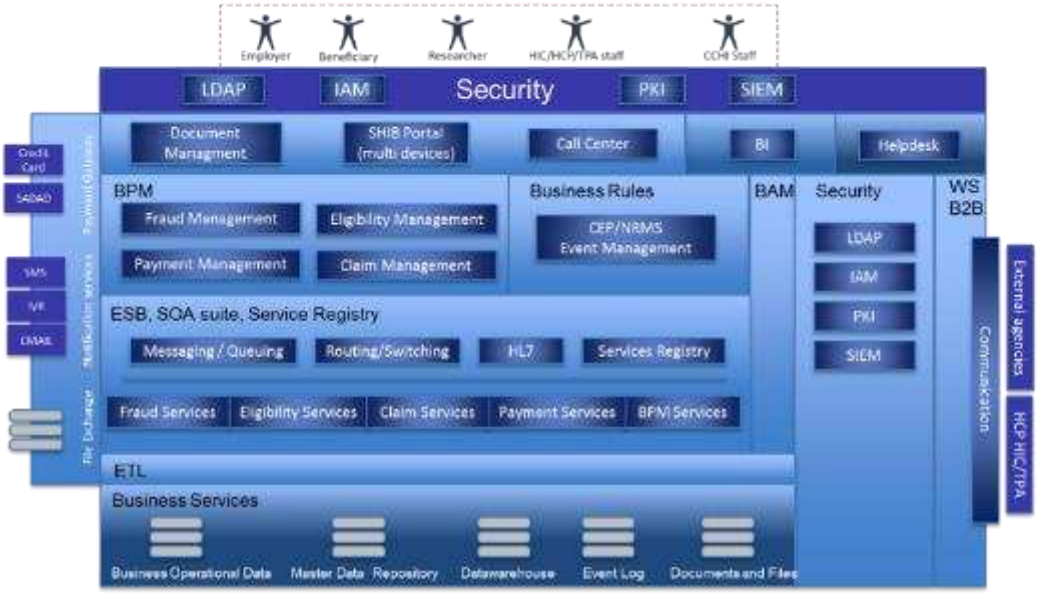

Figure 12: EA's logical view.

ESB exchange include: 1) File-exchange platform to exchange information via a secure channels; 2) e- services for B2B which provides inter-applications communication; 3) Notifications' management of emails or SMS; 4) Payment solution provides the integration with local payment systems; 5) ETL is used for file exchange e-services; 6) Databases are used like: Operational to processes operational data, such as health system data, reimbursements…; Repository contains data on the medical centers, insurance companies, health practitioners…; Journals that contain all the events met throughout the system; Data-warehouse is all the data aggregated from the other databases…; Documentation contains all the e-health's documents.

3.9. The Role of Standards-HL7

e-health's HL7 was selected for messages' management and that stems from the HL7's domain Financial Claims & Reimbursement (FICR) that supports the following scenarios: 1) A storyboard like request; and 2) Offers a development methodology that adapts to targeted *e-health* requirements. In both cases, the GTP-PSIS uses a message framework that supports all types of interactions and a referential model, as shown in Figure 13.

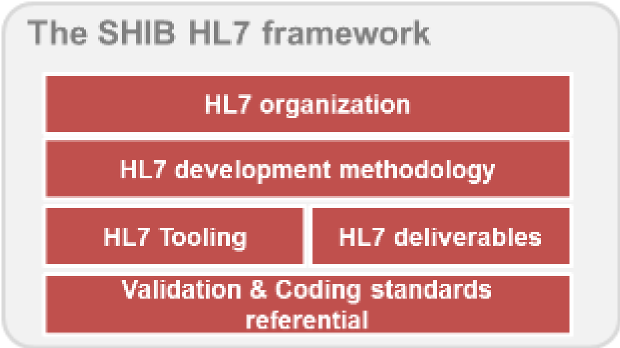

Figure 13: HL7 referential model.

HL7's structure is based on: 1) The portability of its organization (localization) to must comply with the framework established by the HL7 Technical Committees); and 2) KSA's HL7 Affiliate Organization must adopt it with its existing standards. Knowing that HL7 environments use message development methodology that is based on eXtensible Mark-up Language (XML) schemas.

3.10. Detecting Abusive and Fraudulent Accesses

e-health enables the detection of Suspicious accesses usages are treated in a validation flow. Review of validation processes, includes: Checking components, Authority checking, Validation given by a manager, Configuration of control, Stakeholders are notified b of their actions, Fraud is notified in real-time; Use BI to detect fraud.

3.11. Project's Overview CSFs

Table 2: This CSA has the average of ounded 8.15.

Critical Success Factors	AHMM4ERC enhances: KPIs	Weightings
CSF_Project_Overview_AeS	Feasible	From 1 to 10. **09 Selected**
CSF_Project_ACS_SHIB	Very_Complex	From 1 to 10. **07 Selected**
CSF_Project_Phases_Objectives	Complex	From 1 to 10. **08 Selected**
CSF_Project_sICS	Complex	From 1 to 10. **08 Selected**
CSF_Project_Security_Operations_EA_Concept	Feasible	From 1 to 10. **09 Selected**
CSF_Project_Claims_HL7_Fraud_Management	Complex	From 1 to 10. **08 Selected**

valuation

Based on the *M-Model*, PLRP, GAPA, and *Intelligence*, this CSA's CSFs/KPI were evaluated with the PRWC and the results are shown in Table 2 (or the 1st CSA_DT). This CSA's result of 8.15, which is a limit value, that is due to Project's complexities. As the RDP's CSA_DT presented results, the next CSA to be analyzed is the Project's Security Overview.

4. Project's Security Overview

4.1. The Role of Security Basics

e-health's interfaces existing market standard frameworks like: 1) EA (like TOGAF) which can support GTP-PSISs [41]; 2) An IHITF and associated MMs like the proposed *M-Model* [8,9]; 3) Unbundling *GHS's* resources, security mechanisms, and e-services pool [41,42]; 4) AI domains for *e-health* [43,44]; 5) A scalable sICS and an agile group work support [45]; 6);

Problem solving concept that is supported by *Intelligence*; 7) Sherwood Applied Business Security Architecture (SABSA) like environments [46]; 8) The Committee of Sponsoring Organizations of the Treadway Commission (COSO); and many others. The User Management Service (UMS) integrates IAM, which supports: Authentication, Authorization, Access control, Access rights, Entitlements, Access delegation and User Lifecycle Management (ULM) operations. The relation with the SIEM and RBAC services that ensures that illegal actions are detected and traced. Based on Enterprise Manager, the global architecture integrates a Role Based Access Control within every component used. Security-monitoring is based on SIEM that aggregates sICS' logs alerting security-relevant warnings.

4.2. Public Key Infrastructure (PKI) Servers (PKIS) and External Frameworks

e-health's PKI solution is based on leading PKI products as shown in Figure 14.

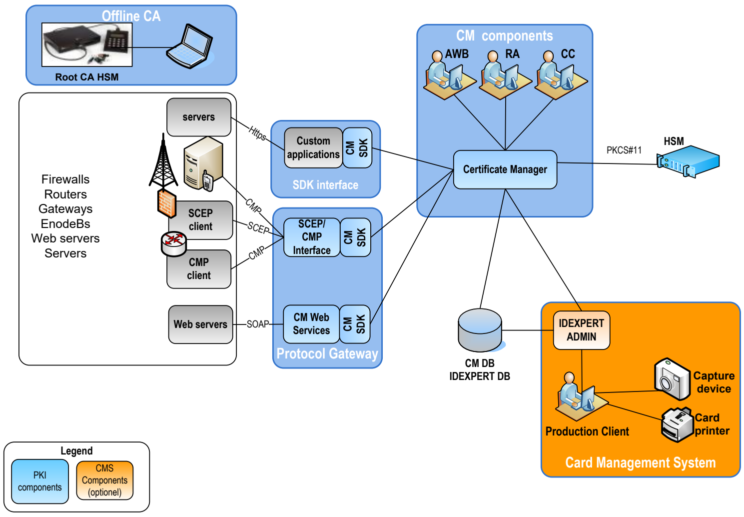

Figure 14: PKI solution for *e-health*.

The PKI solution is flexible and modular with each component performing a single task within the system. Key features and benefits of the proposed PKI solution include: Zero footprint, Flexible and modular, Extensible, Standards-based, High capacity, and High availability. That can supported by the IBM Security Framework (IBMSF) that is shown in Figure 14.

Figure 15: IBMSF's Structure.

As shown in Figure 15, IBMSF defines *e-health* security strategies, architectures, and is used for developing solutions that can be secure from the initial phase. Governance is GTP-PSIS's strategic phase and uses IBMSF that offers guidance to all Project's phases. The IBMSF manages GTP-PSIS/security Critical Risks (GCR) end-to-end across the GHS. ISF supports the GCRs to: 1) Trace and prioritize risks; 2) use holistic flexible infrastructure; 3) Solves security problems; 4) Detects vulnerabilities, attacks, viruses and other malware, spam, phishing, web-threats, and Cybercriminal activities; 5) Governance and compliance; 6) Security based *Intelligence* and analysis; 6) Human factors; 7) Applications and data/information; and 8) Supporting infrastructure. The GTP-PSIS supports the following views: Business**,** Technical, and Solution Architecture. And principles: Defense in depth, Auditability, Least privilege, and Security is model-driven.

4.3. Encryption's Basics

e-health's encryption is used in the following activities: Traffic, Field, Message, Database, and System-wide. GTP-PSIS sensitive information stored in encrypted DB using Transparent Data Encryption (TDE) it offers the masking the use of encryption for *e-health's* applications. *e-health's* encryption must respect performance criterias and information privacy. The TDE manages sensitive data and are also encrypted. This procedure has the advantage of masking the use of encryption for the applications and guaranteeing fine grained encryption. The reason why encryption is not solely implemented at a system wide level is to offer the best performance while making no compromise on information privacy. Particular attention has been paid to avoiding a conflict of interests between security administrators in charge of the keys and system administrators which have access to the data. Here also the tools provided by Advanced Security Options can be used to only authorize database administrators to carry out maintenance and tuning without giving read rights on all or part of a database table. The PKI solution is flexible and modular with each component performing a single task within the system. Key features and benefits of the proposed PKI solution includes: High availability; Physical security service; Host and endpoint security service; and Secured endpoint protection.

4.4. The Role of Security Monitoring

e-health's proactive monitoring supports proactive monitoring service with the goal is to detect the fault before the customer does and then to notify the customer proactively informing of the fault. As shown in Figure 16, proactive surveillance and monitoring inputs: 1) Proactive monitoring; and 2) Standard e-services.

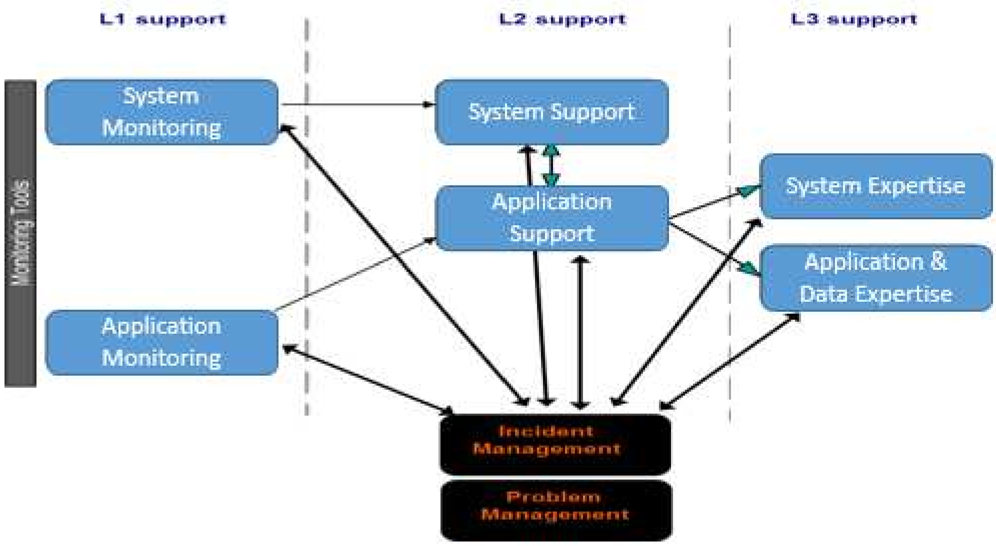

Figure 16: Monitoring and support.

The goal is to 'detect' the incident before SHIB customers does and then to notify SHIB customers proactively informing of the security incidents. Security Incidents: 1) External security breach like: Denial Of Service attacks (DOS); and 2) Internal security breach, like a virus that is generating large volumes of traffic. Impact analysis includes : 1) Capture the impact of the change; 2) The dependency and the relationship of the configuration items; and 3) Impact on affected resources.

4.5. Security's Overview CSFs

Table 3: This CSA has the average of 8.80.

Critical Success Factors	AHMM4ERC: KPIs	Weightings
CSF_SecurityOverview_Security_Conept	Feasible	From 1 to 10. **09 Selected**
CSF_SecurityOverview_PKI	Mature	From 1 to 10. **10 Selected**
CSF_SecurityOverview_Encryption	Mature	From 1 to 10. **10 Selected**
CSF_SecurityOverview_Architecure	VeryComplex	From 1 to 10. **07 Selected**
CSF_SecurityOverview_Frameworks	Complex	From 1 to 10. **08 Selected**

valuation

Factors were evaluated with the PRWC and the results are shown in Table 3. This CSA's result of 8.80 which is satisfying, that is due to mature external security products. As this CSA_DT presented staisfying results, the next CSA to be analyzed is the Project's architecture that is this article's ACS.

5. Project Architecture and Setup

5.1. EA and the Role of e-services

e-health's s and Projects in general need an organizational engineering phase that is based on standards, mapping concepts, modelling technics, and interoperability. EA standards and methodologies support Projects, to become part of the global *e-health* system. XHFRs makes it difficult to follow frequent changes and this fact might cost GHS a lot. A well-planned *Project* is based on a platform of flexible e-services using e-technologies in order to attain the needed level of agility by using an GHS Engineering Pattern (GEP) without incurring high production, maintenance and implementation costs [7,15]. The GTP requires the knowledge of a large set of technologies and methodologies. Adapting just the underlined technologies is not enough and the main problem arises due to lack of business systems' agility. Such an agility approach, as shown in Figure 1, can be built on basic elements called microartefacts [1,8]. GTP changes depends on refactored e-services that includes [30,31]: 1) The interfaces to different services' standards; 2) The e-services based architecture; and 3) The holistic e-services concept, as shown in Figure 17. The evolution of sICS have made Projects more robust and simplified the management of changes by using the holistic e-services concept. And today standards are well established; and they are all operational, in fact there are too many standards, and we can even talk of a standard proliferation [15,48]. The GEP uses BPMs': 1) Engineering; 2) Optimization; 3) e-services' interfacing; and 4) Monitoring. An GEP establishes a common approach to breakdown of the legacy ICS [12,13,14]. The IHITF uses EA methodologies like TOGAF and an adapted e-services based TDM (e-TDM) which can be used for Digital Transformations (DT) [16,17].

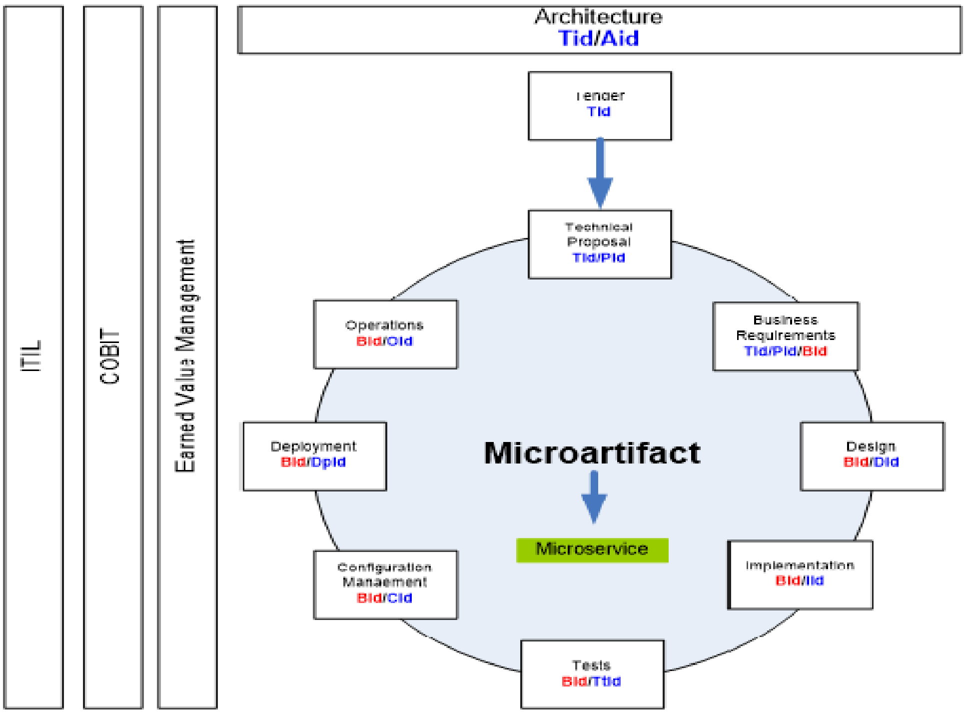

Figure 17: The holistic e-services concept

5.2. The Role of DT Strategy

Today there are many ICS and security frameworks, and they apply siloed-legacy ICS. The GTP-PSIS and its e-health: 1) Supports the automation of a holistic security architecture, design, and integration operations; 2) Its controls uses networked secured Building Blocks (sBB) that originate from various domains like finance, governance and other; 3) It tries to detect sICS problems, financial crimes, business disruptions and corruption; and 4) Implements Cybersecurity mechanisms. Cybersecurity is responsible to avoid security related dangers and threats; and to support an sICS. To deliver an sICS, the e-health's first-step is to successfully implement a DT that offers a common platform for secured e-services and resources. DTs are strategic for Projects, because they support high-adoption rate of sICS/digital technologies. DTs use TDM and secured MDTCAS (sMDTCAS) to integrate digitized Application Domain (APD) models [32,33]. An GHS must offer an all-inclusive DT based on e-health, sMDTCAS, and e-TDM.

5.3. The Role of e-TDM

e-health's e-TDM promotes the usage of existing services architectures like microservices, throughout e-TDM phases. These architecture services can be: 1) Service Oriented Architecture (SOA) and its repository [18]; 2) Building e-services based BBs; and 3) Defining Solution BBs (SBB). In e-TDM's business architecture phase includes the: 1) Mapping of GHS' structure; 2) The definition of strategic goals and objectives; 3) Refinement of *e-health* functions; 4) *e-health* data BBs; 5) BPMs and EA modelling languages; 6) Definition of *e-health* actor's roles; 7) Correlation of *e-health* and GTP functions; and 8) *e-health* data model development [12,13,14,19,20,21,26]. The GEP uses the "1:1" concept which supports: 1) Different BB types; 2) Monitoring and logging activities; 3) sICS alignment; 4) The refactoring of legacy ICS resources; 5) Aligning security requirements; 6) Integration Intelligence; 7) Implementing optimal e-TDM patterns; 8) Defining the role of secured BPMs; 9) The management of frequent changes; 10) The mapping of the e-services to other Project resources; 11) Defining the role of agile project management and FMS; and 12) e-services granularity and integration.

5.4. e-services’ Granularity and Integration

e-health’s e-services control concept supports the unbundling of the legacy ICS by breaking it down into a set of classified and secured e-services, and have the needed level of granularity [27,30,31]. From e-TDM’s perspective a e-service can have any size and it depends on the Project’s vision and how they are classified. These e-service are classified into specialized repositories, granularity depends on e-service’ classification depth that in turn depends on the type of BPMs. e-services’ architecture governance focuses on the life cycle of a services’ architecture from its inception through modelling, assembly, deployment, management and eventually exclusion. Universal Description, Discovery and Integration (UDDI) service catalogues and BPs’ metadata-repositories are integrated with the operation’s Configuration Management Data Base that enables a GTP-PSIS’s platform e-services’ management. The complexity lies in managing e-services and their life cycle and how to operationally monitor them. e-services’ life cycle is based e-TDM’s governance that defines e-services’: 1) Strategy and portfolio; 2) Design processes; 3) Transition that management of change, configuration, releases, plans and tests processes; and 4) Operations management. The GEP is built on e-services’ choreography that are stored in the e-TDM’s continuum that includes [30,31]: 1) A unique e-services’ identifier; 2) Related Project requirements to other resources; 3) Requirements capture both *e-health* and technical requests; 4) Contains an autonomous sICS solution based on e-services; 5) A e-TDM manages the development of the choreography of e-services; 6) Unifies the implementation of GEP; 6) An e-service can be an aggregation of other e-services; 7) An e-service is reusable and can be easily replaceable; 8) An e-service can have many instances; and 9) An e-service enables interoperability, integration, and mapping. Such activities have a deep paradigmatic shift in sICS, and legacy ICS are split across different nides. Stateless domain objects in the form of XML containers are an important change; this is a new transformational shift. Stateless domain objects in XML form unbundles sICS’ nodes into independent BBs which interact across network. *E-health* integrates the Object Mapping System (OMS) template to support dynamic claims system [47], that all needs PEMM.

5.5. The Role of PEMM

e-health’s needs a PEMM, where it is crucial for Projects and GTP-PSIS; which might take many years to finalize. To avoid GHS locked-in commercial sICS/Security and AI products, a recommended way is to apply a Relational DataBase (RDB) based *PEMM*. An RDB-based PEMM can be implemented by using GHS’ sICS/data-storage and RDB Security concepts and mechanisms; without the need for continuous massive investments in siloed-commercial products. A PEMM supports a Project, because the RDB is normally used in all sICS’ and Security subsystems. RDB’s primary advantage is that they contain all the essential security requirements, information, structures, integrity-checking controls, and applied MM constraints/constructs. Another possibility is to use an Asset Management (AM) based PEMM, in which a Project can use the Holistic Project Asset Management *e-health* (HPAMC) to support a PMM. The HPAMC manages and secures GHS assets that includes all its resources/assets: 1) Business cases, requirements, and processes; 2) Financial and real-estates assets; 3) Software, RDBs, sICS components; and other types of assets. The PEMM delivers a transcendent and generic approach which is usable by the secured MDTCAS (sMDTCAS) [49].

5.6. e-TDM's CSFs

Table 4: This CSA has the average of 9.25.

Critical Success Factors	KPIs	Weightings
CSF_Architecture_e-services	Complex	From 1 to 10. **08 Selected**
CSF_Architecture_e-TDM	Possible	From 1 to 10. **09 Selected**
CSF_Architecture_Granularity_Integration	Complex	From 1 to 10. **08 Selected**
CSF_Architecture_DT	VeryComplex	From 1 to 10. **07 Selected**
CSF_Architecture_PEMM	Complex	From 1 to 10. **0 Selected**

valuation

The Factors were evaluated with the PRWC and the results are shown in Table 4. This CSA's result of 8.0, which is low, that is due to the complex unbundling process. As this CSA_DT presented unsatisfactory results, the next CSA to be analyzed is the Project's system implementation.

6. Project's System Implementation

6.1. The SLC

The SLC is related to managing e-services related to *e-health* and the manner how to operationally trace-monitor interrelated e-services' compositions and their interaction with the GHS partners and actors. e-services can use SOA governance model that offers e-services' [60]:

- Strategy that manages the portfolio and ownership.
- Design that delivers solutions for e-TDM, sICS, and other artefacts implementation issues.
- Operations is governed with focus on keeping e-services running.
- Governance can use Information Technology Infrastructure Library (ITIL) which has the focus on sICS e-services.
- Interfacing standard security and common frameworks.

6.2. Using Standard Security Frameworks

e-health can use standard frameworks like COSO defines basic components, a common language and a roadmap for Project's GCR management. GCR's mitigation and management objectives are: 1) Strategic; 2) Operations; 3) Reporting; and 4) Compliance. And related Factors are [55]: 1) Organizational; 2) *e-health's* interfacing; 3) GCR's assessment; 4) Determining GCR's possibilities; 5) Identifying GCR responses and actions; 6) Communication of GCR results and storing them in GTP-PSISs; 7) Monitoring; and 8) Integrating the Digital Forensics and Incident Response (DFIR) *e-health* (DFIRC).

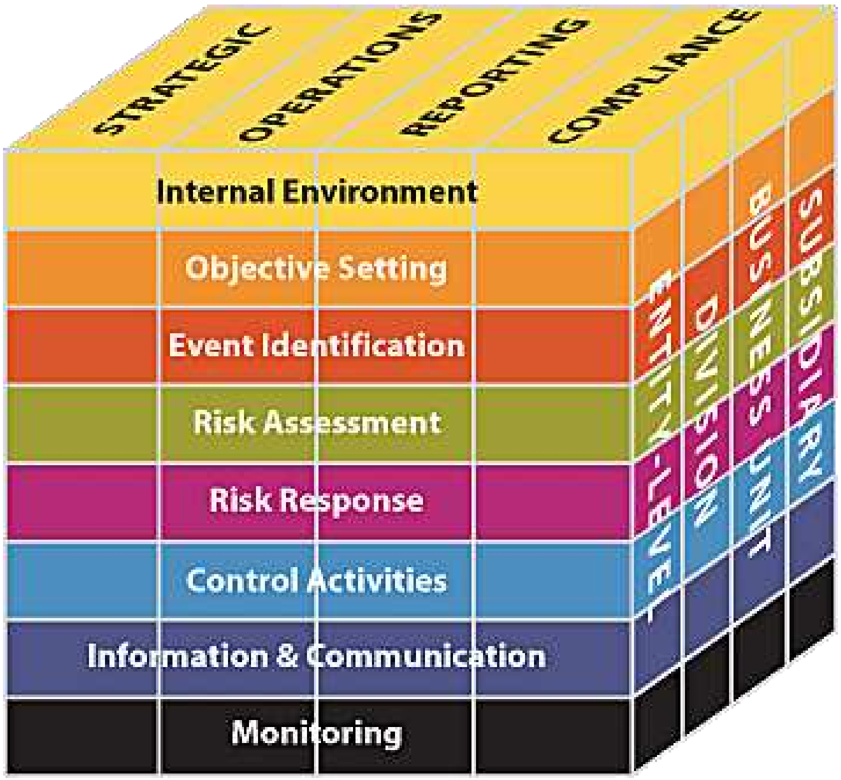

Figure 18: Interfacing the COSO framework [55].

The e-health can interface frameworks like COSO which include common components, a common language and offers a roadmap for risk-management, which modifies and enhances GTP-PSISs. The GHS structure depends on e-services and sICS which are used to (re)organize sUnits. *The e-health* uses sMDTCAS and e-TDM to integrate standard methodologies, like TOGAF and SABSA [46,56].

6.3. Using Common Environments Frameworks

e-health can establish a global Cybersecurity and crimes detection strategy. *The e-health* includes Cybersecurity and governance of GCRs and related Factors, which can be mitigated, to ensure GHS' global evolution and to predict (and eventually) block Cyber (or traditional) crimes/misdeeds. GHS and its partners Cyberspace's resilience, control, and security concepts are siloed, insufficient, chaotic, and concentrate only on sICS/technical-platforms' infrastructural characteristics, which can be fed in GTP-PSISs. GHSs are aggressed by Cybercrimes that are based on Cybersecurity weaknesses and violations that are difficult to detect. Secured Projects and hence *Entities* are very complex to secure, because of various sICS and APD problems, and they depend on the *GHS's* structure and GTP-PSISs management. The sICS related *Projects* use TDM's cyclic phases, which includes sUPs. Figure 18 shows sBPMs' Security roadmap, which can be integrated in GTP-PSISs. Using sBPMs in GTP-PSISs enables: 1) The reduction of GTP-PSISs complexities; 2) Parallel development of sBPMs using secured DevOps (DevSecOps); 3) Valuation and allocation of Security controls to sICS elements, e-services, …; 4) Optimizing interdependencies between sBPMs and Security controls; 5) GHS wide Security monitoring, optimization and improvement of GTP-PSISs using DevSecOps. [57,72]; and 6) Offering Managed Security Services (MSS).

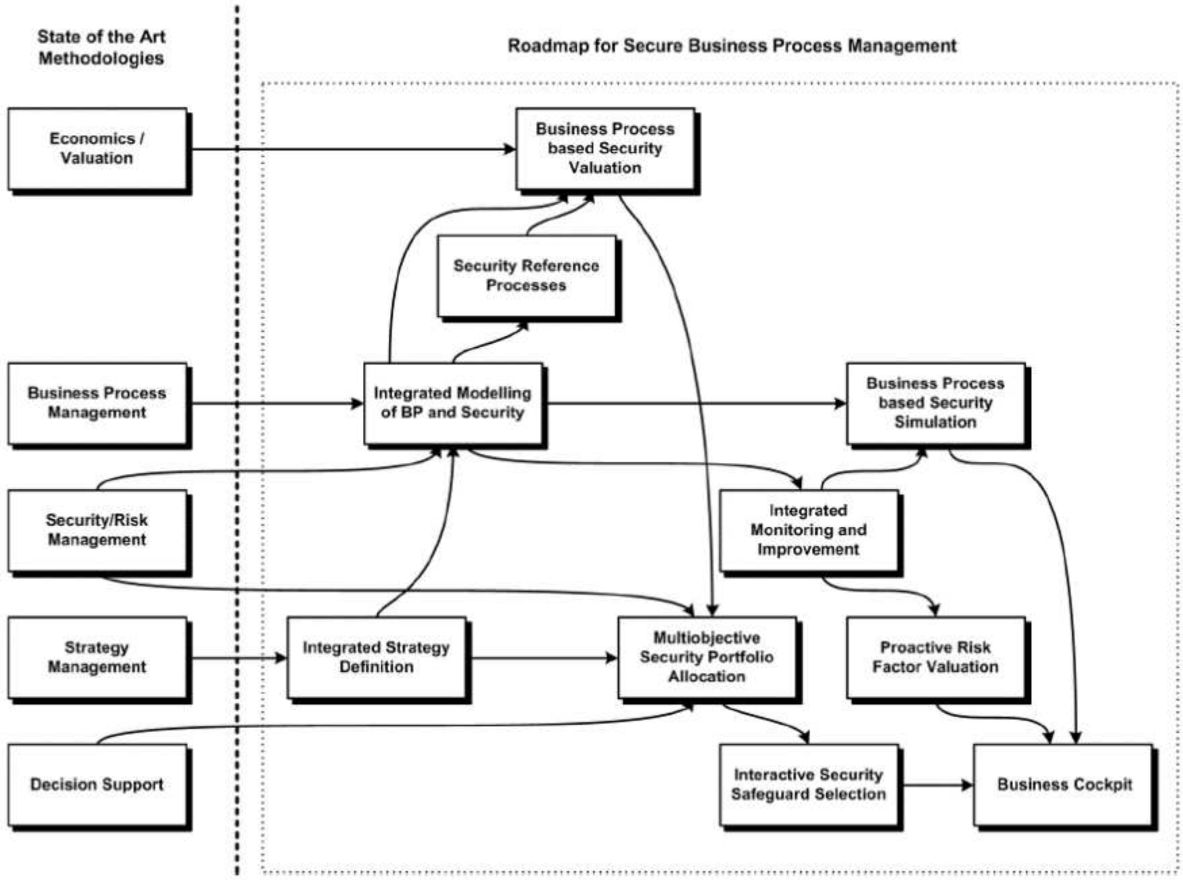

Figure 19: Roadmap for secured sBPMs for GTP-PSISs [57].

6.4. The MSS and SEIM

e-health's MSS and SIEM support:

- Managed firewall and IPS service(s), that offers Monitoring and managing firewalls and IPS' capability to prevent security threats.
- A single point of contact, because it provides real-time monitoring, management and customized protection capabilities.
- Interfaces frameworks like IBMSF, which analysis emerging security issues.
- Manages security information and event management to effectively identify and respond to security threats, manage compliance and other.
- 24/24 security monitoring and reporting to reduce GCRs.
- Managed information and events can: 1) Reduce complexity; 2) Manages resources; 3) Improve security and compliance management.
- Improves operational efficiency.

6.5. Professional Services and Governance

As shown in Figure 20, *e-health's professional services and governance support*

- Defines sICS policies and related standards.
- Includes audit, compliance, and reporting.
- Defines a layered model of governance, GCR management, and compliance that are aligned with sICS policies.
- sICS policies are a set of security controls which are assisted with GHS' legal and regulatory norms.

- Accumulates e-hLPs for developing different governance, GCR management, and compliance controls
- Defines security principles which are the fundamental of a robust GTP-SIP.

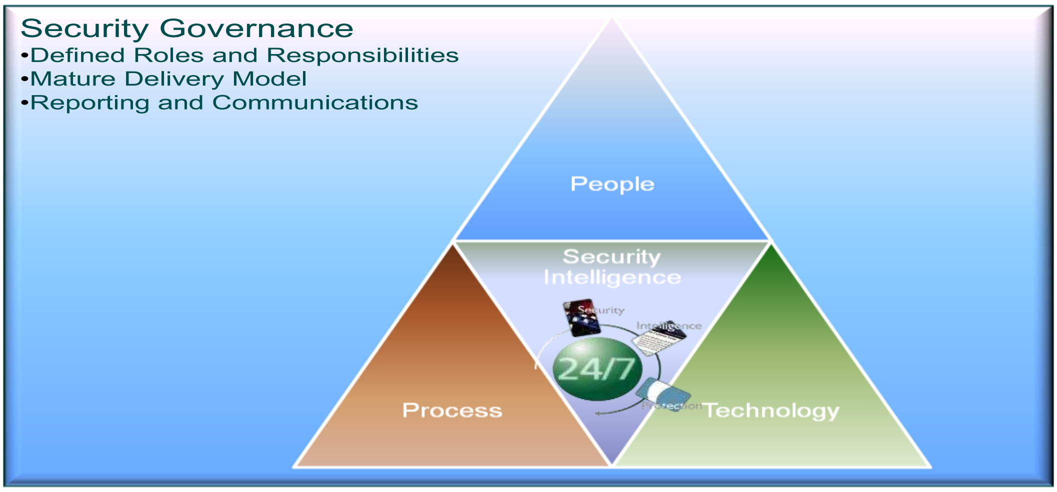

Figure 20: Security Governance diagram

6.6. Project's System Implementation CSFs

Table 5: This CSA has the average of 7.75.

Critical Success Factors	KPIs	Weightings
CSF_System_Implementation_SLC	Complex	From 1 to 10. 08 Selected
CSF_System_Implementation_Security_Frameworks	VeryComplex	From 1 to 10. 07 Selected
CSF_System_Implementation_Common_Frameworks	Feasible	From 1 to 10. 09 Selected
CSF_System_Implementation_MSS_SEIM	VeryComplex	From 1 to 10. 07 Selected
CSF_System_Implementation_Services_Governance	Complex	From 1 to 10. 08 Selected

valuation

Factors evaluated with the PRWC and the results are shown in Table 5. This CSA's result of 7.75, which is very low, is due to siloed architectures. As this CSA_DT presented negative results, the next CSA to be analyzed is the Project's high-level implementation that is this article's ACS.

7. High-Level Implementation

7.1. The Role of PEMM

e-health is an security driven-concept that offers templates to support GHS' Intelligence and also is coupled with the PEMM and sMDTCAS. The PEMM and sMDTCAS support the mapping concept for the common, APD, and Project's requirements. The PEMM and sMDTCAS need a successful sUP... The sUP generates e-services which contain *Intelligence* and application services and for that there is the need to apply the "1:1" mapping concept. *The e-health* use PEMM and sMDTCAS interfaces to interact with various Natural Language Programming (NLP) scripts which's main aim is: 1) To find HDT based solutions; 2) Locate fallouts; 3) Interface different sICS-languages and IDEs; 4) Security components; and 5) Accesses PEMM's dictionaries and registries. GTP-PSISs and related NLP scripts use traditional UDDI or Application Programming Interface (API) to manage accesses to e-services and secured BPMs (sBPM) catalogues. Registries link Intelligence, sBPMs and their interaction with e-services, which are registered by active GTP-PSISs. The PEMM uses the registry and dictionary to interface the sICS and security components. The PEMM can be used to access high-level management tools like in the case of the Strengths, Weaknesses, Opportunities, Threats (SWOT). SWOT to evaluate the effectiveness of *e-health's* integration in a GHS. A PEMM applies SWOT and relates Factors by using *e-health's* for GHS Factors (*e-health*4GHSF) class-structure. Each CSA contains related *e-health's* CSFs and in turn KPIs where each KPI links to an sICS variable (VAR, which is a e-service's attribute(s) and is represented as e-service.VAR) [49, 50], an the various structures are shown in Figure 16.

SWOT2CSA
{…};

CSA2CSF
{…};

CSF2KPI
{…};

Interfacing to secured BBs (sBB) (and secured Composite BBs-sCBB), with KPI elements relate VARs by using the KPI2VAR structure:

KPI2VAR
{…};

Figure 21: *e-health*4GHSF's structures.

7.2. The Role of Implementation

e-health's PEMM and *e-health*4GHSF's, interface the sICS environment's components to persisted GTP-PSISs, by:

- Security concepts and architecture guidelines.
- Behaviour Driven Development (BDD) that is accessed by NLP scripts.
- Modelling languages like UML, OOM, and ArchiMate which include behavioural and structural elements (and a wide-range of relationships) [51].
- Application cartography refinement tools and extracted diagrams, like TOGAF's Application Communication Diagram (ACD) that depicts all used ICS and Security models; with their mappings related to communication between secured applications and accesses sCBBs.
- API's Management (APIM) tools [52].
- Test Driven Development (TDD) is a programming approach and a concept where software developers design the test first concept.
- Acceptance Test-Driven Development (ATDD) that is applied to test the collaboration of business clients, *Project* engineers, *Project* testers and software engineers to finalize a subsystem [53].
- A secured GTP-PSIS Test (sSIPT) that combines TDDs, ATDDs and is based on developing tests where tests represent the results of the requirement's behaviour of a set of NLP scripts.
- Requirements' implementation uses NLP scripts and methodologies like UML.
- *PEMM*'s and sMDTCAS' capabilities to interface GTP-PSIS based *Intelligence*.
- GTP-PSIS accumulated Implementation Development Environments (IDE) and Development and Operations (DevOps) experiences.
- *The e-health* consults Security specialists, executive directors, Project-members, and is designed to identify EA and Security risks [54].

- Integrating standards [2]frameworks, like risk frameworks; like the popular COSO which is presented in Figure 17.

7.3. The Role of DevSecOps

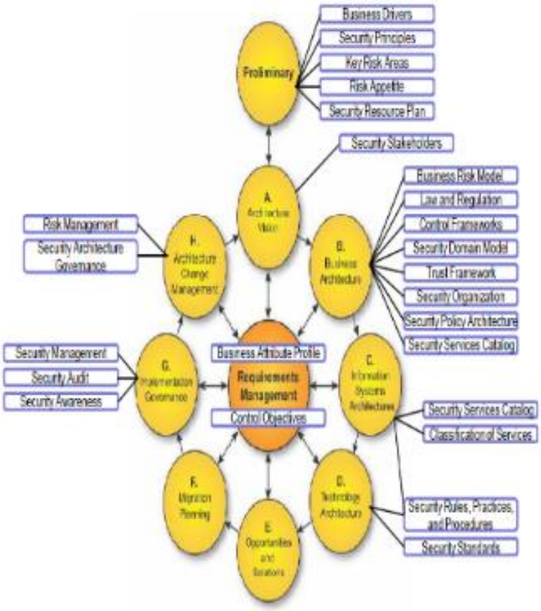

Figure 22: Integration of SABSA with the *e-health* [56].

e-health's DevSecOps manages: 1) *Project's* IDEs, developers, operations and security specialists; 2) Is controlled by a GHS Secured Control and Logging Infrastructure (ESCLI), which feeds GTP-PSISs; and 3) GTP-PSISs editing. Cyberbusiness platforms are not Project and APD agnostic but can offer: 1) Better performance; 2) Reliability; and 3) Cybersecurity/Tracing in GTP-PSISs.

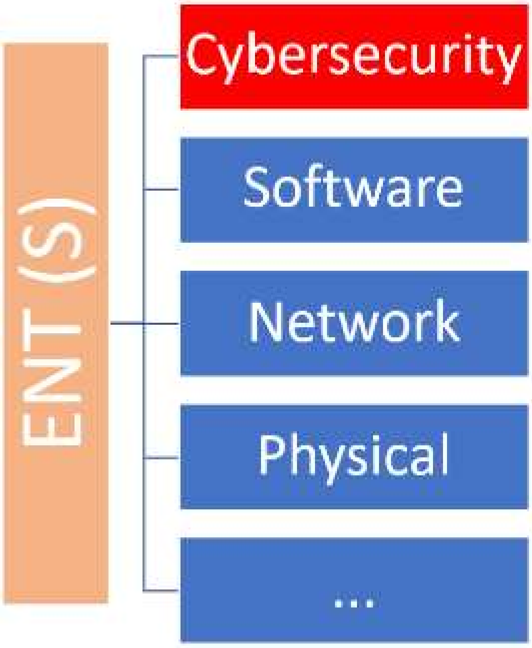

Figure 23: *e-health's* ETP-HSC Approach [1].

sUnits are controlled/monitored in real-time by the ESCLI which is optimal for monitoring and support GTP-PSISs' presentation, sorting, and tuning. An ESCLI can used to analyse, collect and store in GTP-PSISs. A GHS can also build an IHI secured Cloud (sCloud) to avoid locked-in situations and important security breaches. *e-health's* uses EA/TDM to support interfacing market risk frameworks like COSO, which is shown in Figure 19 [25]. *GHS(S/C)* needs the *e-health* to combine many security fields where Cybersecurity is the central issue. Therefore, the *e-health* needs the e-TDM, which interfaces frameworks like ADM/e-TDM, SAFe, COBIT, CISA… Unfortunately, today, we are just tackling isolated fields like Software security, Network Security… As shown in Figure 23.

7.4. The Role of Needed Skills

e-health's needed set of skills are [58,59]: 1) Polymathic Security architecture; 2) Interfacing of EA and Security architectures; 3) Detailed AI and GTP-PSISs modeling and integration; 4) Interfacing AI components; 5) *e-health* related application's sBPMs and e-services; 6) Security and common requirement engineering; 7) Standardized sICS integration; 8) e-TDM/EA, sMDTCAS, and related Business, Data, Application, and Technology Architectures; 9) Generic skills like leadership and audit; 10) Business and organizational engineering; 11) PM technics; 12) ICS IDE technologies; 13) Business use cases design sBPMs integration; 12) Standard frameworks; 13) Building PEMMs*;* and other.

1.1. High-Level Implementation's CSFs

Table 6: This CSA has the average of 8.25.

Critical Success Factors	KPIs	Weightings
CSF_HighLevel_Implementation_PEMM	Feasible	From 1 to 10. 09 Selected
CSF_HighLevel_Implementation_Execution	Complex	From 1 to 10. 08 Selected
CSF_HighLevel_Implementation_DevSecOps	Complex	From 1 to 10. 08 Selected
CSF_HighLevel_Implementation_Needed_Skills	Complex	From 1 to 10. 08 Selected

valuation

Factors were evaluated with the PRWC and the results are shown in Table 6. This CSA's result of 8.25, which is satisfactory, which is due to tools interfacing.

8. The PoC

8.1. PoC's Resources and Environments

The PoC was implemented by using the following resources and environments: 1) The *TRADf* to demonstrate an IHITF; 2) Various EA environments; 3) Java Extended Edition; 4) Microsoft Visual Studio; 5) Microsoft Windows operating system; and 6) Author's previous works and PoCs.

8.2. PoC's User Interface

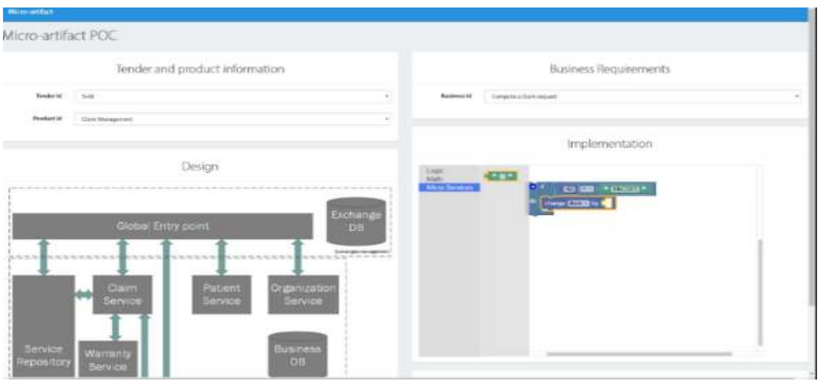

Figure 24: The user interface which manages BBs and other artefacts.

The User Interface, as shown in Figure 24, links Project's Global Unique IDentifiers (GUID) to the defined requirements and unbundled artefacts. Each requirement has a its unique design part-document, which defines an implementation scenario (or a sBPM) that is choreography of e-services.

8.3. PoC's Preparations

The next step is to reuse orevious PoCs modules (like the ETP-HSC's [1]) and then to prepare the IHITF by setting-up the sMDTCAS, e-TDM, and the GTP-PSISs as shown in Figure 25 [61]. This PoC uses various *TRADf* modules, like the sUP and *e-health*, which focus on the extraction and securing of the unbundled e-services.

Figure 25: PoC's preparations sequences [1].

sCBBs are assembled to build e-services' based sBPMs/scenarios and GHS Transactions, which need the optimal level/approach of granularity that respects the "1:1" mapping mechanism. A logical view of a series of e-services based GHS Transactions is presented in Figure 26, and their consumption of e-services. where events are managed by the sICS node-servers, that requires a specific encryption which is managed by the e-TDM. The GHS Transaction uses a set of sCBBs.

sUP-APD Environnement	Provides APD e-services
Controller	Passes an e-service request
Find e-service	Execute
Data Source	Return information and update GTP-PSISs

Figure 26: GHS Transaction's elements.

8.4. PoC's Design

PoC's main constraint is to implement an sICS and adapted security controls, by using the sMDTCAS and e-TDM. The sMDTCAS is used to design e-services, and corresponding diagram. e-services based diagrams are used to design and implement sBPMs (and hence HDT scenarios) in the transformed sUnits. To identify the initial sets of Factors (CSAs' CSFs) and test whether the RQ's of CSFs affect *e-health's* integration. The PoC uses the HDT based mixed qualitative-quantitative method. The PoC in the beginning uses Phase 1 that is mainly based on the HDT CSA_DTs, which uses the PRWC for evaluation purposes. Phase 1 is used to rate/weight the importance of CSAs and CSFs for the usage of *e-health* and that is done using a CSA_DTs [62].

8.5. PoC's Phase 1

PLRP's outcome proved the existence of an important research gap and it's (or Phase 1's) outcome supports RQ's credibility, by the use of the LRP and *TRADf*'s archive or knowledge-base, of an important set of references, previous author's IHITF, articles, works, documents, and links.

Table 7: PoC's phase 1 outcome is (rounded) 8.40.

CSA Category of CSFs/KPIs	Transformation Capability	Average Result	Table
The RDP's Integration	Usable-Mature	From 1 to 10. 9.25	1
Project's Overview	Transformable-Possible-Complex	From 1 to 10. 8.15	2
Security's Overview	Transformable-Possible-Complex	From 1 to 10. 8.80	3
The e-TDM	Complex	From 1 to 10. 8.00	4
System's Implementation	Heterogenous-Complex	From 1 to 10. 7.75	5
High-level Implementation	Complex	From 1 to 10. 8.25	6

Evaluate First Phase

Factors are associated to HDT's NLP (or sBPM) scenarios, where CSFs' are linked to RDP resources. The HDT represents the relationships between this RDP's RQ, GTP-PSIS, and Project requirements, e-services, and selected sets of Factors. PoC's interfaces were implemented using TRADf, which supports *e-health's* calls to e-services. Factors were selected and evaluated (using PPRWC, WGTs, HDT, and *Intelligence*) and the results are presented in Table 7, which shows that the *e-health* is a very important Project's phase and can not be an independent transformation initiative. HDT's main constraint is that CSAs having an average result below 7.5, will be ignored. This mentioned fact leaves this RDP's CSAs and CSA-DTs (marked in green) effective for RDP's and articles conclusion(s); and drops the CSAs marked in red. Phase 1, shows that the GTP-PSIS and *e-health* are very complex but that the PoC can proceed with Phase 2.

8.6. PoC's Phase

Starts with sMDTCAS, e-TDM's, GTP-PSIS's setups and Factors' selection. Phase's 2 setup includes: 1) Sub-phase A or the GTP-PSIS and Architecture Vision phase's goals, establishes a *e-health* approach and goals; 2) Sub-phase B or the Business Architecture phase establishes *e-health's* target e-TDM/EA and related GTP-PSISs' activities; 3) Sub-phase C shows and uses the Application Communication Diagram to describe *e-healths*' activities; 4) Sub-phase D or the Target Technology Architecture shows the needed GTP-PSIS and *e-health's* optimal infrastructure landscape; and 5) Sub-phases E and F, or the Implementation and Migration Planning, presents the transition GTP-PSIS based architecture, which proposes intermediate situation(s) and evaluates GTP-PSIS (and *e-health*'s) status(es). e-services and HDT based *Intelligence* has mappings to GHS's resources and the *e-health* defines relationships between e-services, *PEMM*/sMDTCAS, GTP-PSISs, and Problems (PRB).

8.7. PoC's PRBs Processing in an HDT Node

The *Intelligence* solves *e-health's* PRBs, where Factors link to specific *e-health* PRB type and has a set of actions that are processed in a concrete HDT node. For this goal, the action *CSF_e-health_or_GTP-PSIS_Extraction_Procedure* was called and delivered SOL(s). Solving PRBs involves the selection of actions and possible Solutions (SOL) for multiple *Project* activities.

The HDT is on mixed quantitative/qualitative and has a dual-objective that uses the following steps:

- In Phase 1, *TRADf's* interface implements HDT scripts to process the selected CSAs. And then relates PoC's resources to *CSF_e-health_or_GTP-PSIS_Extraction_Procedure*.
- The *Intelligence* is configured to weight and tuned to support the HDT.
- Link the selected node to HDT to deliver the root node.
- The HDT starts with the *CSF_e-health_or_GTP-PSIS_Extraction_Procedure* and proposes SOL(s) in the form of *e-health* actions/improvements.

HDT scripts support *M-Model*'s instance that are processed in the background to deliver *e-health* or ETP-HSC risk procedures and value(s). The *M-Model* based *Intelligence* uses e-services to deliver *e-health* operations; which are a set of *e-healths* actions that are stored in GTP-PSISs.

8.8. PoC's High-Level Implementation

Using Factors to interface SWOT as by the following steps:

- Linking *e-health* e-services (and resources) to SWOT.
- Links Factors to structures, like CSA2CSF, CSF2KPI, and KPI2VAR…
- Factors tags are linked to various SWOT scenarios.
- From the IHITF's frontend mapping actions are activated by: 1) Selecting HDT nodes that contains *e-health's* Factors, and 2) Selecting the security problem to be solved. SWOT/ STORM uses Intelligence to generate needed actions to solve a request and store the results in GTP-PSISs. Intelligence and its HDT NLP scripts to deliver SWOT's output/solutions.
- Output/solutions are persisted in GTP-PSISs.

9. Conclusions and Recommendations

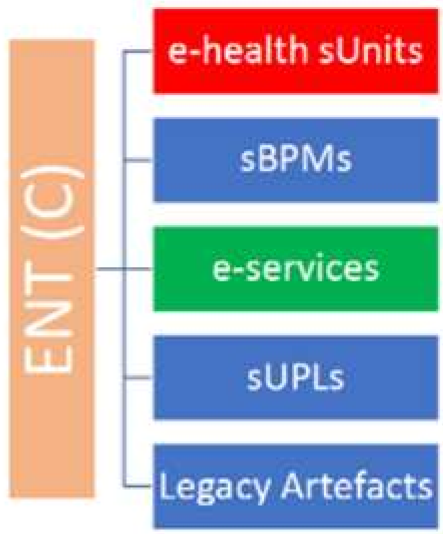

Figure 27: Viewpoint's "C" evolution roadmap.

To transform a GHS is a need for an IHITF and a Polymathic strategy that is based on standards, mapping concepts and e-services interoperability. This article and its PoC offered a set of recommendations knowing that Projects' have XHFRs. e-TDM provides the link between the defined requirements and its Project's implementation and using e- services to serve requests. Today many e-standards exist and a Project must have an agile holistic view on its phases and resources. e-services are sUP's result and used in sBPMs. The GTP-PSIS based PoC proved Project's complexities. *The e-health* supports sICS, e-services and sBPMs to support the transformation of GHS and its sUnits. The GTP-PSIS is optimal for a GHS and its security management. The PLRP presented the research gap, that is due to the fact that are no similar IHITF, *MetaModel/*sMDTCAS approaches and that there is an extreme lack of a Polymathic-holistic approaches. There are siloed and limited manual security tools and methods, but the *e-health* presents the possibility to implement an IHITF and *e-health*. The RDP is a part of a series of publications on Projects, Security strategies, e-health, PEMM, TDM/EA, Polymathic models… The Project uses e-services, HDT and Factors to support *e-health* activities, where the *e-health* focuses on managing secured GHS operations. GTP-PSIS and *e-health* synchronizes a structured relationship between: Health activities, Global Security, GCRs' management, sMDTCAS, e-TDM/EA, and HDT based *Intelligence*. The PoC's Table 7 result of (rounded) 8.40 that used Factors and CSFs' binding to a RDP resources, the *Intelligence*, RQ, *e-health,* and e-services, shows that the *e-health* is very complex due to siloed nature of GHSs and the lack of Polymathic skills and this article's set of recommendations are:

- This article presents the role of Projects and GTP-PSIS; and the focus is on the GHS adapted for the KSA and SHID.
- Projects have XHFRs at about 95 percent; andare due to siloed approaches.
- All author's works are based on TRADf, AHMM, (e-)TDM, and an RDP concept; which are today mature and can be applied in various APDs and any type of transformation initiative.
- *e-health* must avoid locked-in security situations.
- This RDP uses a multi-dimensional *e-health*, because it has: 1) Interoperable e-services; 2) An adapted mixed-research approach; 2) Presents the IHITF; and 3) A methodological approach based on EA/e-TDM and *Intelligence*.
- The PRLR asserted the existence of a research gap.
- Use a MM, like the *M-Model*, to support GTP-PSISs and HDT.
- Cross-functional/Polymathic skills are needed for Projects and *e-health*.
- *The e-health* unbundles the legacy BPMs to support sUnits*,* which can face problems in the alignment of various e-services.
- DevSecOps' integration in *e-health,* enables the automation of all Project's security developments.
- *e-health* coordinates GHS' activities.
- The sMDTCAS, PEMM, and e-TDM support *e-health*.
- *e-health* constraints are controlled and monitored by the sICS.
- sUnit's transformation needs an IHITF and sMDTCAS that transforms and secures a GHS.
- Avoid consulting firms and commercial products to build an IHI *e-health* system.
- GTP-PSIS and *e-health* are very complex.
- Viewpoint's "C" presents a structured evolution's roadmap for the *e-health*, as shown in Figure 27.
- The Project offers a flexible and scalable sICS.
- Use AR based HDT to solve GTP-PSIS problems.
- Use the PRWC based CSA_DTs to filter and weight CSAs.
- *The e-health* interfaces high-level tools and environments like SWOT.

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Comparing LPPLS and GSADF Methods in Detecting Bubbles in Metal Prices

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Abstract

This study investigates the presence of speculative bubbles in the price series of three precious and five industrial metals. Utilizing monthly data spanning from January 1960 to September 2024, we employ two distinct methodologies for bubble detection. The first, the Log-Periodic Power Law Singularity (LPPLS) model, provides a flexible framework for identifying bubbles and forecasting regime shifts. The second, the Generalized Supremum Augmented Dickey–Fuller (GSADF) test, is a recursive sequential right-tailed unit root test. Our findings indicate the presence of speculative bubbles within several metal price series.

Keywords: Bubbles, metal prices.

1. Introduction

Building on the established theoretical framework of metal price dynamics and bubble formation, this study offers a sophisticated analysis of the potential benefits of analyzing metal price bubbles for investors. These benefits include the ability to avoid the illusion of wealth and irrational exuberance. While the Supremum Augmented Dickey-Fuller (SADF) and Generalized Supremum Augmented Dickey-Fuller (GSADF) tests provide valuable retrospective analyses of bubble episodes, their applicability is limited in terms of forecasting future bubble collapse points and elucidating the complex dynamics of bubble formation (Yao & Li, 2021). Consequently, recent scholarship has increasingly adopted the log-periodic power law singularity (LPPLS) model for both the identification and prospective analysis of bubble occurrences and subsequent market corrections. The LPPLS model's ability to anticipate both upward and downward bubble trajectories, along with their impending collapses, presents a significant advantage in constraining the magnitude of bubbles and thereby potentially mitigating associated negative consequences. According to LPPLS theory, asset bubbles originate from imitative behavior among market participants, fostering a positive feedback loop characteristic of herd mentality, with eventual crashes stemming from fundamental market instabilities. This process is marked by logarithmically periodic oscillations in price movements, which escalate in frequency until a critical threshold is reached, rendering a market correction highly probable (Johansen & Sornette, 2001). The LPPLS model has demonstrated its effectiveness in identifying and forecasting bubbles across a range of financial assets, including the S&P 500 Index (Zhang et al., 2016), Bitcoin (Zhang et al., 2024), and the Dow Jones Index (Grobys, 2023). However, to the best of our knowledge, the application of the LPPLS methodology to the specific context of detecting and projecting price bubbles in precious and industrial metals has not yet been thoroughly explored.

In this study, speculative bubble periods observed in the prices of eight metals (Aluminum, Gold, Copper, Lead, Nickel, Platinum, Silver, and Tin) were empirically analyzed using the

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GSADF and LPPLS methods. The analysis results reveal that both methods provide distinct yet complementary information.

2. Literature Review

Several studies have utilized the GSADF test to identify bubble periods in metal prices. Su et al. (2020) identified four explosive copper price bubbles between 1980 and 2019, attributing their emergence and collapse to speculation, US dollar depreciation, supply-demand imbalances, and financial crises. Ozgur et al. (2021) identified bubble periods in a study on various metal prices between 1980 and 2019 and concluded that financial factors best predict precious metal bubbles, while monetary policy and production indices best predict industrial metal bubbles. Peng et al. (2023) identified seven copper price bubbles between 1980 and 2023 and found positive links with aluminum price, production, and GDP, and negative links with China's imports and precious metal prices. Ni and Wang (2024) identified six aluminum price bubbles between 1980 and 2023, finding they were positively influenced by factors such as copper prices, GDP, and China's development, while negatively influenced by global aluminum production, oil prices, and the base metal index.

A survey of the literature reveals a paucity of studies employing the LPPLS method to detect metal price bubbles. Zhou et al. (2018) analyzed Chinese metal futures (Zinc, Aluminum) around the 2008 financial crisis using the LPPLS method and found that futures primarily exhibited risk resistance during anti-bubble phases and weaker resistance during bubble periods. Demirer et al. (2023) did not directly examine metal prices but, using the LPPLS method, demonstrated that the gold/platinum price ratio predicts synchronized positive and negative bubbles in G7 equity markets. They also proved that the gold/platinum ratio is a stronger long-term predictor of negative bubbles (crashes) and a stronger short-term predictor of positive bubbles (bursts), thus helping to explain the synchronicity of bubbles in these markets.

This study contributes to the existing literature by identifying and comparing bubble periods in eight different metal prices using both the GSADF and LPPLS methods.

3. Data

This study utilizes monthly data from the World Bank to identify speculative bubbles in three precious metals and five industrial metals throughout the period from January 1960 to September 2024. The group of precious metals includes gold, platinum, and silver, whereas the industrial metals category consists of aluminum, copper, lead, nickel, and tin. Trends in metal price movements during the 1960–2024 period are illustrated in Figure 1.

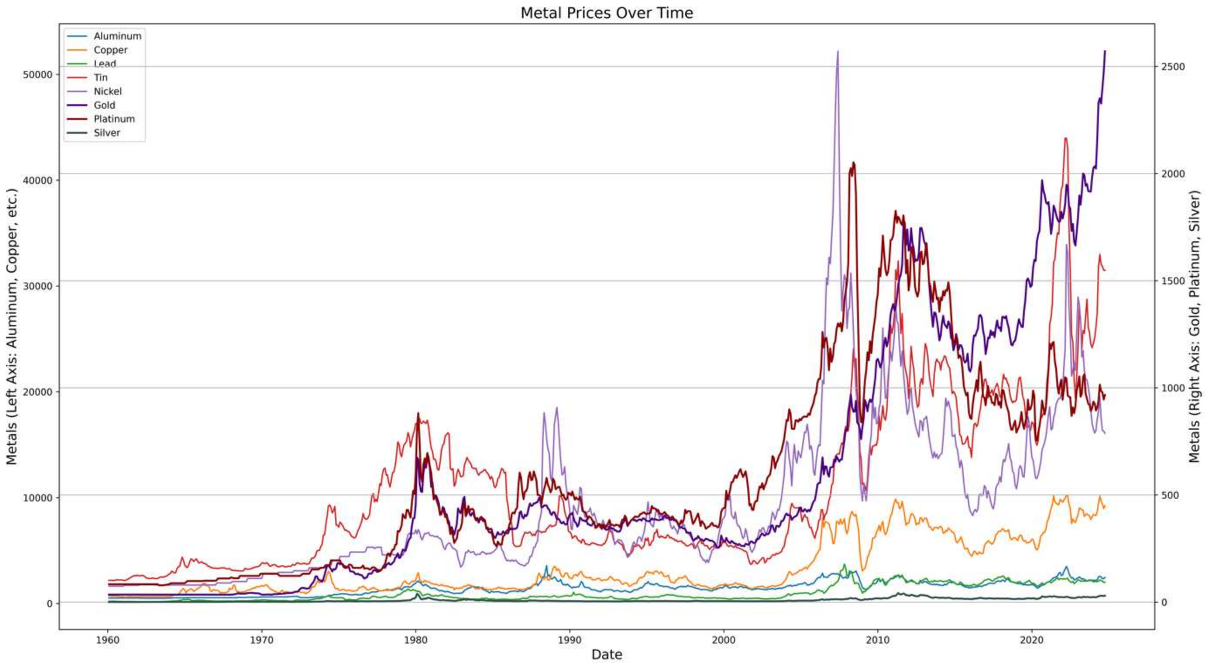

Fig. 1. Historical trends in metal prices from 1960 to 2024.

Note: The prices of industrial metals have been illustrated along the left axis of the graph, whereas those of the precious metals are represented along the right axis.

The price trends indicate considerable volatility across all metals, with particularly pronounced fluctuations observed in the precious metal group. As demonstrated in the accompanying figure, metal prices have exhibited significant volatility, particularly during periods of heightened global economic stress, such as the 2008 financial crisis and the post-2020 pandemic recovery phase. It is evident that nickel and platinum have undergone the most significant price escalations, while gold has exhibited notable upward trends in the post-2008 and approximately 2020 periods.

These pronounced surges underscore the sensitivity of metal markets to macro-financial shocks and systemic uncertainty. As demonstrated by the graphical representation, the price dynamics of the various categories of metal exhibit a heterogeneous yet interconnected nature. The figure under consideration indicates the importance of identifying and analysing speculative bubbles within the given markets. Such episodes have the potential to have far-reaching implications for investment strategies, risk management and policy responses.

According to Table 1, platinum shows the highest mean price among the analyzed precious metals at $583.64, while tin has the highest mean price among industrial metals at $10,784.30.

Table 1. Summary statistics of selected metal prices.

Prices ($)	Mean	Median	Min	Max	Std
Aluminum	1.435,52	1.454,28	496,04	3.577,86	654,40
Copper	3.274,90	1.949,88	606,71	10.230,89	2.644,67
Lead	951,59	600,40	140,70	3.719,72	764,23
Tin	10.784,30	7.188,86	2.162,70	43.983,35	7.987,50
Nickel	9.243,04	6.614,00	1.631,00	52.179,05	7.610,56
Gold	572,97	371,89	34,94	2.570,55	572,96
Platinum	583,64	425,34	78,50	2.052,45	458,25
Silver	9,32	5,46	0,91	42,70	8,38

The maximum values recorded in the dataset also underscore periods of extreme market conditions. For instance, nickel and tin reached peak values of $52,179.05 and $43,983.35, respectively, while gold and platinum peaked at $2,570.55 and $2,052.45. The presence of such extreme values, when considered in conjunction with the broad ranges and standard deviations observed, suggests the likelihood of speculative price dynamics or periods of heightened price inflation in specific temporal contexts. The summary statistics indicate a considerable degree of heterogeneity in the behaviour of prices across metals. This finding suggests a need for further investigation into the underlying drivers of price fluctuations and the potential for the formation of price bubbles.

4. Methodology

This research adopts a dual-method approach in its empirical design. Specifically, it applies the GSADF unit root procedure along with the LPPLS framework to detect episodes of speculative bubbles in metal price data. The inclusion of the LPPLS model is motivated by its ability to capture the nonlinear, self-reinforcing dynamics that typically characterize asset price bubbles, particularly during phases of unsustainable exponential growth followed by abrupt corrections. This framework enables a more refined understanding of speculative behavior beyond what traditional econometric tests can reveal.

4.1. The Log-periodic Power-law Singularity (LPPLS) Model

LPPLS (Log-Periodic Power Law Singularity) is a model used in financial analysis to detect and predict bubbles and crashes in various markets. The LPPLS model is designed to capture the nonlinear dynamics of financial markets, particularly during periods of rapid growth or decline (Wheatley et al., 2019; Zhang et al., 2016). It combines power law dynamics with log-periodic oscillations to describe asset price behavior during bubble formation. The model is based on the theory of rational expectation bubbles and incorporates behavioral mechanisms such as investor imitation and herding (Sornette et al., 2015). It aims to identify critical points or "singularities" in price trajectories, which may signal an impending market transition or crash (Grobys, 2023). One of the key strengths of the LPPLS model is its ability to provide early warning signals for potential market instabilities. It has been applied to various financial assets, including stock indices, cryptocurrencies, and commodities (Demirer et al., 2018). The model's predictive capabilities have been demonstrated in several historical bubbles, such as the 1987 Black Monday crash, the Dot-com bubble, and the 2008 Global Financial Crisis.

In summary, LPPLS is a sophisticated mathematical tool used in financial analysis to detect, quantify, and predict bubble-like behavior in markets. Its applications range from risk management to policymaking, offering insights into the complex dynamics of financial systems and potential future market developments.

4.2. GSADF Test

To address the shortcomings of the SADF procedure in detecting multiple speculative bubble episodes, Phillips et al. (2015) proposed the Generalized Supremum Augmented Dickey-Fuller (GSADF) test. This approach integrates a recursive backward regression technique to more accurately determine the onset and termination of bubble phases. Unlike the SADF test, which maintains a fixed initial observation for recursion, the GSADF method applies a dynamic window structure that permits variation in both the start and end points of the regression subsamples, thereby enhancing overall sample coverage. Functionally, the GSADF test represents a right-tailed, double-recursive unit root testing strategy. Building upon the framework introduced by Phillips et al. (2011), this method systematically adjusts the starting point of the real-time analysis, allowing for more robust detection of multiple bubble regimes.

In the GSADF testing framework, the initial point of the sample, denoted by r_1, ranges from 0 to 1 - r_0, and the detection sample is progressively expanded. For a given starting point r_1, the termination point r_2 spans from $r_1 + r_0$ to 1. The algorithm advances by recursively shifting both the starting and ending boundaries of the testing window forward. The SADF statistic, in this context, is defined as the supremum of a sequence of right-tailed ADF (Augmented Dickey-Fuller) test statistics. The GSADF statistic is subsequently computed as the supremum over this collection of SADF values. The formal expression for the GSADF statistic is provided below.

$$GSADF(r_0) = \sup_{r_2 \in [r_0, 1],\ r_1 \in [0, r_2 - r_0]} \left\{ ADF_{r_1}^{r_2} \right\} \qquad (1)$$

5. Empirical Results

The Generalized Supremum Augmented Dickey-Fuller (GSADF) test was applied to metal price data, and the resulting test statistics and price bubble analysis are presented in Table 2.

Table 2. Empirical Findings from the GSADF Test.

Metal Prices	Test Statistics
Aluminum	6,42*
Copper	8,41*
Gold	19,2*
Lead	9,93*
Nickel	9,2*
Platinum	10,7*
Silver	12,9*
Tin	12,1*

Note: * indicate the significance at the 1% levels.

For each of the eight metals examined (aluminum, copper, lead, tin, nickel, gold, platinum, and silver), the null hypothesis of no price bubble was rejected at the 99% confidence level. Consequently, the price series of these metals during the period spanning 1960 to 2024 exhibit evidence of bubble behavior, characterized by periods of unsustainable and potentially irrational price increases. Employing the GSADF test in conjunction with the LPPLS methodology, this study also identifies and presents the estimated start and end dates of price bubbles for the eight metals. Figure 2 provides a chronology of the identified periods of exuberance for each metal price based on the GSADF results.

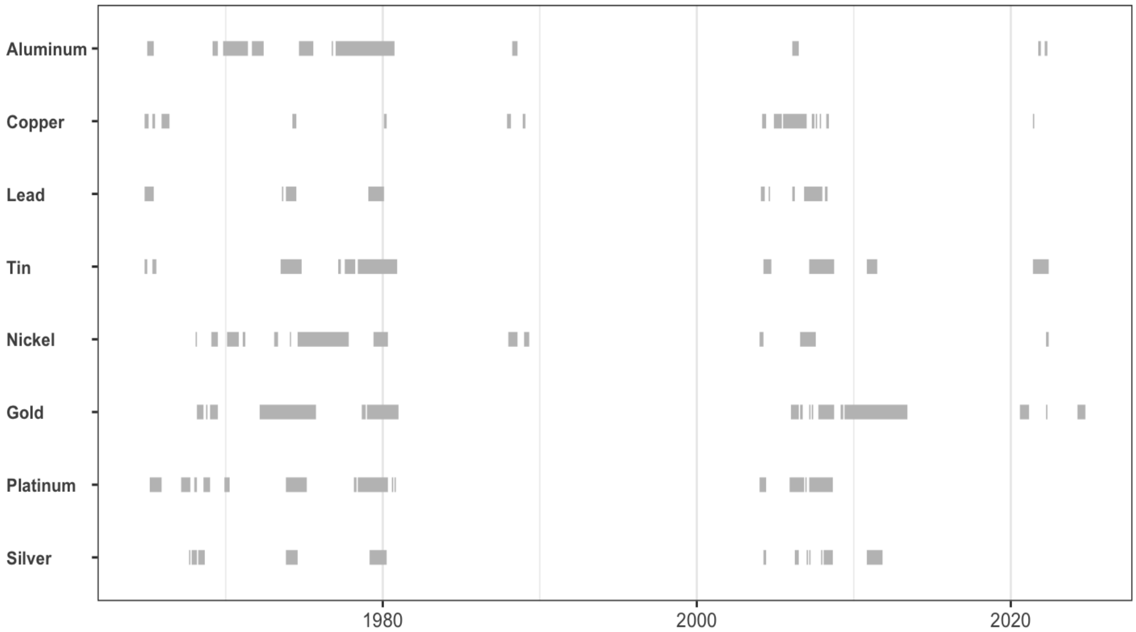

Fig. 2. Bubble periods from 1960 to 2024

The empirical analysis conducted in this study yields several noteworthy findings. Firstly, Gold (169 months) records the highest number of metal price bubbles and features the longest bubble durations. Gold is followed by Tin (106 months), Aluminum (107 months), and Platinum (105 months). These metals exhibit both frequent and relatively long-lasting bubbles.

In contrast, Lead (9 bubble periods, 50 months total duration) shows the fewest bubble periods. Copper (15 bubble periods, 55 months total duration) and Silver (12 bubble periods, 59 months total duration) also have relatively fewer and/or shorter total bubble durations.

Figure 3 visually depicts the positive and negative price bubbles identified for each metal price series using the Log-Periodic Power Law Singularity (LPPLS) methodology.

The LPPLS method has been applied to detect speculative bubble periods in various metal prices, and the results are visually represented in the dataset. Each metal—including Aluminum, Gold, Copper, Lead, Nickel, Platinum, Silver, and Tin—exhibits multiple distinct bubble phases identified by the respective positive and negative bubble date ranges. For example, while aluminum prices exhibited significant bubble activity between 1970 and 1980, there were also periods of significant negative bubbles, such as in December 2013. Gold has demonstrated notable positive bubbles since the early 2000s, reflecting substantial global economic and geopolitical shifts. Conversely, copper and lead exhibited pronounced bubble clusters in the mid-2000s, consistent with the global commodity boom prior to the 2008 financial crisis. Nickel and platinum, meanwhile, have shown multiple bubbles in the 1970s as well as bubble periods prior to the global crisis. Silver also reflects significant speculative phases, particularly from the early 1980s and again between 2005 and 2011. Tin, while showing fewer identified periods, still reflects marked bubbles, such as the one beginning in August 1978. Overall, the temporal distribution of these bubbles corresponds with key historical economic events, including inflationary shocks, financial crises, and surging industrial demand, underscoring the LPPLS model's utility in capturing market exuberance and crash risks in metal commodities.

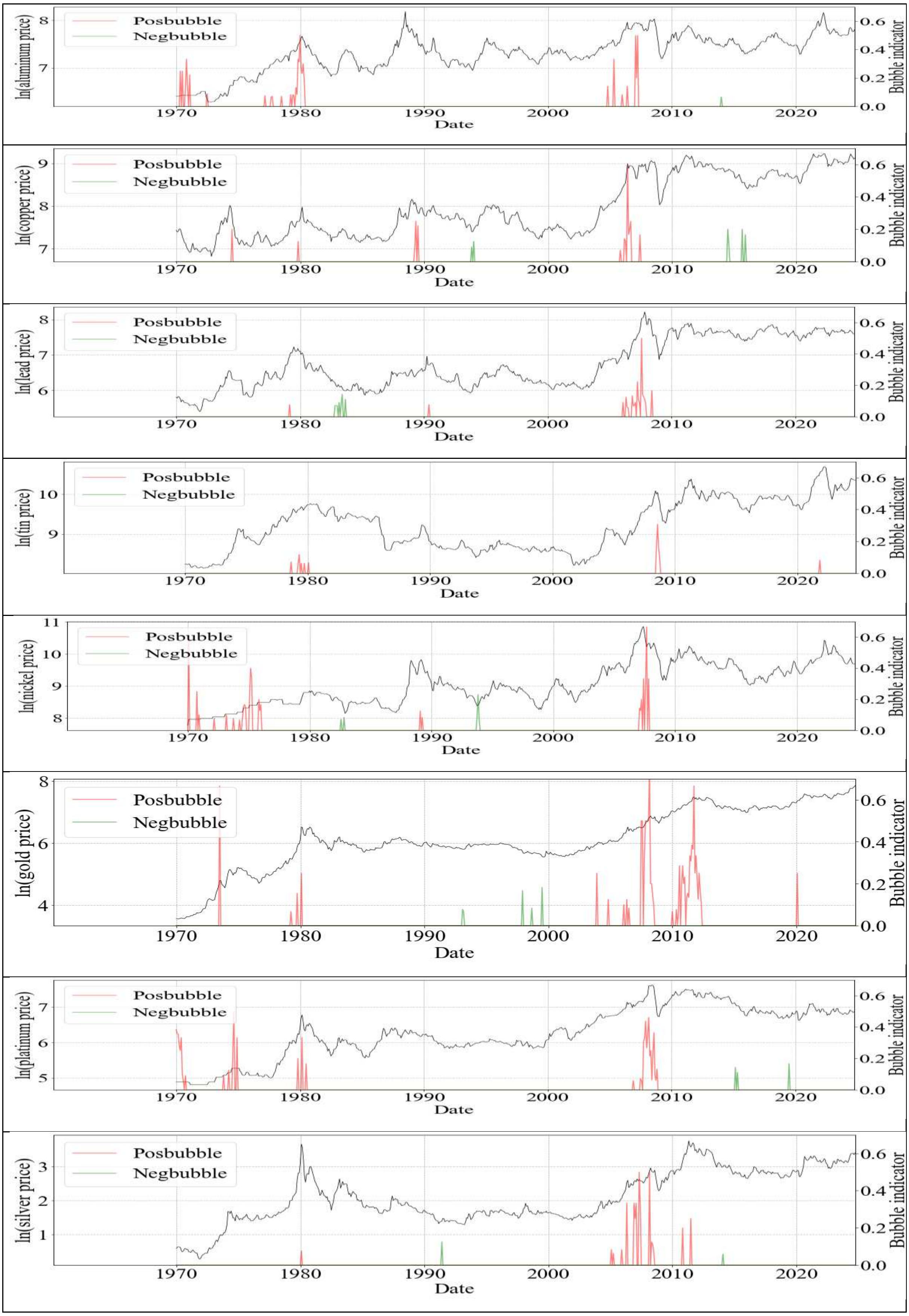

Fig. 3. Positive bubbles (in red) and negative bubbles (in green) of the metal prices.

Comparing the results of the GSADF and LPPLS methods highlights the following points:

1. The LPPLS method generally detects a significantly higher number of speculative events (both positive and negative bubbles) compared to the GSADF method. This suggests that LPPLS might be more sensitive to potentially shorter-term or less pronounced price movements.
2. The ranking of metals based on bubble frequency differs between the two methods. For instance, while Copper is the second most frequent bubble host according to GSADF, it is among the metals with the fewest events detected by LPPLS. However, with both methods, Gold stands out as the metal with the most detected bubbles or highest event frequency.
3. While the GSADF method provides the start, peak, and end dates of detected bubbles, allowing for duration calculation, the LPPLS method offers a different perspective on market dynamics by classifying these events as positive (speculative buying) and negative (speculative selling/crash). LPPLS distinguishes itself from GSADF, particularly by separately identifying crash periods (negative bubbles).

In conclusion, both methods confirm the presence of speculative bubbles in the examined metal markets. GSADF provides information about the lifespan of bubbles, whereas LPPLS offers insights into the characteristics (rally or crash) of these bubbles. Gold attracts attention in both analyses as the metal with the most frequent and/or longest-lasting bubbles, while other metals exhibit varying bubble frequencies and characteristics depending on the method used. The findings from these two methods are complementary in understanding speculative behavior in metal markets.

6. Conclusion

This research distinguishes itself from the extant literature on metal price bubble identification by employing a comprehensive and comparative methodological approach. Specifically, this study undertakes a detailed examination of price bubbles across eight key metals spanning the period from 1960 to 2024. To achieve this objective, the GSADF test is integrated with the LPPLS model for a robust analysis.

When comparing the bubble phases recognized by applying the GSADF and LPPLS methodologies, it is observed that for certain metals and time frames, the findings of the two methods overlap or converge closely. However, the degree of this overlap varies from metal to metal, and both methods have unique detections. It is often observed that the dates provided by the LPPLS method are close to the peak or end points of the bubble periods determined by GSADF.

Overall, it can be stated that the two methods point to similar speculative periods for many metals, particularly in the late 1970s (around 1978-1980) and during the period spanning the mid-2000s to the post-financial crisis era (approximately 2006-2008 and 2010-2011). Overlaps are more pronounced for metals like Gold, Nickel, Silver, Lead, and Tin during these periods. However, due to the different sensitivities and definitions of the methods, not every bubble detected by GSADF is confirmed by LPPLS (and vice versa). It is also observed that LPPLS sometimes generates signals (especially for negative bubbles) during periods where GSADF remains silent. This indicates that the two methods may capture different aspects of market dynamics or events of varying intensity.

The empirical investigation conducted in this reseacrh produces several significant insights. The formation of price bubbles observed across the eight metals under review appears to be influenced by the structural characteristics and regulatory frameworks governing metal markets, overarching macroeconomic trends, inherent price volatility, and persistent market uncertainty. In conclusion, the empirical evidence suggests a discernible difference in the temporal characteristics of identified bubbles: those detected using the GSADF methodology tend to exhibit longer durations, while those identified via the LPPLS model appear more dispersed and are generally of shorter duration. This dual-method perspective can be particularly useful for investors, policymakers, and researchers attempting to anticipate and understand future episodes of market exuberance in commodity markets.

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Environmental Policy and Sustainable Growth in BRICS Countries: A Porter Hypothesis Perspective

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Abstract

The Porter Hypothesis, which suggests that stringent environmental regulations can foster productivity and ability to compete, has gained traction amidst increasing global focus on sustainable competitive advantage. This study aims to empirically examine whether the PH holds true for BRICS countries, using data from 1990-2019. We measure environmental policy stringency via the widely-used EPS Index, while productivity with competitiveness are represented by Total Factor Productivity Index and Trade (% of GDP), respectively. By examining the relationship between these variables within BRICS, a group characterized by abundant natural resources and rapid growth, our research seeks to explore whether stringent environmental policies can be a driver of both competitive edge and sustainable development in emerging economies.

Keywords: Porter hypothesis, BRICS, environment, trade, productivity.

1. Introduction

The contemporary global agenda is marked by the critical imperative to reconcile economic development objectives with environmental sustainability imperatives (Mahalik et al., 2024; Akram & Srivastav, 2024). Historically, environmental regulations were often viewed through the lens of a trade-off, perceived primarily as constraints burdening firms with additional compliance costs, conceivably diminishing productivity with eroding their competitiveness in international markets (Gray & Shadbegian, 2003, Iraldo et al., 2011; Greenstone et al., 2012). This perspective underpins theories like the Pollution Haven Hypothesis, from which it can be predicted that industries could move to areas possessing less stringent environmental regulations to minimize higher expense (Dechezleprêtre & Sato, 2017; Wahab, 2024).

However, this traditional view has faced opposition from the influential PH (Porter & van der Linde, 1995b). It posits that well-designed and properly enforced regulatory framework for the environment, instead of merely imposing costs, can provide an impetus for innovation. By stimulating firms for developing cleaner technologies, improve resource efficiency, and rethink production processes, stringent regulations can lead to "innovation offsets" which might, to some extent or even completely, compensate for expenditures on regulatory adherence (Porter & van der Linde, 1995a; Iraldo et al., 2011). In its stronger form, the hypothesis suggests that these induced innovations can ultimately enhance productivity and strengthen international competitiveness, creating a potential "win-win" scenario for environment as well as the economy (Rubashkina et al., 2015; Fabrizi et al., 2024).

Empirical investigation into the Porter Hypothesis has yielded a complex and often mixed body of evidence. While considerable research provides support for the 'weak' version, demonstrating a positive link between regulatory stringency and specific measures of innovation such as R&D expenditure or patenting activity (Jaffe & Palmer, 1997; Brunnermeier & Cohen, 2003; Iraldo

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et al., 2011; Yang et al., 2012; Rubashkina et al., 2015; Fabrizi et al., 2024), convincing proof of more extensive formulation remains elusive (Jaffe et al., 1995; Dechezleprêtre & Sato, 2017; Benatti et al., 2024). Studies examining productivity impacts, such as Total Factor Productivity (TFP), have found varied effects, sometimes negative (Greenstone et al., 2012), sometimes neutral or context-dependent (Rubashkina et al., 2015; Benatti et al., 2024), and yielding plus effects in some cases, particularly when indirect effects via innovation are considered (Hamamoto, 2006; Yang et al., 2012). Methodological challenges, including measuring regulatory stringency across diverse policy instruments (Botta & Koźluk, 2014; Kruse et al., 2022; Fabrizi et al., 2024) and addressing potential endogeneity, further complicate the analysis (Dechezleprêtre & Sato, 2017; Benatti et al., 2024).

Crucially, much of the existing empirical literature has focused on developed nations, primarily within the OECD (Greenstone et al., 2012; Frohm et al., 2023; Akram & Srivastav, 2024; Benatti et al., 2024; Fabrizi et al., 2024). There is a comparative scarcity of rigorous testing of the Porter Hypothesis within the unique context of major emerging economies, such as the BRICS nations (Wahab, 2024). These countries (Brazil, Russia, India, China, South Africa) represent a critical area for investigation, given their significant and growing contribution to global economic activity and environmental pressures (Güneş et al., 2022; Akram & Srivastav, 2024). They face the distinct challenge of pursuing rapid economic development and industrialization, often from a starting point of historically less stringent environmental policies (Wahab, 2024), while simultaneously needing to address substantial environmental degradation and increasing international pressure to adopt sustainable practices (Stavropoulos et al., 2018; Mahalik et al., 2024). Understanding whether stricter environmental standards hinder or potentially foster competitiveness in these dynamic economies is therefore of paramount importance.

This study assesses to contribute to understanding via validating through empirical observation the validity of the PH for the BRICS countries, utilizing panel data spanning the period 1990–2019. We specifically investigate the relationship between the rigor of environmental effect, as measured by the OECD's EPS Index, and two key indicators of economic performance: productivity, represented by the Total Factor Productivity (TFP) Index, and international competitiveness, proxied by trade openness (Trade as % of GDP). By examining this nexus within the BRICS bloc – a group characterized by abundant natural resources, rapid growth, significant environmental challenges, and evolving regulatory landscapes (Akram & Srivastav, 2024) – this research seeks to provide empirical insights into whether stringent environmental policies can act as a driver for enhancing both economic competitiveness and sustainable development in these pivotal emerging economies.

2. Literature Review

The effect of environmental rules on corporate financial performance and nations has been a central and often contentious topic in environmental economics and policy debates. The traditional perspective, rooted in neoclassical economics, largely views environmental regulation as an external constraint that imposes additional costs on businesses, diverting resources from productive investments and potentially hindering productivity growth and eroding international competitiveness (Gray & Shadbegian, 2003; Iraldo et al., 2011; Isaksson, 2007). This viewpoint underpins theoretical frameworks such as the PHH, which posits industries, particularly contaminating ones, could establish themselves elsewhere to jurisdictions with less stringent environmental standards to minimize compliance costs (Dechezleprêtre & Sato, 2017; Wahab, 2024).

However, this conventional wisdom was significantly challenged by the groundbreaking work of Porter (1991) and Porter and van der Linde (1995b), who proposed what is now widely referred to as PH. The PH suggests that appropriately structured environmental regulations, far from being exclusively burdensome, possess the potential to stimulate innovative movement. By creating the impetus for firms to rethink products and durations, regulations can spur the advancement and uptake of sustainable technologies and more resource-efficient practices. These induced innovations can lead to "innovation offsets," potentially reducing or even sufficiently counterbalancing the primary outlays required for regulatory compliance (Porter & van der Linde, 1995a; Iraldo et al., 2011; Ramanathan et al., 2017). The literature typically distinguishes between varying manifestations of the PH (Jaffe & Palmer, 1997; Iraldo et al., 2011; Dechezleprêtre & Sato, 2017): the 'limited' type posits that adjustment stimulates specific types of (ecological) innovation; the 'strong' type argues that these innovations can enhance overall productivity and competitiveness, leading to a net positive economic outcome (a "win-win"); and the 'narrow' version proposes that market-oriented or flexible regulatory tools supply more robust innovation motivations than traditional command-and-control approaches (Sun et al., 2024; Fabrizi et al., 2024).

Data-driven analysis of the Porter Hypothesis has yielded a substantial, yet complex and often mixed, body of evidence (Jaffe et al., 1995; Isaksson, 2007; Dechezleprêtre & Sato, 2017). There is considerable validation for the less stringent interpretation of the PH. Numerous studies, using various proxies for innovation such as R&D expenditures or patent counts, have observed a positive correlation among ecological regulatory stringency and innovative activity, particularly in specific green technologies or environmental patents (Jaffe & Palmer, 1997; Brunnermeier & Cohen, 2003; Lanoie et al., 2008; Rubashkina et al., 2015; Yu et al., 2024; Han et al., 2024). For instance, Rubashkina et al. (2015) found a beneficial contribution on patent applications, supporting the weak PH in European manufacturing sector. Similarly, studies focusing on specific policies like carbon emission trading schemes (CETS) in China have shown increased innovation activity among regulated firms (Yu et al., 2024). Han et al. (2024) further advise that even environmental judicature (specialized courts) can drive green innovation, highlighting the role of enforcement mechanisms.

Evidence concerning the solid pattern of the PH, that links regulation to enhanced overall productivity (often measured by Total Factor Productivity - TFP) or competitiveness, is far more contested and inconclusive (Jaffe et al., 1995; Dechezleprêtre & Sato, 2017). Several studies report negative or statistically insignificant effects of environmental regulations on productivity (Greenstone et al., 2012; Rubashkina et al., 2015; Benatti et al., 2024). Rubashkina et al. (2015), for example, found no evidence that regulation affected overall productivity in their European sample, thus rejecting the strong PH. Benatti et al. (2024), via the OECD's EPS index and firm-level data for the euro area, similarly found that the intensification of environmental policy exerted a detrimental influence on the rate of productivity growth among high-emission firms, contradicting the strong PH. Fabrizi et al. (2024), in a study specifically focusing on BRICS firms, also found a negative relationship between EPS and productivity, further challenging the strong PH in this context.

However, other research offers a more nuanced picture, suggesting that positive productivity effects might exist under certain conditions or manifest with a time lag. Lanoie et al. (2008) observed that while the contemporaneous effect of adjustment on TFP in Quebec was negative, a positive effect emerged with lagged regulatory variables, supporting a dynamic interpretation of the PH. Some studies focusing on green TFP (GTFP), which accounts for environmental outputs, find positive impacts. For instance, Wang et al. (2022) pointed a U-shaped link among regulation and GTFP in China, with FDI playing a crucial mediating role. Peng (2024) also found that agricultural environmental regulation in China promoted agricultural GTFP, primarily through technological progress, with innovation investment acting as a key channel. Sun et al. (2024) corroborates the positive link between regulation (both formal and informal) and GTFP in China, identifying a specific pathway through R&D and innovation quality leading to technical progress. This suggests that the choice of productivity measure (TFP vs. GTFP) can influence the results. Isaksson (2007) provides a broader overview of various TFP determinants beyond regulation, including knowledge creation, human capital, and institutions, emphasizing the complexity of productivity analysis. Miller & Upadhyay (2002) focus on the convergence of TFP, linking it to broader economic competitiveness.

The heterogeneity in findings highlights the importance of context and mechanism. The narrow PH finds support in studies indicating that market-based instruments might be less detrimental or potentially more beneficial than command-and-control regulations (Sun et al., 2024; Fabrizi et al., 2024; Benatti et al., 2024). The design of regulation (flexible vs. inflexible), firm characteristics (size, ownership, innovative capabilities, pollution intensity), industry structure, and the specific environmental dimension targeted all appear to moderate the relationship (Lanoie et al., 2008; Ramanathan et al., 2017; Yu et al., 2024; Benatti et al., 2024; Han et al., 2024; Sun et al., 2024). Ramanathan et al. (2017), through case studies, emphasize the role of firm resources and proactive strategies in leveraging regulations for private benefits. Furthermore, the impact can vary significantly depending on the geographical context and level of development (Ogura, 2020; Wahab, 2024). Wahab (2024), for instance, found the PH to be operative for extra-BRICS commercial exchanges, yet not for trade conducted within the BRICS bloc, indicating complex interactions between exporter and importer regulations. Ogura (2020) also found results contradicting the PH in the context of renewable energy component trade involving OECD and BRICS nations. The role of mediating factors like financial development (Akram & Srivastav, 2024) or FDI (Wang et al., 2022) adds another layer of complexity.

The literature on the Porter Hypothesis is extensive and methodologically diverse, offering valuable understanding into the complicated interaction among ecological protection via economic activity (Iraldo et al., 2011; Dechezleprêtre & Sato, 2017). Its strength lies in moving the debate beyond a simple trade-off narrative and highlighting the potential role of innovation. Methodological advancements, including better proxies for regulatory stringency (like the EPS index used by Benatti et al., 2024; Fabrizi et al., 2024; Akram & Srivastav, 2024; Wahab, 2024) and more sophisticated econometric techniques to address endogeneity and heterogeneity (Rubashkina et al., 2015; Benatti et al., 2024; Fabrizi et al., 2024), have improved the rigor of empirical analysis.

However, a significant weakness, as identified in our introduction, is the persistent focus on developed economies, particularly the US and Europe (Rubashkina et al., 2015; Lanoie et al., 2008; Benatti et al., 2024). While recent articles have begun to explore the PH in emerging contexts like China (Wang et al., 2022; Peng, 2024; Yu et al., 2024; Han et al., 2024; Sun et al., 2024) and partially in BRICS (Ogura, 2020; Akram & Srivastav, 2024; Fabrizi et al., 2024; Wahab, 2024), comprehensive and rigorous testing across the entire BRICS bloc, focusing specifically on core economic performance indicators like overall productivity and competitiveness, remains scarce. Existing BRICS-related studies often focus on specific sectors (e.g., agriculture - Peng, 2024), specific outcomes (e.g., financial development - Akram & Srivastav, 2024; carbon efficiency - Yu et al., 2024), or specific trade dynamics (Ogura, 2020; Wahab, 2024), rather than the general validity of the strong PH for overall economic performance across these diverse economies. Fabrizi et al. (2024) provide a direct test on BRICS firms' productivity but conclude against the strong PH.

This study contributes by directly addressing this geographical gap. By employing the OECD's EPS index and examining its relationship with both TFP and trade openness (as a proxy for international competitiveness) using panel data for the BRICS nations from 1990–2019, we provide a much-needed data-based analysis of the PH in the context of these crucial emerging economies. This analysis will offer valuable insights into whether, for the BRICS bloc, stricter environmental policies represent a pathway towards, or a barrier against, enhanced productivity and competitiveness on the global stage.

3. Data

To test the Porter hypothesis in the BRICS countries, we obtained data from the data service of World Bank from 1990 to 2019 / 2020. We employ two different models to measure the influence of EPS. In first model we consider Trade (% of GDP) and in the second model the study employs TFP as the dependent variables.

Models:

Trade (% of GDP) $= \beta_0 +$ *Environmental Policy Stringency Index (EPS)* $+ u_i$

TFP $= \beta_0 +$ *Environmental Policy Stringency Index (EPS)* $+ u_i$

4. Methodology

The empirical assessment of the interconnections under examination within this research proceeds via a bifurcated econometric methodology. The initial stage involves an evaluation of the stochastic properties of each variable, specifically their stationarity, through the application of the Augmented Dickey-Fuller (ADF) unit root test. Subsequently, the Autoregressive Distributed Lag (ARDL) bounds testing framework is leveraged to ascertain the presence of enduring equilibrium associations, or cointegration, among the series.

As a preliminary step to investigating cointegration, establishing the order of integration for each time series is imperative. Although the ARDL methodology is robust to mixed orders of integration, it is crucial to confirm through unit root diagnostics that no series is integrated of order two, I(2), as this would compromise the validity of the F-statistics derived from the bounds test (Duasa, 2007; Ozturk & Acaravci, 2011). For this purpose, the research utilizes the Augmented Dickey-Fuller (ADF) test. This test, an advancement of the original Dickey-Fuller (1979) procedure, mitigates potential serial correlation in the residuals through the incorporation of lagged differences of the dependent variable (Said & Dickey, 1984; Xiao & Phillips, 1998). The ADF procedure tests the null postulate that a given time series contains a unit root (exhibiting non-stationary behavior) against the alternative postulate of stationarity. The standard specification for the ADF test regression is formulated as follows:

$$\Delta Y_t = \alpha + \beta_t + \rho Y_{t-1} + \Sigma \delta_i \Delta Y_{t-i} + \varepsilon_t$$

where Δ is the first difference operator, Y_t is the variable under investigation, α is the intercept, t is a time trend, ρ is the coefficient of interest, and ε_t is the white noise error term. The number of lagged difference terms ($\Sigma \delta_i \Delta Y_{t-i}$) is typically determined by an information criterion such as the Schwarz Bayesian Criterion (SBC) or Akaike Information Criterion (AIC) to ensure that the residuals are serially uncorrelated.

Subsequent to the verification of the integration order for each time series and the exclusion of any variables found to be integrated of order two (I(2)), the research proceeds to examine potential long-run equilibrium relationships. This is achieved through the application of the Autoregressive Distributed Lag (ARDL) bounds testing approach, a methodology pioneered by Pesaran and Shin (1995) and further developed by Pesaran et al. (2001). The ARDL technique presents several distinct advantages over conventional cointegration analysis methods, such as the Engle-Granger or Johansen procedures. A key strength lies in its applicability to variables irrespective of whether they are integrated of order zero (I(0)), order one (I(1)), or a combination thereof (Odhiambo, 2009; Duasa, 2007). Moreover, this framework is recognized for its robust performance even with limited sample observations (Duasa, 2007; Ali et al., 2017) and offers the flexibility to accommodate distinct optimal lag structures for individual variables within the specified model (Duasa, 2007).

The core of the ARDL bounds testing framework involves the estimation of an Unrestricted Error Correction Model (UECM), which is specified as follows:

$$\Delta Y_{\mathrm{t}} = \alpha + \lambda Y_{t-1} + \delta X_{t-1} + \sum_{i=1}^{p} \phi_i \Delta Y_{t-i} + \sum_{j=0}^{q} \theta_j \Delta X_{t-j} + \varepsilon_t$$

where Y_t is the dependent variable, X_t is a vector of independent variables, Δ is the first difference operator, α is the intercept, and ε_t is the white noise error term. The terms $\sum_{i=1}^{p} \phi_i \Delta Y_{t-i}$ and $\sum_{j=0}^{q} \theta_j \Delta X_{t-j}$ represent the short-run dynamics, while λ and δ represent the long-run coefficients.

The determination of an enduring equilibrium association among the variables is accomplished by performing an F-test, or alternatively a Wald test, on the collective statistical significance of the coefficients associated with the lagged level variables. Specifically, the null hypothesis (H_0), stipulating no cointegration. The computed F-statistic is then evaluated against two distinct sets of asymptotic critical values, as proposed by Pesaran et al. (2001). These comprise a lower critical bound, predicated on the assumption that all regressors are integrated of order zero (I(0)), and an upper critical bound, assuming all regressors are integrated of order one (I(1)). Rejection of the null hypothesis, and thus inference of cointegration, occurs if the F-statistic surpasses the upper critical value. Conversely, if the F-statistic is less than the lower critical value, the null hypothesis of no cointegration is not rejected. An F-statistic falling within the corridor between the lower and upper bounds renders the test inconclusive regarding the presence of cointegration. It is pertinent to note that for analyses constrained by limited sample sizes, the critical values developed by Narayan (2005) are frequently employed as they are considered more appropriate under such conditions (Duasa, 2007; Ali et al., 2017).

Upon confirmation of a cointegrating relationship, the estimation of the conditional ARDL long-run model for Y_t is undertaken. Following this, the short-run adjustment dynamics are elucidated through the specification and estimation of an Error Correction Model (ECM):

$$\Delta Yt = \alpha_0 + \sum_{i=1}^{p-1} \lambda_i \Delta Y_{t-i} + \sum_{j=0}^{q-1} \omega_j \Delta X_{t-j} + \psi ECM_{t-1} + v_t$$

where ψ is the coefficient of the error correction term (ECM_{t-1}). This coefficient indicates the speed of adjustment back to long-run equilibrium after a short-run shock. For convergence to equilibrium, the coefficient ψ is expected to be negative and statistically significant (Odhiambo, 2009; Ali et al., 2017).

5. Empirical Results

As a first step of the study, we first apply the ADF unit root test to determine the integration levels of the variables and provide the findings in the following:

Table 1. The Findings of ADF Unit Root Test

Series	t-Stat	Prob.	Lag
EPS_BRAZIL	-1.1337	0.6891	0
EPS_CHINA	0.7569	0.9915	0
EPS_INDIA	1.4268	0.9986	3
EPS_RUSSIA	-1.0486	0.7225	0
EPS_SAFRICA	-1.1016	0.7008	2
TFP_BRAZIL	0.2455	0.9709	0
TFP_CHINA	-1.4497	0.5437	1
TFP_INDIA	1.3086	0.9981	0
TFP_RUSSIA	-0.9872	0.7417	0
TFP_SAFRICA	-0.7254	0.8248	0
TRADE_BRAZIL	-1.9094	0.3226	6
TRADE_CHINA	-1.888	0.333	1
TRADE_INDIA	-1.92	0.318	6
TRADE_RUSSIA	-0.0023	0.9494	6
TRADE_SAFRICA	-1.8009	0.3729	0

The results in Table 1 indicate that all variables exhibit a unit root, I(1), hence we analyse the long-run link among the variables using the ARDL Bounds Test which has good sample properties in the small-samples. We consider EPS as the independent variable and TFP or Trade as the dependent variable. We tabulate the findings in Table 2:

Table 2. The Findings of the ARDL Test

Country	Depentent Variable	Test Statistics
Brazil	TFP	3.063667
	TRADE	1.971041
China	TFP	1.148626
	TRADE	1.660739
India	TFP	6.191011*
	TRADE	1.323831
Russia	TFP	3.125708
	TRADE	18.85906*
South Africa	TFP	0.987839
	TRADE	1.103602

The critical values at the 5% levels are 3.62 and 4.16.

Since the test statistic for the ARDL test exceeds the upper critical value, it is ponted that there is a long-run link for India for the relationship between TFP and EPS, and for Russia for the relationship between TRADE and EPS.

We, next, forecast the long-run and present the findings in the following:

Table 3. Long-run coefficients

Country	Dependent Variable	Regressors	t-stat	p-values
India	TFP	EPS_INDIA	0.166774	0
		C	0.584069	0
		Russia		
Russia	Trade	EPS_RUSSIA	-15.49574	0.0002
		C	65.40527	0

The findings in Table 3 show that the EPS has a positive effect on TFP for India, while it has a negative effect on Trade for Russia in the long run.

6. Conclusion

This paper embarked on an empirical investigation into the legitimacy of the PH within the distinct economic and ecologic context of the BRICS nations, thanks to panel data from 1990 to 2019. By examining the relationship between EPS, proxied by the OECD's EPS Index, and two key economic performance indicators—Total Factor Productivity (TFP) and trade openness (Trade as % of GDP)—our research aimed to shed light on whether stringent environmental regulations can foster productivity and competitiveness in these pivotal emerging economies.

The empirical results, derived from ARDL bounds testing and long-run coefficient estimation, present a nuanced and heterogeneous picture across the BRICS bloc, underscoring the country-specific nature of the environment-economy nexus. For India, evidence of a statistically significant positive long-run linkage was identified among EPS and TFP. This finding lends credence to the 'solid' type of the PH, proposing that, in the Indian context, more stringent environmental policies may indeed stimulate innovation and efficiency improvements that ultimately enhance overall productivity. This implies that well-designed environmental regulations could be a strategic tool for fostering sustainable economic development in India.

Conversely, for Russia, the analysis revealed a statistically significant negative long-run relationship between EPS and trade. This outcome appears to contradict the strong PH's assertion that stringent regulations enhance international competitiveness. It suggests that, for Russia, during the period under review, the costs associated with stricter environmental compliance may have outweighed any innovation-induced benefits, thereby potentially hindering its international trade performance. For the residual BRICS countries—Brazil, China, and South Africa—the ARDL bounds tests did not establish a significant long-run cointegrating relationship between EPS and either TFP or trade with the employed model specifications. This lack of a discernible consistent impact across the entire bloc highlights the complexity of the PH and suggests that its tenets may not be universally applicable without considering specific national characteristics, industrial structures, and the precise nature and enforcement of environmental policies.

This study, while providing valuable insights, has certain limitations. The use of aggregate country-level data for TFP and trade, and a composite EPS index, may mask significant sectoral, firm-level, and policy-instrument-specific heterogeneities. Future research could delve deeper by:

- Employing firm-level or industry-specific data to provide a more granular understanding of the processes through which ecological regulations affect fertility and competitiveness.
- Disaggregating the EPS index to examine the heterogeneous outcomes stemming from multiple types of ecological policy mechanisms (e.g., market-based vs. command-and-control).
- Exploring the influence of other contextual factors, such as institutional quality, level of economic development, technological capabilities, and natural resource dependence, in moderating the PH.
- Expanding the timeframe and incorporating more sophisticated dynamic panel data techniques to capture lagged effects and address potential endogeneity more comprehensively.

In conclusion, while the Porter Hypothesis offers a compelling vision of a "win-win" scenario regarding the objectives of ecological care and economic performance, its applicability in the BRICS context is conditional and varies significantly by country and by the specific economic outcome considered. Our findings underscore the need for nuanced, context-specific policy design and further research to fully understand and harness the potential synergies between environmental sustainability and economic prosperity in these globally significant emerging economies.

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