Proceedings of the Fibonacci International Conference on Engineering, Technology, and Mathematics (ITECX'25)

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Fibonacci

ITECX'25

UNIVERSITÀ TELEMATICA INTERNAZIONALE UNINETTUNO

November 21st-25th, 2025, Rome, Italy

Theme

The First Fibonacci International Conference on Engineering, Technology, and Mathematics (ITECX'25), to be held in Rome, Italy, will celebrate the convergence of cutting-edge research across multiple disciplines. This conference aims to foster interdisciplinary collaboration by bringing together scholars, industry experts, and practitioners from engineering, technology, and mathematics. The event will highlight the critical role of these interconnected fields in addressing global challenges through innovative solutions. What sets ITECX'25 apart is its emphasis on integrating diverse methodologies and perspectives, creating a platform where mathematical theories fuel technological innovations, and engineering advances drive real- world applications. By uniting thought leaders from a broad spectrum of disciplines, we aim to inspire high quality contributions that push the boundaries of knowledge, promote sustainable development, and encourage cross-border collaboration. Rome, with its rich history of mathematical and scientific excellence, provides the perfect backdrop for this pioneering conference series, ensuring a unique and inspiring environment for participants.

List of Conference Topics

Mathematics and its Applications

- Applied and Computational Mathematics
- Mathematical Modeling in Engineering and Technology
- Optimization Algorithms and Techniques
- Discrete Mathematics and Combinatorics
- Data Science and Statistical Analysis
- Differential Equations and Dynamical Systems
- Probability Theory and Stochastic Processes
- Cryptography and Information Security

Engineering Innovations

- Mechanical and Structural Engineering
- Civil and Environmental Engineering Solutions
- Advanced Manufacturing and Industrial Engineering
- Engineering for Sustainable Development
- Robotics and Automation
- Electrical and Electronics Engineering
- Energy Systems and Smart Grids
- Aerospace and Transportation Engineering

Technology and Digital Transformation

- Artificial Intelligence and Machine Learning Applications
- Big Data Analytics and Cloud Computing
- Internet of Things (IoT) and Smart Cities
- Cybersecurity and Blockchain Technologies
- Digital Twins and Virtual Simulations
- Quantum Computing and Emerging Technologies
- Biotechnology and Bioinformatics
- 5G Networks and Future Communication Systems

Interdisciplinary Themes

- Engineering and Technology in Healthcare
- Mathematical Approaches to Sustainability
- AI and Machine Learning in Engineering Systems
- Technology-driven Solutions for Climate Change
- Cross-disciplinary Approaches to Smart Infrastructure
- Innovative Educational Technologies in Science, Engineering, Technology, and Mathematics (STEM)
- Mathematics in Materials Science and Nanotechnology
- Multi-scale Modeling in Engineering and Technology

Special Issues

Selected papers from ITECX'25 will have the opportunity to be published in special issues of the following prestigious journals, subject to their peer-review process:

- *Journal of Transportation and Logistics*
- *The Journal of Operations Research, Statistics, Econometrics and Management Information Systems*
- *Journal of Information Analytics*

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INVITED SPEAKERS

Prof. Dr. Anett Wolgast

FHM University

Short-Bio:

Prof. Dr. habil. Anett Wolgast is a professor of psychology with a focus on educational psychology, statistics, and research methods at the University of Applied Sciences FHM, Campus Hanover, Germany. She has published extensively in applied research that draws on classical test theory and item response theory, often within interdisciplinary collaborations. Her work integrates innovative technological tools in higher education and lifelong learning. Examples include research on simulating student behavior in a virtual classroom environment, developing virtual training programs, and leading a current research network that investigates the role of emerging technologies, education, and technology acceptance in addressing health, behavioral, and environment-related challenges. Specifically, her current research encompasses social perspective-taking and cooperation in educational contexts, including sustainable strategies for adaptation to climate change, emotion regulation, and dealing with antisocial behavior.

INVITED SPEAKERS

Prof. Dr. Euripides Hatzikraniotis

Aristotle University of Thessaloniki

Short-Bio:

Euripides Hatzikraniotis is a retired Professor in the fields of “Electronic Properties of Semiconductors & Semiconductor Devices” and “Didactics of Physics” at the School of Physics, Aristotle University of Thessaloniki (AUTH) – Greece. He was the Director of the Program of Post-Graduate studies on Didactics of Physics and Educational Technology, and the Director of the Laboratory of Science Education and Educational Technology. His research interests cover the development & evaluation of Teaching-Learning Sequences in STEM, Nano-Technology, Inquiry-based Learning and Experimentation with digital media & mobile devices. He has supervised 23 Doctoral dissertations, 23 Master's theses, and 10 undergraduate theses. He has participated in about 30 research projects as coordinator or principal investigator. He has 20 contributions in book-chapters, more than 240 publications in international journals & conferences and about 2300 references to his work (h-index:23, i10-index:51).

INVITED SPEAKERS

Assoc. Prof. Dr. Ovidiu Ivancu

Vilnius University

Short-Bio:

Ovidiu Ivancu is currently an Associate Professor at Vilnius University, Faculty of Philology. He teaches Romanian Language and Culture, English for Academic Purposes and Research, and World Literature within the Faculty of Philology and the Institute of Political Science and International Relations.
He holds a PhD in Philology from the University of Alba Iulia, Romania, Faculty of History and Philology. His doctoral dissertation, Cultural Identity and the Collective Romanian Mentality in Post-Communism: Images, Myths, Perceptions, Repositions (published in 2013), explores issues of identity and cultural representation in post-communist Romania.
Between 2009 and 2013, Dr. Ivancu served as a Visiting Lecturer at Delhi University, India, where he taught Romanian Language and Literature. In 2017–2018, he was a Visiting Lecturer at the State University of Comrat, Republic of Moldova.
His main research interests include imagology, the theory of mentalities, literary theory, literary criticism, and the history of literature.

INVITED SPEAKERS

Dr. Julija Grigorjevaitė

Vilnius University

Short-Bio:

Dr. Julija Grigorjevaitė is the head of the Didactic Centre and Assistant Professor of the Faculty of Chemistry and Geosciences of Vilnius University (Lithuania). Additionally, Julija is a chemistry teacher at the Business and Hospitality Training Centre and head of the Non-formal School of Young Chemists 'Pažinimas' (Exploring Chemistry), a program dedicated to engaging young students with practical chemistry. Her extensive teaching career spans six years, encompassing current roles at both the university and high school levels, where she teaches students. Her lectureship encompasses essential courses such as analytical chemistry laboratory work, general chemistry, and chemistry didactics. She holds a lead role in the educational research project, "Unveiling Chemistry Didactics: Exploring Research for Efficient Teaching," which focuses on exploring research for efficient teaching. Her work focuses on training high school chemistry teachers to transition their labs from traditional "cookbook" procedures to inquiry-based practicals. This methodological shift directly enhances student engagement and deepens their understanding of scientific concepts, leading to improved performance. Through roles at the Didactic Centre and as a project lead, she equips teachers with the tools and confidence to design educational research-based activities, ensuring their instruction is optimised for efficient teaching and maximising student learning outcomes.

INVITED SPEAKERS

Prof. Dr. Carina Gonzalez

University of La Laguna

Short-Bio:

Carina González is a Full Professor of Computer Architecture Technology at the University of La Laguna (Spain), teaching across engineering, education, arts, and social sciences. She holds dual PhDs in Computer Science and in Social Sciences and Education, along with advanced certifications from Tufts University and MIT.

She leads the Interaction, ICT, and Education (ITED) research group and serves as Chair of both the Women's Studies Research Institute and the Digital Culture division at ULL. Carina played a key role in creating the university's Virtual Campus and digital learning platforms and has directed several online master's programs. She also teaches and manages MOOCs on the Miriadax platform.

Carina is President of the Red Universitaria de Campus Virtuales and an active IEEE Senior Member, serving as Editor-in-Chief of IEEE RITA and Associate Editor of IEEE Transactions on Education. She has received multiple national and international awards for her contributions to educational technology.

For over 20 years, her research has focused on educational informatics and human–computer interaction, including intelligent tutoring systems, adaptive interfaces, educational games, gamification, e-learning, and digital culture.

INVITED SPEAKERS

Prof. Dr. Ángeles Bueno Villaverde

Universidad Camilo José Cela (UCJC)

Short-Bio:

Prof. Dr. Ángeles Bueno Villaverde is a distinguished scholar and educator at Universidad Camilo José Cela (UCJC) in Madrid, where she has been a faculty member since 2000. She holds a PhD in Educational Psychology from the Complutense University of Madrid, along with advanced qualifications in international education, bilingual education, and giftedness and neuropsychology. Throughout her career, she has served in several academic leadership roles, including Academic Secretary of the Faculty of Education, Quality Coordinator, and Coordinator of the International Baccalaureate Certificate in Teaching and Learning. Her research focuses on student and family engagement, cooperative learning, differentiated instruction, inclusion of gifted learners, and international bilingual education. Prof. Bueno Villaverde has supervised numerous doctoral dissertations and contributed to scholarly publications and conferences, advancing evidence-based and inclusive teaching practices in both national and international contexts.

INVITED SPEAKERS

Dr. Akın Gürbüz

Muğla Sıtkı Koçman University & Vilnius University

Short-Bio:

Dr. Akın Gürbüz serves as a Lecturer at the School of Foreign Languages of Muğla Sıtkı Koçman University in Turkey. He earned his bachelor's degree in Foreign Languages Education at Istanbul University – Hasan Ali Yücel Education Faculty in 2004, a master's in English Language Education at Gaziantep University in 2013, and a doctorate in English Language Education at Çukurova University in 2021. His research focuses on EFL/ESL teaching, syllabus design, cultural diversity in language learning, and assessment practices. He has published articles in peer-reviewed journals and authored book chapters on topics such as intercultural communicative competence and online testing processes

PROGRAM OVERVIEW

Location: Ergife palace hotel, Largo Lorenzo Mossa, 8 - 00165 ROME - Italy

Saturday, November 22

08:30 – 09:00	Registration	Conference Registration Desk	
09:00 – 09:30	Openning Ceremony	Orhan CEVIK Assoc. Prof. Dr. Süleyman METE Assoc. Prof. Dr. Dario ASSANTE	Main Hall
09:30 – 11:00	Invited Speaker Sessions	Prof. Dr. Anett Wolgast Prof. Dr. Euripides Hatzikraniotis Assoc. Prof. Dr. Ovidiu Ivancu Dr. Julija Grigorjevaitė Prof. Dr. Carina Gonzalez Prof. Dr. Ángeles Bueno Villaverde Dr. Akın Gürbüz	Main Hall
11:00 – 11:30	Coffee Break		
11:30 – 12:45	Session I (In-Person)		Main Hall
12:45 – 13:00	Coffee Break		
13:00 – 14:15	Session II (In-Person)		Main Hall
14:15 – 14:30	Coffee Break		
14:30 – 15:45	Session III (In-Person)		Main Hall
15:45 – 16:00	Coffee Break		
16:00 – 17:00	Session IV (In-Person)		Main Hall

PROGRAM OVERVIEW

Location: Ergife palace hotel, Largo Lorenzo Mossa, 8 - 00165 ROME - Italy

Sunday, November 23

10:00 – 11:15	Session V (In-Person)	Main Hall	Virtual Session I
11:15 – 11:30	Coffee Break		
11:30 – 12:45	Session VI (In-Person)	Main Hall	Virtual Session II
12:45 – 14:00	Lunch		
14:00 – 15:15	Virtual Session III		
15:15 – 15:30	Coffee Break		
15:30 – 16:30	Virtual Session IV		

DETAILED PROGRAM

SESSION I	
22.11.2025 - SATURDAY Time (GMT + 1) : 11:30 – 12:45	
Chair: Prof. Dr. Rüstem Barış YEŞİLAY	
Hall 1	Design Science and Applied Mathematics in Smart Manufacturing and Logistics: Toward a Big Data-Driven System *Ângela Filipa Brochado*, Eugénio Rocha*
	Integrated parallel machine scheduling and AGV routing: A constraint programming approach *Zeynel Abidin Çil*, Damla Kizilay, Hande Öztop*
	The Physical Internet: A Paradigm Shift in Logistics and Supply Chain Management *Andrea Falegnami*, Andrea Tomassi, Dario Assante*
	Nonlinear Optimization Model for Container and Operational Planning *Eugénio Alexandre Miguel Rocha*, Ângela F. Brochado*
	Supplier Selection in the Context of Twin Transformation *Tuba Koçer*, İrem Helvacıoğlu*

SESSION II	
22.11.2025 - SATURDAY Time (GMT + 1) : 13:00 – 14:15	
Chair: Assoc. Prof. Dr. Zeynel Abidin ÇİL	
Hall 1	Simulation of electric vehicle charging stations with lateral transshipment *Sinem Özkan*, Zeynel Abidin Çil, Damla Kızılay Ödemiş*
	Wearable technologies and sports: Innovations in performance monitoring, health tracking, and athlete development *Cengiz Güler**
	Smart Waste Management Using EGrab-Bot 2.0: An AI and Robotics-Based Approach *Bhai Nhuraisha Deplomo**
	Eco-Friendly Sand-Concrete Composite: Integrating Recycled PVC for Improved Thermal and Environmental Properties *Hamed Aboulkacem Moutie*, Zeghichi Leila , Gadri Karima*
	Pre-Service Teachers' Perspectives on AI-Supported Learning: Insights from a Qualitative Study *Bülent DÖŞ**

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	Research Trends on Drone Applications in Humanitarian Aid Logistics *Zeynep Yüksel*, Süleyman Mete*
	A Decision Support Model for the Optimal Placement of Smart Benches *Hüseyin Başaran*, Süleyman Mete*
	Examining the Effect of Artificial Intelligence-Based STEAM Activities on Middle School Students' Mathematics Achievement *Özge Yoldaş**
	Identifying Algebraic Thinking Patterns of Graduate Mathematics Teachers *İrem Dağ*, Ali Bozkurt*

SESSION IV	
22.11.2025 - SATURDAY Time (GMT + 1) : 16:00 – 17:15	
Chair: Dr. Andrea FALEGNAMI	
Hall 1	From Cave Walls to Artificial Intelligence: The Historical Evolution of Educational Technology *Bekir Demircan**
	Real-time anomaly detection in the fog computing architecture of the internet of things *Rıza ALTUNAY**
	Investigation of Digital Laziness in The AI Age *Gizem Değirmenci, İrem Nil Tatar*, Ada Köse, Burçe Ada Yılmaz, Defne Yeniocak, Ece Dünya Küçük, Esma Kabaali, Eylül Gümüş, Hamza Taşçıoğlu, Nadire Kuseyrioğlu, Nilbade Yıldız, Nurten Nil Köse, Rüzgar Boyacı, Serra Şengül*
	Technology Use in the Context of 21st-Century Teacher Competencies *MEHMET UÇAR**

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23.11.2025 - SUNDAY Time (GMT + 1) : 10:00 – 11:15	
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Hall 1	The Global Cybersecurity Index and Türkiye: An Assessment of Increasing Measures in Digital Transformation *Rüstem Barış YEŞİLAY**
	EditorAI *Adem Ünlü*, Kutluhan Danayiyen, Mehmet Atilla Alp Arslan, Cesur Kuzey Aycan*
	Silent Call - Health Tech *Hüsamettin GÖKOĞLU**
	Time is Life: Artificial Intelligence-Supported Smart Stop Cancellation System in Patient Elevators *Nazlı Aydın*, Elif Zehra Taşdemir, Ulus Atalay, Osman Batu Erol*
	STAR (Voice Detection and Perception Guide) *Nazlı Aydın*, Demir Bülbüloğlu, Yiğit Çalışkan, Cantuğ Mete Yaya, Batuhan Kuşderci, Berika Su Erdem, Onur Taha Akyol*

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Chair: Prof. Dr. Caner GİRAY	
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	Reimagining Early Literacy: An AI-Powered Interactive Book Selection System for Preschool Children *Halil Çatak, Ali Kendir, Ayaz Baki Durkut*, Doğan Adnan Akarsu, Berke Yavuz, Ahmetcan Kul*
	Production of Bioplastics for Waste Management and Sustainable Material Technologies *Defne Yeniocak*, İrem Nil Tatar, Rüzgar Boyacı*

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Online Session : https://zoom.us/j/93303823003?pwd=iZcOgKjGmkyu0CB4qKD4rZtPbXAE3q.1	
Chair: Assist. Prof. Dr. Yunus Eroğlu	
Online	A Comparative Analysis of Random Forest Model for Breast Cancer Prediction Using a Novel Feature Engineering Technique with Feature Selection and Variance Inflation Factor *Johnson Fashanu*, Ahmed Ameen, Mariagorretti Richman*
	Leveraging AI for Improved Requirements Engineering_ A Complete Approach *Vaishnavi Gudur**
	An AI-Based Decision Support System for Multi-Dimensional Sustainability in Logistics Operations *Nur Sena Ertem*, Eren Özceylan*
	Kicking Ahead: Ball Trajectory Prediction with Recurrent Neural Networks in Soccer *Hanan Abu Kwaider*, Faruk Serin*
	Trend Analysis and Machine Learning-Based Forecast Method of Climatic Parameters and Evapotranspiration for Southern Turkey *Ali Cüvitoğlu*, Fatma Deniz*

VIRTUAL SESSION II	
Online Session : https://zoom.us/j/93995879367?pwd=3laDbijktOlQEkPVSC0jGlXe0FQ6ad.1	
Chair: Assist. Prof. Dr. Ömer Nedim KENGER	
Online	Cracking the Code of Big Data Analytics *Goutam Ghoshal**
	Joint optimization of disassembly line balancing and vehicle routing in a green supply chain context *Hayrettin Gök*, Ömer Nedim Kenger, Zülal Kenger*
	Facility Location Optimization for Fire Stations in the Central District of Gaziantep *Ömer Nedim Kenger, Zülal Diri Kenger**
	Disassembly Line Rebalancing under Robot Failures and Preventive Maintenance: A Human–Robot Collaboration Based Mixed Integer Programming Model *Dursun Emre Epcim*, Süleyman Mete*
	Disassembly Line Balancing Problem Based on Human-Cobot Collaboration with Ergonomics Constraints In The Industry 5.0 Era *Seda Hezer**

VIRTUAL SESSION III	
Online Session : https://zoom.us/j/99136249224?pwd=gaRMgitb7GoJbzUuwWPq7c378LqafY.1	
Chair: Assist. Prof. Dr. İbrahim Miraç ELİGÜZEL	
Online	Comparative Analysis of ByteTrack, YOLOv11n, SAM2 and RF-DETR in Multi-Human Tracking *Rahef Elibraş*, Faruk Serin*
	A Comparative Analysis of Machine Learning Algorithms for Predicting Fire Radiative Power *İbrahim Miraç ELİGÜZEL*, Hüseyin TERZİ*
	Comparative Analysis of Repetitive Movements in Videos Using Various Methods *Yasin Badur*, Faruk Serin*
	Logistics Optimization in Smart Cities Improving E-Commerce Delivery *Gizem Şahin*,Yunus Eroğlu*
	Central Bank Digital Currencies (CBDCs): Redefining Money and Banking *Nihad Babayev*, Aygun Abdulova*

VIRTUAL SESSION IV	
Online Session : https://zoom.us/j/91211158354?pwd=5ESLxJba7aNDTmpFaLoIuIoC1LJ6d0.1	
Chair: Assist. Prof. Dr. Zülal KENGER	
Online	Study in Compound-Gaussian Lognormal Texture Modeling *Douiou Zoulikha*, Ali Atallaoui*
	Poincaré-Friedrichs Inequalities For Broken-Sobolev/Polynomial Spaces *Oussama Boussoufa**
	How a Magnetic Field Changes the Polarization of Twisted (Radially Polarized) Light *Fatma TAMBAĞ*, Koray KÖKSAL*
	Generation of Orbital Angular Momentum (OAM) Beams from Natural Light Sources *Mahmud Tekin*, Koray Köksal*

Contact Information

For any inquiries or issues related to ITECX'25, please reach out to our dedicated team. We are here to assist you with all aspects of the conference. All questions and concerns can be directed to our official email:

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itecx2025@gmail.com

Website
https://itecx.international

Location
Ergife palace hotel
Largo Lorenzo Mossa, 8 - 00165 ROME - Italy

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FULL PAPERS

A Comparative Analysis of Random Forest Model for Breast Cancer Prediction Using a Novel Feature Engineering Technique with Feature Selection and Variance Inflation Factor

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Abstract

Breast cancer has been extensive studied over the years, and the application of various machine learning models have ensured a way of detecting the disease early enough for treatment to mitigate its devastating mortality rate among women. This research focuses on Random Forest model which as an ensemble model has been used in various research on breast cancer diagnosis with impressive results. It leverages innovative feature engineering using linear equations to retain the structure of the features of the dataset and degree 7 polynomial equations to transforms the features, these equations (both linear and polynomial) are derived from Fibonacci numbers, this innovation broadens the feature spaces and ensures the model captures non-linear relationship which traditional method may miss. The degree 7 polynomials are variant polynomial regression; hence highly correlated features were dropped whose correlation matrix exceeds the threshold value of 0.85 and applying Variance Inflation Factor (VIF) to cub multicollinearity. Fibonacci pattern has been adopted in natural science, its incorporation in feature engineering is fitting since the Wisconsin Diagnostic Breast Cancer (WDBC) dataset stems from a natural source. The innovative framework achieves an accuracy of 99.12% for random forest feature selection and VIF filtered features, and a Mean Cross-Validation score of 97.20% and 96.33% for random forest feature selection and VIF filtered features respectively.

Keywords: Breast cancer, Fibonacci numbers, Feature engineering, Random Forest, Machine learning, Variance inflation factor

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1. Introduction

Breast cancer, a leading cause of female cancer mortality (World Health Organization, 2021), necessitates early detection. Machine learning, particularly Random Forest, shows promise in classifying tumors from complex medical data (Santos et al., 2022; Dai, Chen, Zhu, & Zhang, 2018; Mao, & Wang, 2012).

This research introduces a novel feature engineering approach, utilizing Fibonacci-derived linear and polynomial transformations, to enhance Random Forest's predictive accuracy. By expanding the feature space with these mathematical sequences, the study aims to capture subtle, non-linear patterns, potentially improving diagnostic precision compared to traditional feature engineering methods (Kuhn & Johnson, 2013; Bengio et al., 2013; Liu X. et al., 2020).

This interdisciplinary approach focusing on feature engineering, leveraging mathematical concepts like Fibonacci sequences (Livio, 2003; Ameen & Fashanu, 2025), aims to address a critical medical challenge, with experiments conducted on breast cancer datasets (Buttan, Chaudhary, & Saxena, 2022; Sung et al., 2021).

1. Materials and Methods

This study explores the effectiveness of Fibonacci-derived linear and polynomial equations for feature engineering in breast cancer prediction, integrated with a Random Forest classifier. Specifically, our objectives are:

I. To design an enhanced feature space using Fibonacci-derived transformations, expanding 30 features to 60.

II. To apply Random Forest feature selection to select 50 features and improve model efficiency.

III. To assess the performance of the proposed feature engineering method using a Random Forest classifier before and after removal of highly correlated features and removal of features who's VIF threshold exceed 8.

IV. To compare results.

1.1. Data Description

The study utilizes the Wisconsin Breast Cancer Dataset (WBCD) from the UCI Machine Learning Repository, a widely used benchmark dataset for breast cancer classification (Dua & Graff, 2019). The dataset consists of 569 instances and 30 numerical features, including measurements of cell nuclei extracted from digitized images of fine needle aspirate (FNA) biopsies. The target variable is binary, categorizing tumors as either malignant (1) or benign (0).

1.2. Feature Engineering Using Fibonacci-Derived Transformations

2.2.1 Fibonacci-Derived Linear Equations

The first step in the feature engineering process involved applying a set of Fibonacci-derived equations to transform each feature in the dataset. These equations take the form:

$aK + b$ (for linear equations)

((aK + b)Kj) - ((cK + d)Kj-1) - (6(aK + e)Kj-2) + (5(cK + d)Kj-3) + (10(aK + e)Kj-4) - (6(cK + d)Kj-5) - (4(aK + e)K) + (cK + d) (for polynomial equations)

Where 'a', 'b', 'c', 'd', and 'e' are Fibonacci sequence-derived constants, j = 7, and K represents the feature value. The transformed feature set provides additional representations of the original attributes, enabling the model to capture subtle relationships within the data.

1.3. Feature Selection

The sets of linear equations are applied to retain the structure of the features; they determine which of the 10 polynomial equations will be used to transform features. For example, the graphs of Fig. 1 and Fig. 2 displays samples of features from the Wisconsin Breast Cancer dataset and the derived linear equation feature respectively, various linear equations were employed in the transformation using an algorithm yet the structure do not change.

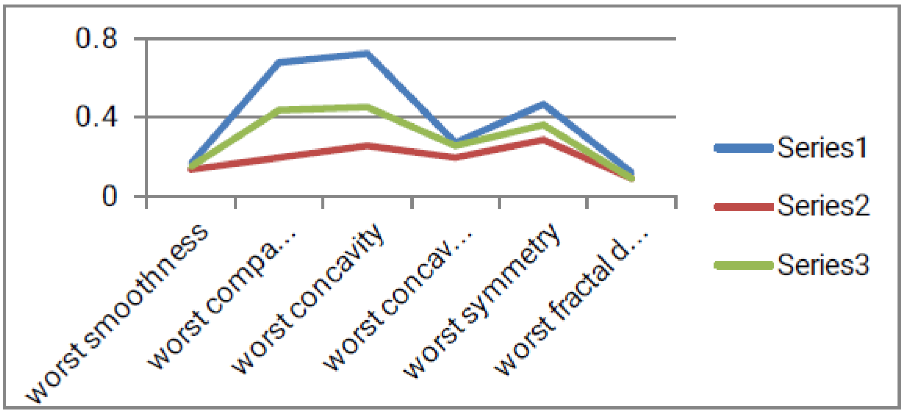

Figure 1. Graph of Sample of Original Feature from Wisconsin Breast Cancer Dataset

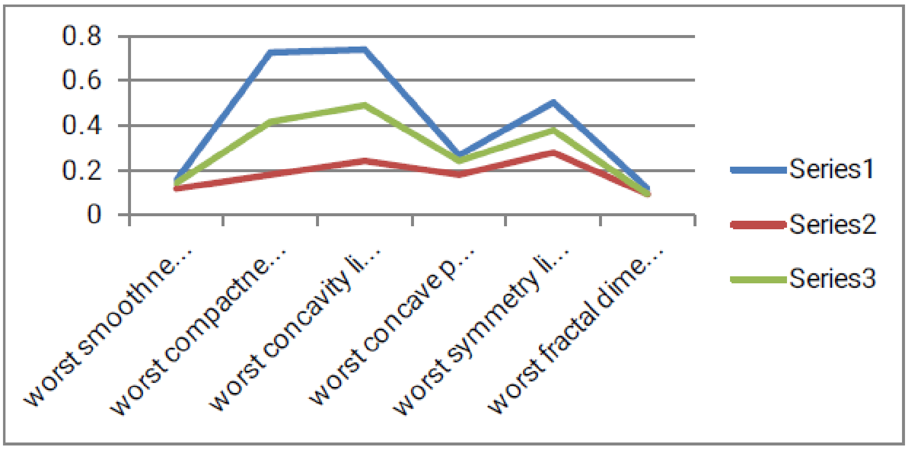

Figure 2. Graph of Sample of Derived Linear Feature

The model was trained on 80% of the dataset and tested on the remaining 20%, ensuring an unbiased evaluation.

2. Results and Discussion

The implementation of feature engineering techniques, using polynomial features with coefficients derived from the Fibonacci sequence, yielded significant insights and classification capabilities for the Wisconsin Breast Cancer Dataset. The combination of features increased accuracy to 99.12% (Table 1), indicating the importance of non-linear relationships. However, the initial 50 features selected by Random Forest (Fig. 3) showed high multicollinearity, indicated by deep colors in the correlation matrix, potentially affecting model stability. This prompted further analysis to remove features with correlation exceeding 0.85 and VIF (Variance Inflation Factor) exceeding 10, resulting in 30 key features (Fig. 4).

Table 1. Performance metrics of model with 50 combined features

Class	Precision	Recall	f1-score	Support
0	1.00	0.98	0.99	43
1	0.99	1.00	0.99	71
Accuracy			0.99	114
Macro avg	0.99	0.99	0.99	114
Weighted avg	0.99	0.99	0.99	114

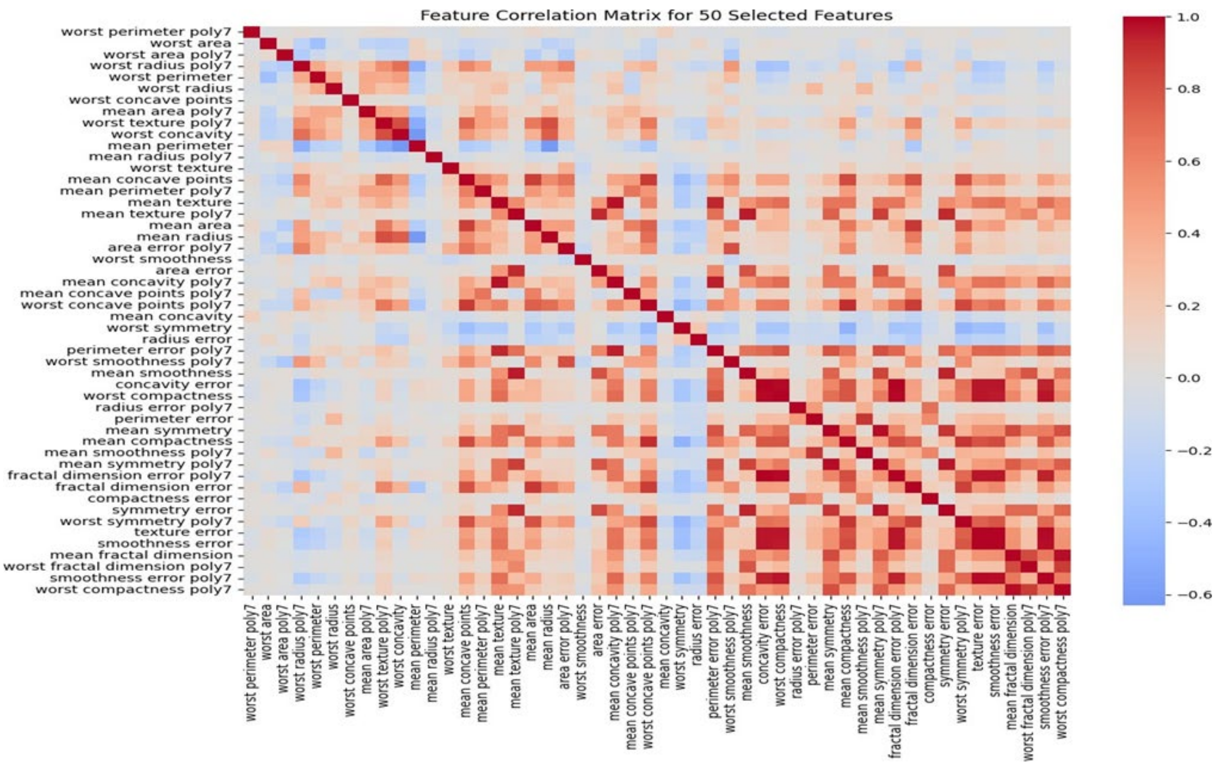

Figure 3. Correlation matrix of 50 combined features

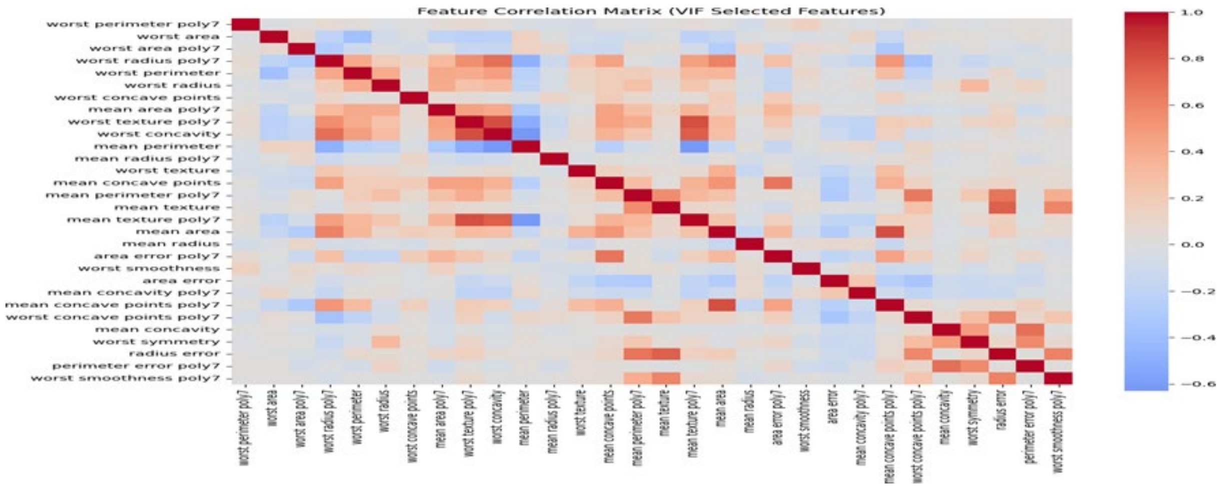

Figure 4. Combined features after VIF filtering

The refined feature set also achieved 99.12% accuracy, with a slightly lower cross-validation mean of 96.33% compared to the initial 97.20% (Fig. 5 & 6), demonstrating a trade-off between model stability and performance.

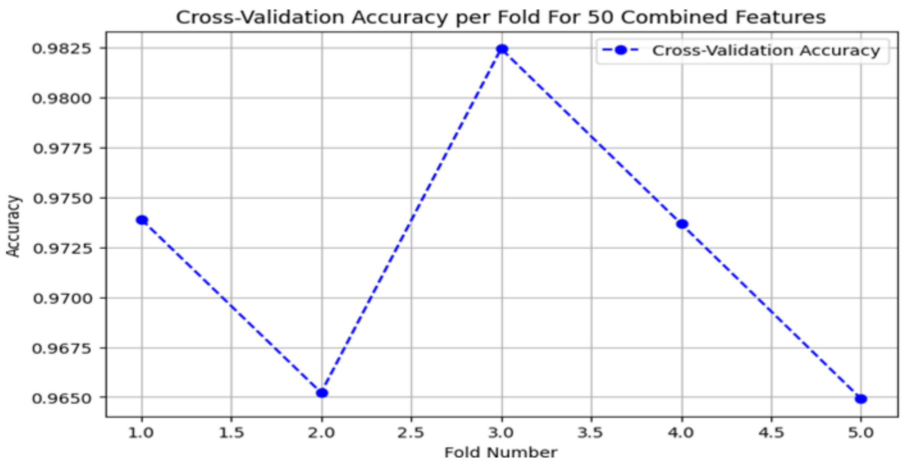

Figure 5. Cross-Validation Score for 50 combined features

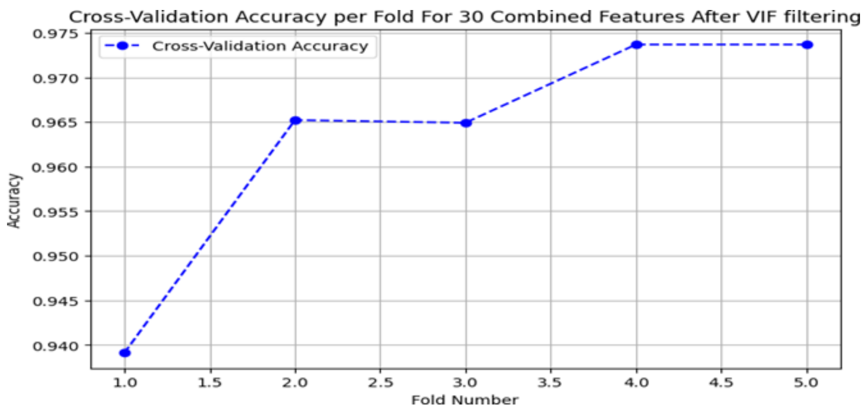

Figure 6. Cross-Validation Score for 30 combined features after VIF filtering

Unlike traditional feature selection, the inclusion of Fibonacci-derived features highlights their contribution to model performance. The exclusion of original features from the top-ranked components suggests redundancy in the raw dataset compared to engineered features, aligning with prior research on the benefits of non-linear transformations (Bengio et al., 2013). This suggests that Fibonacci-derived transformations can serve as an alternative to traditional feature selection, potentially paving the way for a new approach in medical AI where mathematical transformations play a primary role in predictive modeling.

2.1. Model Performance Metrics

The proposed model was evaluated using accuracy, precision, recall, F1-score, and cross-validation to assess its classification effectiveness. Table 2 summarizes the model's performance metrics, while Fig. 3 is a graph of a 5 fold cross-validation.

Table 2. Performance metrics of model

Class	Precision	Recall	f1-score	Support
0	1.00	0.98	0.99	43
1	0.99	1.00	0.99	71
Accuracy			0.99	114
Macro avg	0.99	0.99	0.99	114
Weighted avg	0.99	0.99	0.99	114

3. Conclusion

This study introduced a Fibonacci-derived feature engineering technique for breast cancer classification, combining mathematical transformations, Random Forest feature selection, and VIF. The experimental results demonstrated that the proposed approach significantly improved classification accuracy, achieving 99.12% accuracy, with a mean cross validation score of 97.20% for Random Forest Selection and 99.12% accuracy, with cross validation score of 96.33%. While achieving high accuracy, a slight decrease in cross-validation scores was observed after feature reduction, indicating a trade-off between model stability and performance. A key finding was that Fibonacci-derived features contributed to the general performance of the model. This study demonstrates the significant potential of mathematical transformations, specifically Fibonacci-derived features, to enhance medical machine learning models.

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Cracking the Code of Big Data Analytics

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Abstract

Big data is defined by four key characteristics—volume, variety, velocity, and veracity—which inherently demand advanced analytical approaches. A fundamental question arises: what are the defining features of big data analysis? In this context, analytics refers to the overarching methodology rather than individual analytical techniques. This paper introduces six key techniques in big data analytics: ensemble analysis for handling large volumes of data, association analysis for managing unknown data sampling, high-dimensional analysis to address data variety, deep analysis and precision analysis—both targeting data veracity—and divide-and-conquer analysis for processing high-velocity data. At its core, big data analytics involves structural analysis guided by optimal principles from physics, computation, and human cognition. Two major theoretical challenges are highlighted: the breakdown of the assumption of independent and identically distributed data, and the need to extend traditional set theory. The paper also explores three types of associations in geographical big data, including geometrical associations in space and time, statistical spatiotemporal correlations, and semantic relationships across space and time. Furthermore, it illustrates three approaches to spatiotemporal data analysis: adjustment of geometrical measurements through observation, analysis of human spatial behavior using trajectories, and data assimilation that integrates physical models with diverse observational data. Together, these methods form a foundation for effective and comprehensive spatiotemporal big data analysis.

Keywords: Big Data; Ensemble Techniques; Association Methods; High-Dimensional Analytics; Deep Analytics; Precision Techniques; Divide-and-Conquer Strategies.

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1. Big Data and Its Four Key Characteristics

Big data originates from two primary sources: collective gathering, such as smart city data, national geographic monitoring, and Earth observation data, typically obtained through sampling strategies with high data quality, and individual generation, like e-commerce data, social media data, and crowdsourcing data, which are collected with more freedom but tend to have lower usability; big data technology has emerged with advancements in computer and communication technology, which has led to a paradigm shift in how we understand and interact with the world, where computers, particularly digital and intelligent technologies, have improved data sampling, storage, computation, and communication, reducing the cost of data collection, while humans have increasingly shifted from rationalism to empiricism in constructing knowledge, with big data now encompassing the full lifecycle of collection, management, analysis, and application, from space- and ground-based sensor networks to crowd-sourced data, distributed file systems, and cloud computing for managing unstructured data, to the application of statistics and machine learning in analysis, enabling precision industries like agriculture, medicine, and marketing, with the term "big data" originating in the computer science community, where the core challenges involve computability, algorithm complexity, and distributed intelligence, illustrated by Gödel's incompleteness theorem and Turing's halting problem, both showing limitations in solving certain computational problems, with time and space complexity being central to algorithmic challenges, but advancements in multi-core computing and networked storage helping mitigate some issues, while artificial intelligence emerges as a major challenge, and ultimately, big data is characterized by the 4Vs—volume, variety, velocity, and veracity—indicating large amounts of diverse, high-speed, and valuable data, with veracity emphasizing the importance of data quality and usability in practical applications.

2. Reexamining two mathematical theories for big data analysis

Data initially consist of values from qualitative or quantitative variables. In data analysis for statistics and optimization, the Independent and Identically Distributed (IID) theory and set theory are commonly applied. When IID is violated, spatiotemporal autocorrelation and generalized distributions are frequently assumed in the analysis of geographical big data. In the context of big data analysis, set theory is expanded to include probability-measured sets, metric spaces, and topological spaces.

2.1. Independent and Identical Distribution

Statistics is the science of data sampling and inference. In a direct sense, big data science is considered an extension of statistics, referred to as big data statistics. Through market research, big data analysis is primarily focused on statistics and machine learning. Statistics is seen as the optimal decision for sample estimation of a population in asymptotic theory. Machine learning can be viewed as either statistical learning or function approximation based on specific domain criteria.

In probability theory and statistics, a sequence or collection of random variables is independent and identically distributed (IID) if each random variable has the same probability distribution and is mutually independent. It is important to note that an IID sequence does not require the probabilities for all elements of the sample or event space to be the same. The IID assumption of random variables and assigned observations simplifies the underlying mathematics in many statistical inferences.

In particular, the IID assumption is crucial in the central limit theorem, which states that the probability distribution of the sum (or average) of IID variables with finite variance approaches a normal distribution. The normal distribution, also known as the Gaussian distribution, is a fundamental probability distribution that can be extended into mixed Gaussian distributions and generalized distributions. Under the assumption of a Gaussian distribution and linear models, the least squares estimate equals the maximum likelihood estimate. In mathematical analysis, the Gaussian distribution function is closely related to the linear model in algebra.

To solve more complex problems, the mixed Gaussian and generalized distributions in mathematical analysis correspond to nonlinear models in algebra. For example, the power law distribution, a type of exponential distribution, is widely used for modeling heavy-tailed human behavior distributions, such as those found in social media. However, the assumption of completely independent and identically distributed variables may not always be realistic in big data analysis and geographical data analysis.

Newton's law of universal gravitation (1687) states that any two bodies in the universe attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. Similarly, Tobler's first law of geography (1970) asserts that everything is related to everything else, but nearer things tend to be more related than distant ones. This law implies spatial dependence and spatial autocorrelation, which are used specifically in spatial interpolation methods like inverse distance weighting and Kriging interpolation in the theory of regionalized variables.

In nature, spatial statistics, including geostatistics, spatial regression, and random point processes, represent the probabilistic realization of the first law of geography. To test violations of the independent assumption, the empirical autocorrelation of a given dataset is evaluated and plotted. To test spatial autocorrelation, Moran's I is computed and the Moran scatter plot is generated.

2.2. Set Theory

It is argued that big data should be retrieved with precision rather than analyzed in a trivial manner. In relational databases or very large databases, a relation is defined as a set of tuples that share the same attributes or fields. A tuple represents an object and its associated information. A domain is a set of possible values for a given attribute and can also be seen as a constraint on the attribute's values. Relational algebra or relational calculus is the theoretical framework for relational databases. Relational algebra is based on a set of tuples and five key set operations: {union, intersection, join, projection, selection}.

The union operator combines the tuples from two relations, removing any duplicate tuples from the result. The intersection operator generates a set of tuples that are common to both relations. The join operator produces the Cartesian product of two relations, with some join criteria limiting the result. Specifically, spatial join operators are applied by spatially conditioning spatial databases (spatial data tables). The projection operation extracts only the specified attributes from the tuples. The selection operator retrieves specific tuples from a relation or table, limiting the result to those that meet a predefined criterion, thereby forming a subset of the set.

Statistics is perhaps the most crucial branch of mathematics for big data analysis. A probability measure is a real-valued function defined on a set of events in a probability space, satisfying measure properties such as countable additivity and assigning a value of 1 to the entire probability space. A probability triple, (Ω, F, P), is a mathematical model used to represent a real-world process of randomly occurring states. A probability space is a probability-measured set, consisting of:

- A sample space, Ω, which is the set of all possible outcomes.
- A set of events, F, where each event is a set containing zero or more outcomes.
- A probability-measure function, P, that maps events to probabilities.

For complex system modeling and big data analysis, a probability space is often characterized by mixed Gaussian and generalized distributions. In geographical data analysis, a probability distribution function, parameterized with spatial covariance, is particularly important in spatial statistics.

Machine learning is another commonly used computational tool for big data analysis. A mathematical space is defined as a set with an added structure. In addition to probability space, terms such as topological space, Euclidean metric space, norm space, inner space, and vector space are frequently used in machine learning. For instance, topological space and Euclidean space are utilized in manifold learning, L0 and L1 norm spaces are employed in compressed sensing, inner space is applied in kernel learning, and vector space is used in principal component analysis.

3. Six Techniques of Big Data Analysis

Raw data, or unprocessed data, consists of a set of numbers or characters. Data is sampled and analyzed to extract information that supports decision-making, while knowledge is derived from extensive experience in a particular subject. Physical experience occurs when an object or environment changes. Social experience, which shapes norms, customs, values, traditions, social roles, symbols, and languages, equips individuals with the skills and habits necessary to participate in their societies. In philosophy, phenomena refer to what is experienced and is considered the foundation of reality. Phenomena are often understood as things that appear or are experienced by humans. In physics, a phenomenon can be an observed feature or event involving matter, energy, and the motion of objects.

Data can thus be viewed as an observation or experience of real phenomena. In this context, geographical data are seen as observations of physical and human geography phenomena. Essentially, geographical big data analysis aims to explore the complexity of geographical reality.

Regarding data storage and structural analysis, the characteristics of big data analysis are derived from the inherent features of big data. Therefore, six techniques for big data analytics are proposed.

3.1. Ensemble Analysis

Ensemble data analysis, also known as multi-data set or multi-algorithm analysis, refers to analyzing an entire dataset or a large volume of data. Big data is considered as the complete dataset without the need for sampling. The whole data set may include resampled data, labeled data, unlabeled data, prior data, and posterior data. The term "ensemble" appears in various contexts, such as ensemble learning in machine learning, ensemble systems in statistical mechanics, and ensemble Kalman filtering in data assimilation.

In supervised learning and image classification, the data is typically divided into three subsets: training data, test data, and validation data. The image classifier is trained using the training data, tested on the test data, and the results are validated against the ground truth. Usually, a classifier performs better on the training data than on the test data. To strike a balance between the model's complexity and its performance on training data, ensemble analysis is employed to optimize performance across the entire set, including training, test, and validation data. In support vector machine (SVM) learning, structural risk minimization is used to avoid overfitting, ensuring that the model generalizes well to test data, rather than being overly tailored to the training data.

To extract insights from a subset of data, a single algorithm is designed. For extracting information from the entire dataset, multiple algorithms are integrated. Ensemble analysis encompasses techniques like bootstrapping, boosting, bagging, stacking, and random forest learning. Typically, integrating multiple learning algorithms leads to better performance compared to using any individual algorithm. However, determining the consistency among the constituent algorithms and assigning appropriate weights to each remains a challenge. Inspired by Markov Chain Monte Carlo (MCMC) statistics, Efron's bootstrap resampling (Efron, 1979) and Valiant's Probably Approximately Correct (PAC) learning (Valiant, 1984) present potential theories for ensemble analysis. PAC provides a framework to decide how much data is necessary for a classifier to achieve a specified probability of correct predictions on future test data. In short, PAC helps build a hypothesis with high probability that it is approximately correct, or that the selected function will have a low generalization error. PAC is a key component of computational learning theory, which includes Bayesian learning, minimum description length learning, Vapnik-Chervonenkis theory (Vapnik, 2000), and classical frequentist statistics. Here, machine learning can be seen as statistical estimation and function approximation. At a fundamental level, the Weierstrass approximation theorem states that every continuous function defined on a closed interval [a, b] can be uniformly approximated as closely as desired by a polynomial function.

3.2. Association Analysis

Big data is typically collected without specific sampling strategies. Often, there is a distinction between the data producers and data users, which means the cause-and-effect relationships hidden within the data may not be clear to the users. Set theory, which deals with the relationships between elements in a set, provides a general framework for data analysis and problem-solving. In this context, the relationships between set members can be seen as associations within big data. Association analysis plays a crucial role in multi-sourcing, multi-type, and multi-domain data analysis. It is commonly exemplified by association rule algorithms in data mining (Agrawal & Srikant, 1994), data association in target tracking, and link analysis in networks.

The Apriori algorithm, introduced by Agrawal and Srikant, is one of the foundational algorithms for association rule mining. An association rule consists of two parts: an antecedent (the "if" condition) and a consequent (the "then" condition). Association rules are derived by analyzing data to identify frequent if/then patterns, using criteria such as support and confidence to measure the significance of these relationships. Support indicates how frequently items appear in the transaction database, while confidence measures how often the if/then statements are true. Association rule mining can be seen as estimating the conditional probability P(consequent/antecedent) using transaction data. Unlike the asymptotic analysis of statistical estimators, the effectiveness of mined association rules depends on thresholds of support and confidence, which are determined by the user.

In target tracking, multiple sensors are typically employed, and several targets may be moving in a complex environment. To track these targets, three types of associations need to be analyzed: measurement (observation) data association, target state association, and target-to-measurement association. To ensure the tracking system works correctly, the most likely measurement of a potential target location is used to update the target's state estimator. The probability that a given measurement is correct is determined by a distance function that compares the predicted state to the measured state. Kalman filtering, a time-varying recursive estimator, is well-suited for real-time data stream processing. Also known as linear quadratic estimation or trajectory optimization, Kalman filtering uses a sequence of noisy measurements over time to estimate unknown states (variables) more accurately than relying on a single measurement. State error covariance and forecast operators are treated as state associations, both stochastically and deterministically. Similarly, measurement error covariance and observation operators are treated as measurement associations in both stochastic and deterministic terms. Kalman filtering, in essence, combines data association with the rapid processing of big data.

In social media, the relationships among social individuals and the social network itself form a social network. Similarly, in natural language or mental models, concepts and their relationships create a semantic network. These social and conceptual relations are often represented by links in networks, sometimes referred to as linked data. In nature, a network is a topological model, where links represent adjacency or nearness—essentially an association. As mentioned in Section 2.2, big data is modeled at various levels of mathematical spaces, typically metric and topological spaces. A network is one form of topological space, and network links represent qualitative nearness within these spaces. Ultimately, associations in big data can be understood as relations in set theory. When metrics are applied, associations are formalized as advanced relations. For example, statistical correlations and geometric relations are associations that are assigned probability and geometric metrics, respectively.

3.3. High-Dimensional Analysis

Big data is characterized by a high degree of variety. In mathematical terms, the dimension of a space or object is informally defined as the minimum number of coordinates needed to identify any point within it. In the context of vector spaces, dimension refers to the number of vectors in a basis for that space, or equivalently, the number of coordinates required to represent any vector. This dimensionality is an inherent property of the object itself, not dependent on the surrounding space in which it exists.

In practical terms, dimensions can be thought of as the different viewpoints from which the real world is perceived. Classical physics describes the world using three spatial dimensions—up/down, left/right, and forward/backward—originating from any given point. While classical mechanics treats time symmetrically, thermodynamics assigns a direction to time, as described by the second law of thermodynamics: in an isolated system, entropy tends to increase, and the system naturally progresses toward a state of thermodynamic equilibrium with maximum entropy.

In statistics and econometrics, multidimensional analysis involves examining samples made up of several random variables. High-dimensional statistics focuses on datasets where the number of variables (dimensions) exceeds those typically seen in classical multivariate analysis. In many cases, the dimensionality of data vectors can be even greater than the number of observations. This often leads to the "curse of dimensionality," where increasing the number of dimensions causes the data to become sparse in the space. Traditional algorithms (Marimont and Shapiro, 1979) struggle with this sparsity, which can reduce statistical significance and increase the apparent dissimilarity between data points. This issue is specific to high-dimensional spaces and does not occur in lower-dimensional contexts.

To address these challenges while preserving as much of the original variable variability as possible, dimension reduction techniques are used. These methods aim to reduce the number of random variables by identifying a representative subset, referred to as a subspace, based on distance or variance metrics. Dimension reduction techniques include both linear and non-linear transformations. For example, principal component analysis (PCA) is a widely used linear method. Non-linear approaches include Isomap, which preserves global geodesic distances, and locally linear embedding (LLE), which maintains local Euclidean distances.

Beyond standard Euclidean distance, other distance measures used in statistics include Mahalanobis distance, Kullback-Leibler divergence, and Wasserstein distance. Dimension reduction is also useful for simplifying features of entities and structures within graphs.

In compressive sensing, sparsity is incorporated into the model through a regularization term added to the cost function. This term is typically the count of non-zero values, known as the zero norm or L0 norm. However, because L0 is not computationally convenient for optimization, it is often approximated by the L1 norm to enable convex optimization, facilitating more efficient numerical computation.

3.4. Deep Analysis

Today, the vast volume of data being generated provides sufficient resources for training complex artificial neural networks. At the same time, advancements in high-performance computing—such as multi-core CPUs, GPUs, and FPGAs—have significantly reduced the time required to train these networks. In this context, traditional artificial neural networks have been enhanced by incorporating hidden layers of latent variables, giving rise to what is known as *deep learning*, in contrast to *shallow learning*. Similarly, human understanding of the real world deepens with accumulated experience. Deep analysis holds great potential for uncovering the complex structural characteristics of big data. It can reveal unobservable variables, hidden parameters, hierarchical structures, local correlations, and intricate distributions of random variables. Common models used in deep analysis include latent Dirichlet allocation, deep Boltzmann machines, deep belief networks, hidden Markov models, and Gaussian mixture models.

Deep learning systems are built using multi-layered artificial neural networks (LeCun, Bengio, and Hinton, 2015). These networks consist of numerous non-linear processing units, or neurons, often using activation functions like the sigmoid function. Each layer's neurons are treated as multiple variables. Deep analysis operates as either a deterministic or stochastic transformation function that maps inputs to outputs. Numerical approximation techniques, data-fitting methods, and maximum likelihood estimation are all potential theoretical foundations for constructing multi-layered neural networks. With their combination of multiple layers, variables, and non-linear activation functions, these networks are highly effective at modeling complex data. However, no universal approximation theory currently exists for deep learning models capable of representing all complex functions. Moreover, comparing the performance of different architectures is difficult in practice, especially when they are not evaluated on the same datasets.

In multivariate, multi-layer neural networks—whether fully connected or sparsely connected—a large number of parameters need to be estimated. These include the number of layers, the number of units per layer, and the weights and thresholds of each activation function. When trying to find the best solution for fitting the data or estimating statistical models, issues such as ill-posed problems and reduced computational performance can arise, often requiring substantial computing resources. To address these challenges and prevent overfitting, regularization techniques are employed. Additionally, various numerical optimization strategies—such as pre-training, concave-to-convex approximation, and computing gradients over multiple training datasets simultaneously—have been developed to improve computational efficiency.

3.5. Precision Analysis

In numerical analysis, accuracy refers to how close a calculated value is to the true value, while precision refers to the level of detail or resolution in the representation, often indicated by the number of decimal or binary digits used. In statistics, the terms bias and variability are preferred over accuracy and precision. Bias measures the degree of inaccuracy, and variability reflects the degree of imprecision. In practical terms, trueness describes how close the average of multiple measurements is to the actual value, while precision indicates how close the measurements are to each other. Ideally, a measurement system should be both accurate and precise—producing results that are both close to the true value and tightly grouped together. A system may be accurate but not precise, precise but not accurate, neither, or both. When systematic error is present, increasing the sample size improves precision but not accuracy. On the other hand, removing systematic error enhances accuracy but does not affect precision.

Precision analysis evaluates data quality and reliability from the standpoint of data utility and truthfulness. Drawing an analogy to linguistics, veracity in big data can be compared to semantics (meaning), while utility aligns with pragmatics (use or application). More broadly, the uncertainty inherent in the human–machine–environment (or earth) system, as shown in Figure 2 (Shu et al. 2003), is relevant to big data. Data is often collected from interactions among humans, computers, and environmental systems. User preferences are increasingly recognized as a distinct type of data. These preferences may be required for building comprehensive models and optimization frameworks in big data analytics.

Precision analysis is commonly applied in fields such as marketing, medicine, and agriculture—referred to as precision marketing, precision medicine, and precision agriculture, respectively. In modeling user preferences or requirements, individuals are differentiated, and sometimes connected within a social network to enhance understanding.

In marketing, personal preferences are often gathered directly from users. Personalized marketing—also called personalization or one-to-one marketing—focuses on tailoring marketing strategies for individual consumers. The goal is to offer unique products or services to each person based on their preferences. In 2015, U.S. President Barack Obama announced funding for the national "Precision Medicine Initiative" (Lauran 2015). This initiative aimed to shift healthcare away from generic treatments by customizing medical care based on individual characteristics. Such personalized healthcare takes into account a person's genetic makeup, environmental exposures, and lifestyle factors.

Similarly, precision agriculture was defined in a 1997 report by the National Research Council as a management approach that uses information technology to integrate data from multiple sources for informed crop production decisions. This involves observing and modeling variations between and within fields to manage crops more effectively. In the 21st century, precision agriculture seeks to optimize field-level management by:

1. Enhancing crop science through better alignment of farming practices with crop needs (e.g., targeted fertilizer application),

2. Promoting environmental sustainability by minimizing the ecological impact of farming (e.g., reducing nitrogen runoff), and
3. Improving economic outcomes through more efficient practices (e.g., optimized input management such as fertilizers and water use).

3.6. Divide-and-Conquer Analysis

Divide-and-conquer is a fundamental computational approach designed to improve the efficiency of problem-solving and the speed of big data processing. In this method, a problem is recursively divided into smaller sub-problems during the divide phase, until the sub-problems become simple enough to be solved directly during the conquer phase. Once these smaller problems are solved, their solutions are combined to address the original problem as a whole. From this perspective, distributed computing—including cloud computing and distributed intelligence—can be viewed as applying divide-and-conquer across space, while parallel computing—such as multi-core and cluster computing—applies it across time. Stream processing and real-time computing utilize divide-and-conquer principles to manage unstructured data and time-sensitive tasks. Cloud and distributed intelligence computing also employ this approach through the lens of virtualized resources and agent-based models of cognition.

In high-performance parallel computing on shared-memory multiprocessor systems, parallel algorithms are employed, while distributed systems use distributed algorithms to manage coordination across multiple nodes. Divide-and-conquer analysis is naturally suited for multiprocessor machines, where distinct sub-problems can be handled by different processors, exchanging data via message passing. Parallel computing enables simultaneous processing of multiple segments of a problem, breaking it into independent components that are solved concurrently. These processing elements may include multi-core processors within a single computer or networked computers across a cluster. Due to the limitations of frequency scaling, multi-core systems have become prevalent, making parallel algorithms widely used. A multi-core processor integrates several processing units (cores) onto one chip. In such systems, memory can be either shared—accessible to all processors in a single address space—or distributed—where each processor has its own local memory space.

Parallel computing is based on performing many calculations at once, operating under the principle that large problems can be broken down into smaller ones, which can then be solved simultaneously. It includes several levels: bit-level, instruction-level, data-level, and task-level parallelism. Task parallelism involves decomposing a task into sub-tasks and assigning each to a processor, which then executes them simultaneously, often in coordination. Programming interfaces such as OpenMP support shared-memory parallelism, while Message Passing Interface (MPI) is commonly used for message-passing systems. *MapReduce* is a popular parallel computing paradigm for cluster environments. It processes data structured as (key, value) pairs. Each map operation runs independently in parallel, and all outputs with the same key are processed together by a reducer. While MapReduce is suitable for simple or one-time tasks, it lacks the structured data schemas and fast-access capabilities of relational databases (e.g., B-trees, hash partitioning).

Real-time computing emphasizes meeting deadlines, handling time constraints, and ensuring the timeliness of data analysis. A real-time database differs from traditional databases in that it must manage continuously changing data in real-time. Streaming data, often unstructured and of potentially infinite size, is typically read-only and processed in real-time. Compared to archived data, stream data is transient and processed using time-windowed techniques such as segmentation, incremental updates, or Kalman filtering, which rely on sampling rates and the temporal correlation of data windows.

In cluster computing, multiple standalone computers, or nodes, are connected via a local network using similar hardware. These nodes collaborate closely and function collectively like a single system. In contrast, grid computing spans geographically and administratively distributed systems with heterogeneous hardware. Grid computing is one of the most distributed forms of parallel computing, using internet-connected systems to collaboratively solve problems.

In distributed computing, a task is divided into multiple subtasks, each handled by one or more computers. These computers (or nodes) communicate through message passing and typically maintain separate memory spaces. A distributed database system consists of loosely connected sites that do not share physical components, yet offer users a seamless experience as if interacting with a single logical database. Moreover, distributed systems maintain *transaction transparency*, ensuring data integrity across all databases during operations.

Cloud computing—also known as on-demand computing—provides scalable access to shared computing resources via the internet. It offers tools and infrastructure to develop data- and computation-intensive parallel applications more affordably than traditional techniques. The key technology behind cloud computing is *virtualization*, which allows one physical machine to be split into several virtual machines, each capable of performing computing tasks independently. Cloud computing builds on service-oriented architecture (SOA), which lets users break down problems into modular services that can be integrated into comprehensive solutions. Cloud services are offered in a layered model: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). These services can be deployed in private, community, or public cloud environments.

In distributed intelligence computing, the interaction among humans, machines, and the environment can be modeled as a system of agents. According to Herbert Simon's theory of bounded rationality (1982), decision-making is limited by available information, computational complexity, cognitive constraints, and time. A *rational agent* is one that has clear preferences, models uncertainty through expected values, and always chooses the action that maximizes its expected utility from all feasible options. Rational agents may be human, machines, or software. An *intelligent agent* is an autonomous system that perceives its environment via sensors, acts through actuators, and strives to achieve specific goals. These agents can also learn and apply knowledge. Marvin Minsky's *Society of Mind* theory (1986) conceptualizes human intelligence as the outcome of interactions among many simpler agents, forming a model that aligns with distributed intelligence systems.

4. Geographical Big Data Analysis

The six core techniques used in general big data analytics are also applicable to geographical big data. However, what distinguishes geographical big data is its inherent spatiotemporal associations—such as geometric relationships, statistical correlations, and semantic connections. Spatiotemporal data analysis can broadly be divided into three categories: geometric measurement analysis, human geography data analysis, and physical geography analysis. These categories contribute to broader concepts like the digital earth, smart earth, and earth simulation systems.

With advances in computer and communication technologies, the interaction between humans, machines, and the environment is increasingly recorded in digital formats. Vast amounts of geographical data—from sources like earth observation satellites and mobile internet—are collected both collectively and individually. Often, geographical big data encompasses entire datasets regardless of domain or sampling methods. As a result, ensemble data analysis is widely employed in this field.

Spatiotemporal relationships fall into three main types: geometric, statistical, and semantic. In mathematical terms, space and time are often represented as geometric quantities. For example, in surveying, least squares estimation is used to adjust measurements of angles, distances, and elevations—geometric features. Time is scaled based on object motion, such as celestial movements or atomic clock frequencies. Modern surveying technologies enable the collection of extensive georeferenced data related to both physical and human geography. In digital earth systems, such data capture topographic and geographic phenomena, with geometric relationship analysis playing a key role in big data processing.

The widespread use of mobile devices and internet connectivity allows for easy tracking of mobile object trajectories, typically represented as sequences of space-time coordinates (x, y, t). These trajectories can help analyze spatial behaviors and group or individual movements. Time geography and spatial cognition provide foundational theories for understanding human geographical data. In time geography, movement is represented geometrically using concepts like prisms (Hägerstrand, 1970). This model has evolved to include probabilistic and multi-scale trajectory representations (Miller, 1991). In spatial cognition, mental maps are made up of landmarks (nodes), paths, and regions, with an emphasis on the prominence of specific features (Golledge & Stimson, 1997). In AI, general problem-solving is often framed as wayfinding, where states (initial, intermediate, final) are mapped as nodes and transitions between them as paths (Newell, Shaw, & Simon, 1959). As highlighted in Section 2.1, exploring spatial and spatiotemporal relationships is central to geographical big data analysis. For example, remotely sensed images can be viewed as samples of vector random fields, with each pixel and spectral band treated as random variables, leading to high-dimensional analyses of multi-spectral and high-resolution imagery. Similarly, crowdsourced data represents a type of data with unknown sampling characteristics. In smart earth systems, spatial cognition and spatiotemporal statistics offer valuable theoretical frameworks for analysis.

On the Earth's surface, physical phenomena change across both space and time. These changes in mass and energy follow conservation and transformation laws, typically modeled by partial differential equations (PDEs). In land surface or earth system modeling, trajectories can be described by nonlinear functions of space and time. Numerical solutions to these PDEs produce sequences of changing spatial-temporal states. For example, dynamic geographical systems can be modeled using cellular automata (CA), which operate over two-dimensional grids with a large number of states and neighborhood interactions. Each CA consists of a grid of cells, where each cell can be in a finite number of states. A neighborhood is defined for each cell, and future states are calculated based on current states and those of neighboring cells using fixed rules or mathematical functions. As time advances in steps, the states are updated accordingly.

Large-scale data is gathered through various sensors mounted on satellites, weather stations, ships, buoys, and other platforms. The corresponding models for land surface systems involve numerous PDEs and physical variables. To efficiently solve such complex models, both model and dimensional reduction techniques are required. Even minor initial disturbances in nonlinear PDEs can lead to butterfly effects in forecasting, necessitating multi-resolution analysis due to the multi-scale nature of both observations and processes. Sub-grid computing is often necessary to handle localized subprocesses in numerical simulations.

Data assimilation plays a critical role in integrating observations into the forecast states of numerical models. From a Bayesian perspective, this process involves recursive estimation based on Bayes' theorem. A typical cost function in data assimilation combines the weighted squared differences between model forecasts and observations, aiming to minimize this cost for better accuracy. The goal is to produce high-resolution, high-precision simulation outputs by merging data from diverse observation sources with earth system models.

5. Conclusions

With the rapid advancement of computer and communication technologies, the interactions within the human-machine-environment system are now increasingly captured through digital sensor networks deployed in space, air, and on the ground. Building upon the widely recognized 4V characteristics of big data—volume, variety, velocity, and veracity—this paper has proposed six key techniques for big data analytics.

In general terms, ensemble analysis and association analysis are suited to addressing the volume aspect of big data. High-dimensional analysis responds to the variety of data types and sources. Deep analysis and precision analysis are targeted at enhancing the veracity or trustworthiness of data. Divide-and-conquer analysis helps manage the velocity, or speed, of data processing. Underpinning these techniques are two fundamental theoretical challenges: the breakdown of the assumption of independent and identically distributed (i.i.d.) data, and the need to extend classical set theory for more complex data relations.

For geographical big data, we have discussed specific types of associations—geometric associations across space and time, statistical spatiotemporal correlations, and semantic space-time relationships. Additionally, we explored three representative forms of spatiotemporal data analysis: the adjustment of geometric measurements, the analysis of human spatial behaviors using trajectory data, and the data assimilation that integrates observational data with physical models.

While the six proposed techniques are broadly applicable to various forms of big data, spatiotemporal association analysis is uniquely significant for geographical data. Just as the four V's were proposed by the industrial community to describe big data characteristics, these six analytic techniques are derived from practical experience. However, it is important to note that these methods are neither mutually exclusive nor collectively exhaustive from a theoretical standpoint.

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The Physical Internet: A Paradigm Shift in Logistics and Supply Chain Management

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Abstract

The Physical Internet (PI) is a visionary concept that proposes a paradigm shift in how goods are transported, stored, and handled, inspired by the transformative impact of the Digital Internet on information exchange. This position paper introduces the Physical Internet and its foundational principles of modularity, standardization, open protocols, and hyperconnectivity. We first highlight the critical inefficiencies and fragmentation plaguing current logistics systems – from empty trucks and underutilized warehouses to excessive emissions – underscoring the unsustainability of the status quo. We then articulate how the PI (or π) offers a systemic solution: a globally hyperconnected logistics network in which products move in standardized, modular containers through open, interoperable networks as seamlessly as data packets through the digital internet. We argue that adopting the Physical Internet paradigm is not an optional innovation but a necessary evolution to achieve major gains in efficiency, sustainability, and resilience in supply chains. Key challenges – including the need for universal standards, collaborative business models, technological infrastructure, and supportive governance – are discussed, along with strategies to address them. Ultimately, we position the Physical Internet as a necessary transformation for global logistics, and we call for coordinated action in policy, research, and industry to bring this vision to reality.

Keywords: Physical internet, Logistics, Supply chain, Modularity, Standardization, Sustainability, Hyperconnectivity, Open protocols

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1. Introduction

Over the past few decades, global supply chains have grown in scale and complexity, exposing fundamental limitations of traditional logistics paradigms. Today's logistics networks are rife with inefficiencies and fragmentation, leading to economic waste, environmental harm, and reduced service levels. In fact, "the way physical goods are currently transported, handled, stored and supplied throughout the world is unsustainable economically, environmentally, and socially" (Montreuil, 2011a). Symptoms of this unsustainability are visible at every step of the supply chain – for example, a significant fraction of freight vehicles travel empty or only partially loaded, and distribution facilities often sit idle. One study notes that about 20% of heavy trucks in the United States and up to 30–40% in the EU are travelling empty at any time, wasting capacity and energy (Matusiewicz, 2020). Such under-utilization of assets, along with the lack of interoperability between proprietary logistics networks, contributes to excessive costs and greenhouse gas emissions. Clearly, incremental improvements to the current system will not suffice; a fundamental, systemic change is needed. Analogous to the revolution in information exchange triggered by the Digital Internet, researchers have suggested a similar paradigm shift in logistics – the Physical Internet (PI) – as a solution to the "global logistics sustainability grand challenge" (Van Deursen & Van Dijk, 2011; Zhong et al., 2017). The Physical Internet is inspired by the Digital Internet's approach to data transfer, aiming to create an open, interconnected network of logistics networks through which physical goods can move as seamlessly as information flows through the web. This paper introduces the Physical Internet concept and argues that it constitutes a necessary evolution in logistics and supply chain management. We outline the core principles of the PI, examine how it addresses key shortcomings of current logistics systems, and discuss the challenges and imperatives for making this vision a reality. The goal is to articulate a clear position: embracing the Physical Internet paradigm is crucial for the future efficiency, sustainability, and resilience of global supply chains, and it demands concerted action from industry, researchers, and policymakers.

2. Challenges in Current Logistics Systems

Modern logistics systems have achieved remarkable feats but still suffer from chronic inefficiencies and structural problems that limit their sustainability and effectiveness. We identify several key problems that the Physical Internet seeks to address:

•*Low Asset Utilization and Inefficiency*: Inefficiency is built into many freight operations today. Trucks, railcars, and containers often travel half-empty or even completely empty on return trips or re-positioning journeys. As noted, roughly a fifth of trucks on the road carry no load (empty backhauls), and many more run with unused space. Likewise, warehouses and distribution centers may be underutilized for significant periods, yet at other times they are overburdened by peak demand. This mismatch leads to excessive capacity buffers, higher costs, and unnecessary trips. The fragmented nature of supply chains – where each company runs its own dedicated logistics with little sharing – means that opportunities to consolidate loads or share infrastructure are often missed, leaving systemic capacity untapped and fuel wasted. The result is not only economic inefficiency but also avoidable environmental impact from wasted fuel and emissions.

•*Fragmentation and Lack of Interoperability*: The global movement of goods today is handled by a patchwork of proprietary networks and modes that often do not interconnect seamlessly. Different carriers, modal operators, and logistics service providers use their own standards and closed systems, creating silos in the flow of goods. There is no universal "routing" mechanism for freight as there is for data on the internet. Shipments frequently must hop between disparate networks via ad-hoc arrangements, incurring delays and costs. No coherent, unified physical network exists – instead, we have parallel networks that only partially overlap. "Current solutions rely on a combination of national, regional, and local networks with no common structure, resulting in a chaotic and ineffective transport model," as one analysis observes. This fragmentation leads to redundant routes, incompatible handling systems, and an inability to easily reroute or share capacity across networks. In sum, today's logistics resemble the pre-internet era of computing: disconnected and inefficient.

•*Environmental and Social Sustainability Challenges*: The transport sector is a major contributor to greenhouse gas emissions and pollution. Inefficient logistics magnify this problem – empty or half-empty runs mean more trips are needed per unit of goods delivered, directly translating to higher fuel consumption and emissions per shipment. Moreover, excessive congestion in freight hubs and urban areas, partly due to poorly coordinated deliveries, increases local air pollution and noise. Socially, the strain on truck drivers and logistics workers is significant in the current paradigm – for instance, drivers often endure long periods away from home to reposition equipment or chase loads due to network inefficiencies. The lack of a sustainable logistics model undermines efforts to improve working conditions and reduce the sector's carbon footprint.

•*Lack of Resilience*: Fragmented and inflexible supply chain networks are also more brittle in the face of disruptions. When each company's logistics network is optimized in isolation, it is harder to recover from major events (natural disasters, pandemics, etc.) because capacity cannot easily be shared or rerouted across the broader system. The COVID-19 pandemic, for example, revealed how rigid supply lines struggled to adapt to sudden shifts in demand and supply, partly because interchange of freight between different carriers and modes was limited. A more open and integrated network of logistics infrastructure could improve resilience by allowing shipments to dynamically find alternate paths – a concept at the heart of the Physical Internet vision.

These systemic issues highlight why a fundamentally new approach to logistics is needed. The Physical Internet directly targets these problems by proposing a paradigm of openness, standardization, and connectivity that would enable drastic improvements in asset utilization, interoperability, sustainability, and adaptability.

The Physical Internet Concept and Principles

The Physical Internet (PI) is a bold vision for a globally integrated logistics network modeled after the Digital Internet's design and success. The term was first coined by Benoît Montreuil (2011) as a response to the glaring inefficiencies in worldwide logistics and has since evolved into a growing field of research and experimentation (Sohrabi & Montreuil, 2011). The Physical Internet's design principles – modular encapsulation, standard interfaces/protocols, and global hyperconnectivity under open governance – collectively enable a logistics system where any standardized load unit can move through any part of the network, autonomously guided by global protocols to reach its destination. The vision is often summed up by the phrase: an open global logistics system founded on physical, digital, and operational interconnectivity. By fundamentally reconceiving logistics as a scalable, plug-and-play network, the PI promises to unlock unprecedented levels of efficiency and flexibility.

1.1. PI foundational principles

At its core, the Physical Internet envisions that moving physical goods could be as simple, efficient, and transparent as moving data across the internet. To achieve this, the PI paradigm is built on several foundational principles.

1.1.1. Principles of Encapsulation and Modularity

Just as data on the Internet is broken into standard packets, in the Physical Internet products are encapsulated in standardized, modular containers (sometimes dubbed "π-containers"). These containers come in predefined sizes that align to modular dimensions, enabling them to be efficiently combined like building blocks. For example, a set of smaller PI containers could fit together perfectly to fill a standard 20- or 40-foot ISO container, much like pieces of a Tetris puzzle. Each PI container is secure, smart (embedded with tracking and sensing capabilities), and labeled with the necessary information for handling and routing. Modularity allows heterogeneous goods from different senders to be consolidated, moved, and stored together seamlessly, maximizing load factors. Ultimately, encapsulation isolates the contents from the handling processes, meaning that regardless of what goods are inside, the logistics system treats the container as a standardized unit. This is a radical departure from today's bespoke handling of pallets and packages, and it lays the groundwork for universal interoperability.

1.1.2. Principles of Standardized Interfaces and Open Protocols

In the Digital Internet, any device can communicate with any other because of common protocols (like TCP/IP) and addressing systems. Similarly, the Physical Internet relies on standard interfaces and communication protocols that allow all logistics nodes (trucking companies, rail operators, warehouses, ports, etc.) to work together using a shared "language." This includes physical interfaces – such as container handling mechanisms and load unit dimensions – as well as digital interfaces for data exchange (shipment manifests, routing instructions, tracking updates). All PI participants agree to follow a set of open standards and protocols for how containers are labeled, routed, handled, stored, and transferred. Because these protocols are open and globally standardized, a PI container can travel through any compliant node or network, just as an email packet can travel through any internet router. For example, a universal routing protocol would enable a shipment to be automatically directed through a series of PI hubs from origin to destination, regardless of which companies or countries are involved, based on real-time network conditions and efficiency criteria. Standardization in the PI thus breaks down the silos between logistic providers, enabling true interoperability. Every node becomes "plug-and-play" in the worldwide logistics web, analogous to how any brand of computer can connect to the internet if it adheres to the internet protocols.

1.1.3. Principle of Hyperconnectivity (Network of Networks)

The Physical Internet creates a single, vast logistics web by connecting currently isolated networks into an open, universal system. In essence, it is a "network of logistics networks", or a logistics web of hubs and routes spanning the globe. This hyperconnectivity means that a shipment is no longer restricted to a single carrier's network or a single mode of transport – it can dynamically traverse an optimal path that may involve multiple carriers, transport modes, and transfer hubs, all coordinated through the PI protocols. Pan describes this as a hyperconnected logistics infrastructure comprising certified open hubs, open transportation lanes, and digital platforms that work together to route and reroute containers as needed (Pan et al., 2017). The connectivity is ubiquitous: every participating logistics facility (a warehouse, cross-dock, port, or even a retail store), and every transport vehicle or vessel, becomes a node that can link with others on the fly. Because of this network-of-networks approach, capacity can be shared across the entire system. A modular container might start its journey on one company's truck, move to a public PI warehouse for consolidation, then continue on a train or ship operated by another company, and finally be delivered by a local courier – all orchestrated by standardized PI protocols. This open transit is analogous to how a data packet on the internet might hop across networks of different telecom providers to reach its destination. Hyperconnectivity breeds agility: the system can automatically find alternate routes when disruptions occur, and it can optimize flows continuously at a global scale, something impossible in the current fragmented regime.

1.1.4. Collaborative Governance and Universal Accessibility

Underpinning the Physical Internet vision is the idea that the logistics network should be open to all who adhere to the standards, much like the Internet is generally open and neutral. This requires a form of collaborative governance – stakeholders must agree on rules and standards (through international organizations or industry consortia) and abide by them. No single entity "owns" the Physical Internet; instead, many participants (shippers, carriers, infrastructure operators, technology providers, governments) collectively make it work, reaping mutual benefits. Universal accessibility means any company, whether a small manufacturer or a large 3PL (third-party logistics provider), can send and receive goods via the PI just by using PI-compatible containers and protocols. In practice, this principle might manifest as open logistics hubs where loads from any shipper can be dropped off or picked up, very much like how one can connect to any ISP and reach the same internet. It also implies transparent pricing and service mechanisms (perhaps analogous to how bandwidth or cloud storage is purchased today) so that using the shared network is straightforward. Crucially, a governance framework would ensure fair play, data security, and conflict resolution in the system. While governance is not a "technology" per se, it is a foundational aspect needed to maintain trust and widespread adoption of PI. The success of the Digital Internet was not only due to technology but also due to open governance bodies (like IETF, ICANN) that steered protocol development and ensured no one company controlled the network – a lesson that the Physical Internet community is actively applying.

3. Potential Benefits of the Physical Internet

Adopting the Physical Internet paradigm would constitute a systemic transformation of supply chains, with far-reaching benefits. We highlight the most salient advantages that make the PI so attractive as the future of logistics:

•*Dramatically Improved Efficiency*: Efficiency gains are the most immediate promise of the Physical Internet. By standardizing containers and opening up networks, the PI would enable much higher utilization of transport capacity and infrastructure. Empty trips and idle storage space could be minimized or virtually eliminated through global load consolidation. For example, instead of half-empty trucks from different companies passing each other on the highway, in a PI network those shipments would be combined into one vehicle through consolidation hubs, with standardized containers making it a frictionless process. One vision of the PI future is that goods are almost constantly in motion from origin to destination – when a container arrives at a PI hub, it is quickly transferred to the next vehicle heading toward its destination, similar to how data packets are instantly routed at Internet routers. This would slash waiting times and storage needs in transit. Studies and pilot projects have suggested that widespread PI adoption could reduce logistics costs and inefficiencies by 20-50% in many cases, thanks to better asset sharing. In monetary terms, this means huge savings for businesses and economies. From an operational standpoint, faster and more reliable transit (through optimized routing) can also improve customer service levels (shorter delivery times, fewer stockouts). By pooling resources, even small shippers gain access to a vast, efficient network without having to build it themselves. Overall, the logistics sector's productivity would be boosted significantly by the Physical Internet model.

•*Environmental Sustainability*: The Physical Internet is heralded as a key enabler of green logistics. By increasing load factors and eliminating redundant moves, the PI would cut total freight mileage and energy usage per unit of freight. Fewer trucks on the road (because of higher consolidation) and better routing (avoiding unnecessary detours or empty repositioning) translate directly into lower fuel consumption and emissions. One analysis emphasizes that eliminating empty movements is critical to reducing road transport inefficiencies and their environmental impact. Additionally, the PI's connectivity facilitates shifting freight to more energy-efficient modes like rail or water for long hauls whenever possible (often referred to as synchromodality or intermodal optimization). In a PI network, a container might seamlessly switch from a truck to a train mid-journey if that reduces emissions and cost, with protocols ensuring the transfer is smooth. This flexibility can increase the share of rail and other low-carbon modes in freight transport. The expected outcome is a substantial reduction in carbon footprint of logistics – a crucial contribution towards global climate goals and corporate sustainability targets. Moreover, by alleviating congestion (fewer vehicles carrying more consolidated loads) the PI can reduce local air pollution and noise in urban delivery environments. In summary, the Physical Internet could enable freight transport to grow in volume while dramatically shrinking its environmental impact, decoupling logistics activity from carbon emissions – a cornerstone of sustainable development.

•*Greater Supply Chain Resilience*: A hyperconnected logistics network is inherently more resilient to disruptions. In the PI, if a particular route, hub, or carrier becomes unavailable (due to disasters, strikes, etc.), containers can be rerouted quickly via alternate paths, much as internet data finds new routes when circuits fail. This dynamic routing capability – supported by real-time digital information on network conditions – means the system can adapt on-the-fly to shocks. For companies, this flexibility translates to less risk of supply chain breakdowns. For example, if a major port is closed, a PI-enabled network could divert incoming containers to other ports and then overland via different carriers with relatively minimal delay, since the protocols and container standards are uniform everywhere. In today's logistics, such rerouting is ad-hoc and often impossible if pre-arranged contracts or mode-specific packaging prevent easy transfer. The PI's openness and standardization remove those barriers, building resilience through redundancy and agility. Additionally, the shared capacity model of the Physical Internet means surges in demand or capacity crunches in one region can be mitigated by drawing resources from the wider network. For instance, during an emergency, needed supplies could rapidly move through any available channels (military, commercial, etc.) as long as they are PI-compliant, bypassing the slower traditional hierarchies. The end result is a supply chain infrastructure much better equipped to handle uncertainty and ensure continuity of supply.

•*Innovation and New Business Opportunities*: By rewriting the rules of logistics, the Physical Internet opens the door for innovative services and business models. We can expect the rise of logistics service platforms that operate much like Internet Service Providers, brokering transport and storage services across the open network. Companies could specialize as PI-hub operators, PI-container pooling providers, or data-driven route optimization services. The barrier to entry for offering logistics services may be lowered, since an entrepreneur with a single warehouse can plug into the global network and attract customers far and wide, provided they meet the standards. This could spur competition and creativity in the logistics sector, leading to better services and lower prices. Furthermore, ancillary technologies such as IoT sensors, blockchain for security, AI for dynamic routing, and automation in handling will find ready applications in the PI framework – accelerating their development and deployment. The modular containerization in PI might also encourage innovations in product packaging and unitization, and facilitate circular economy practices (e.g., reusable containers, efficient reverse logistics for recycling). In sum, the Physical Internet could be a platform for logistics innovation much as the digital Internet was a platform for countless digital innovations.

•*Social and Labor Benefits*: An often-overlooked aspect is how the Physical Internet might improve the human element of logistics. Consider trucking: today, a long-haul trucker's life is stressful, with long unscheduled trips and months on the road. In a PI system, because freight can be relayed via hubs, drivers could operate on shorter regional loops and be home regularly. A driver might take a container from a local facility to a nearby hub and hand off the load, instead of driving it across the country. Then they pick up another load for the return leg back to their home city. This relay model, enabled by PI infrastructure, can greatly improve driver quality of life and safety (less fatigue), helping address driver shortages and reducing accident rates. More broadly, if logistics costs drop and service levels improve, consumers and businesses benefit through lower prices and more reliable product availability. By reducing environmental externalities, public health improves. These social gains, while indirect, are part of the holistic value proposition of moving to a Physical Internet paradigm.

It should be emphasized that these benefits are interrelated and compounding – efficiency gains drive cost savings and sustainability gains; resilience ensures those efficiency gains are reliable under stress; new business opportunities further drive efficiency and service improvements, and so on. Various pilot projects and simulations in Europe and North America have already demonstrated portions of these benefits (for instance, sharing warehouse capacity among firms, or using collaborative transport exchanges to cut empty miles). The Physical Internet, as a comprehensive framework, bundles these improvements together on a global scale. As a recent analysis succinctly put it, the Physical Internet promises "increased efficiency and, consequently, huge financial savings and environmental and social benefits" (Matusiewicz, 2020). However, realizing these gains is contingent on overcoming significant challenges. The next section examines the main hurdles on the path to a full-fledged Physical Internet and how they might be addressed.

4. Challenges to PI Adoption and Implementation

Transforming today's entrenched logistics practices into the Physical Internet paradigm is an ambitious undertaking. There are formidable challenges and barriers that must be acknowledged and addressed:

Standardization and Technological Readiness: The backbone of the PI concept is global standardization of containers, interfaces, and protocols. Achieving consensus on these standards is a non-trivial challenge. It requires broad agreement across industries and countries on issues like container dimensions (beyond the existing ISO containers), handling equipment designs, communication protocols, and data formats. Bodies such as the International Standards Organization (ISO) and industry consortiums (like ALICE in Europe) are working on proposals, but getting everyone to adopt them takes time and persuasion. Moreover, certain enabling technologies need to mature and be widely deployed. Real-time digital connectivity is essential – every PI container and node should ideally be IoT-enabled, providing live tracking and status data. Platforms for digital freight matching and system-wide optimization must be developed to orchestrate the PI's flow of goods. While the technology (sensors, ICT systems, optimization algorithms, etc.) is largely available, it has to be scaled and integrated into a coherent platform. Upgrading legacy logistics infrastructure to PI-compatible systems (for example, equipping old warehouses with automated container handling or updating software to interface with PI exchanges) could be capital-intensive. Until robust standards and technologies are in place, many companies will be hesitant to commit to the PI approach.

Industry Collaboration and Trust: Perhaps the biggest hurdle is the cultural and business paradigm shift required for the Physical Internet. Companies that are used to operating their own dedicated logistics networks will need to embrace a model of open collaboration and asset sharing, even with competitors. This is a fundamental change in mindset. Understandably, there is reluctance: firms worry about losing control, exposing proprietary data, or diluting their service differentiation. A recent survey indicated a clear "reluctance toward sharing information and connecting to a common platform" among stakeholders. Building trust is critical – participants must be confident that sharing capacity or data will be mutually beneficial and handled fairly. Issues of data security and commercial confidentiality need robust solutions (for example, using secure data exchange platforms or blockchain to ensure information is only used as intended). There is also a first-mover problem: the benefits of PI materialize at scale, so individual companies may be unwilling to be the first to invest in PI capabilities unless they see others doing likewise. Overcoming this impasse may require neutral facilitators or initial government incentives to encourage collaboration. Industry alliances and pilot programs can demonstrate the benefits in a smaller setting to build confidence. Essentially, the PI requires a cooperative ecosystem instead of the purely competitive landscape we have now – fostering this will take time, leadership, and perhaps new business models that reward sharing.

Governance, Policy, and Legal Frameworks: Because the Physical Internet envisions a highly interconnected, border-spanning system, governance and regulatory alignment become very important. Who will set the rules of this new logistics web? There is a need for international governance structures or agreements to manage standards, certifications (for PI-compliant hubs and services), liability issues, and dispute resolution. For example, if a shipment is damaged after passing through five different carriers in a PI network, how is liability determined and regulated? Current laws and contracts are not designed for such fluid handoffs. Policymakers will need to update regulations to facilitate open sharing – for instance, anti-trust regulations may need clarity so that competitors can cooperatively utilize capacity without legal barriers. On the policy side, governments can play a positive role by incentivizing PI adoption – investing in physical infrastructure upgrades (like open hubs and intermodal terminals), supporting R&D for PI technologies, and using procurement policies to favor PI-based services (thus providing early demand). The European Union has been proactive in this regard: it established the ALICE (Alliance for Logistics Innovation through Collaboration in Europe) technology platform in 2013 specifically to advance the Physical Internet, and funded a number of Horizon 2020 projects exploring PI components. Such public-sector leadership helps create a roadmap for adoption. Globally, alignment between major trading blocs on standards will be necessary – coordination through bodies like the UN or World Trade Organization could eventually come into play to ensure the PI doesn't splinter into regional internets. In summary, governance and policy frameworks must evolve in tandem with technology to enable a truly open global logistics system.

Infrastructure and Investment Needs: The vision of a hyperconnected logistics network will not materialize without targeted investments in infrastructure. While PI leverages a lot of existing infrastructure (e.g., roads, ports, warehouses), certain new elements are needed. These include PI hubs in strategic locations – effectively next-generation logistics centers capable of high-speed handling of modular containers and cross-docking between modes. Many existing facilities might be retrofitted, but new designs optimized for PI (automated container sorting, etc.) could be required in some cases. Container pooling systems will be needed to manage fleets of the new modular boxes so that they circulate efficiently. Transport equipment (trailers, railcars, ships) might need modifications or modular attachments to securely carry the PI containers if they differ from current sizes. All this represents substantial capital expenditure. The question of who pays and who owns the infrastructure is important. If the burden falls entirely on private companies, progress may be slow and uneven. Public-private partnerships could be a solution, especially for backbone infrastructure like major hubs or IT platforms that have a strong public interest component (similar to how highway or communication infrastructures are often co-developed by government). The investment case for PI infrastructure rests on long-term gains – making sure stakeholders can finance the transition in the short-term is a challenge. However, one can argue that the cost of inaction – continued inefficiency and unsustainability – is higher in the long run. Articulating this economic case convincingly will help mobilize the necessary investments.

Interim Transition and Network Effects: The Physical Internet cannot be implemented overnight; there will be a transition period where the old and new paradigms co-exist. During this phase, there is a risk of inefficient fragmentation if there are multiple competing standards or only partial adoption. Early adopters might not realize full benefits if most others remain on legacy systems. This raises the classic issue of network effects: the value of joining the PI increases as more players join. Thus, coordination of the rollout is important. It may be beneficial to start with regional pilot networks – say, a cluster of companies in one country agree to adopt PI standards among themselves and demonstrate the concept at a smaller scale. As these pilots show success, they can be linked together, gradually expanding the network. Another transitional challenge is ensuring backward compatibility – i.e., PI-enabled systems must still interface with traditional logistics for those not yet on board. This might mean dual labelling of freight (both PI routing code and the old system) or hybrid operations at hubs. Managing this complexity requires careful planning and likely the guidance of standard-setting organizations. Patience is warranted, as building the Physical Internet is a long-term endeavor; Montreuil and others have estimated timelines of several decades for full realization. The key is to avoid disillusionment during the early stages: consistent support and iterative improvements will be needed, even if initial implementations are modest.

Despite these challenges, none appear insurmountable. Historical precedent in the digital realm is encouraging – the development of the Internet itself faced technical, political, and competitive hurdles, yet the advantages of connectivity eventually won out. Similarly, the compelling benefits of the Physical Internet provide strong motivation to solve these challenges. Overcoming them will require a combination of collaborative innovation, enlightened policy, and perhaps most importantly a shared vision among stakeholders that the old ways of logistics must give way to something fundamentally better. In the next section, we reinforce why moving toward the Physical Internet is not just an intriguing idea, but an imperative for the logistics sector, and outline how various stakeholders should approach this transformation.

5. The Physical Internet: From Vision to Necessity

We contend that the Physical Internet should be viewed as a necessary evolution for logistics and supply chain management, rather than merely one option among many. Several converging factors underline the urgency of the PI vision. Firstly, the sustainability imperative can no longer be ignored. Transport emissions continue to rise, and logistics inefficiency is a big part of the problem. Achieving global climate targets (such as those in the Paris Agreement) and mitigating environmental damage demands significant improvements in freight efficiency and a shift to lower-carbon operations. The incremental tweaks offered by conventional approaches (e.g. slightly more efficient engines, better driver training, etc.) while helpful, will not deliver the step-change needed. The Physical Internet, by fundamentally redesigning how we move goods, offers an *order-of-magnitude improvement* potential in resource utilization and emissions reduction (Montreuil, 2011b). It aligns directly with the push for a circular, sustainable economy. In policy circles, there is growing recognition that without concepts like the PI, sustainable logistics at scale may remain out of reach.

The explosive growth of e-commerce and on-demand logistics is straining existing systems. Consumers and businesses now expect fast, flexible deliveries, but our current fragmented networks struggle to meet these expectations efficiently. The PI's hyperconnected model is inherently more suited to handle such dynamic flows, because it can route shipments through multiple options and utilize real-time data for decision-making across the network. *In other words, the Physical Internet is the infrastructure that can underpin the "logistics internet" required by digital-age commerce.* If we fail to build it, we risk escalating costs and service failures in trying to satisfy ever-increasing demand through outdated means.

From an economic and strategic standpoint, regions that aggressively pursue Physical Internet development could gain a competitive edge. Imagine a country or trade bloc where logistics costs are drastically lower and services far more reliable thanks to PI implementation – manufacturers and retailers would find it very attractive to base operations there or route goods through there. The European Union, through programs like ALICE and Horizon projects, clearly sees the PI as a way to future-proof its supply chain infrastructure and support its industries. Similarly, China and other nations are studying the concept as part of smart logistics initiatives. To avoid falling behind, logistics stakeholders globally should consider engaging with the PI movement early on. The alternative could be a patchwork of incompatible mini-Internets, which would squander the network effect benefits. A coordinated global approach, with each region contributing and learning, is far superior.

Finally, and most fundamentally, there is the argument of inevitability through analogy. History has shown that when presented with the choice of maintaining siloed, closed systems or moving to open, standardized networks, industries eventually choose the latter because it unleashes innovation and efficiency. It happened with telecommunications, with computing networks, with containerization in shipping (the adoption of the ISO container in the 1960s was itself an early Physical Internet-like standardization that revolutionized trade). Logistics is arguably one of the last domains that remains highly fragmented and bespoke. The writing is on the wall that a more unified, internetworked approach to logistics is the future. Montreuil's original insight – to *"exploit the Digital Internet metaphor to develop a Physical Internet vision"* – rings even more true today in our hyper-digital world. The question is not so much if the Physical Internet will happen, but when and how. It is the logical direction for a global logistics system under pressure to become smarter and greener.

Approach for Policy, Research, and Industry: In light of this, how should different stakeholders proceed?

- Policymakers should treat the Physical Internet as strategic infrastructure. This means funding research and pilot deployments (as the EU has done), convening industry groups to set standards, and smoothing regulatory pathways. Policies that encourage data sharing and collaboration (while protecting privacy and competition) are key. Governments could also lead by example, using PI principles in military or postal logistics (large national operations that can serve as testbeds). A supportive policy environment can accelerate the network effects needed for PI to take off.
- Research and Academia have a critical role to play in solving open questions that PI raises. Areas for research include: advanced algorithms for routing and load consolidation; design of modular container families and handling equipment; interoperability protocols and software architecture;

economic modeling of PI networks and incentive mechanisms; transition strategies and change management; and not least, the human factors and workforce implications of the new system. Interdisciplinary collaboration – among engineers, computer scientists, economists, and social scientists – will be necessary, reflecting the multifaceted nature of the PI. Already, annual international Physical Internet conferences (IPIC) and journals are publishing burgeoning research, but continued efforts and innovation will be needed to refine the concept and prove it out in practice. Living lab experiments and simulation studies can provide evidence to convince skeptics and refine the technical details.

- Industry should start engaging with the Physical Internet vision now, even if full implementation is years away. This could involve participating in standard-development committees, joining pilot programs or consortiums, and gradually incorporating PI principles into operations. For example, a logistics company might begin by adopting modular containers in its fleet or opening up certain lanes for collaborative use with partners. Manufacturers and retailers can push their 3PL providers to explore PI-based services or at least to increase data integration and sharing (a stepping stone to PI). Forward-thinking firms may find new business models in offering "logistics as a service" on an open network. It's also prudent for companies to invest in the digital infrastructure – IoT, data analytics, cloud platforms – that will be indispensable in a Physical Internet era. Ultimately, those in industry who proactively adapt are likely to be the leaders in the new logistics landscape, whereas those clinging to closed, legacy approaches risk obsolescence.

6. Conclusion

Logistics and supply chain management stand at a crossroads. The Physical Internet concept offers a compelling blueprint for the future – one that reimagines how we distribute goods by borrowing the powerful principles of openness and connectivity that revolutionized information exchange. In this paper, we have articulated how the Physical Internet directly addresses the chronic problems of today's logistics systems: it attacks inefficiency by enabling near-full utilization of transport capacity; it dismantles fragmentation through universal standards and protocols, fostering seamless interoperability; it boosts sustainability by slashing wasteful moves and optimizing modal choices; and it enhances resilience and innovation by virtue of a diverse, flexible network of networks.

Crucially, we have argued that moving toward the Physical Internet is not optional if we are to meet the demands of the 21st century. The current logistics paradigm – often proprietary, inefficient and carbon-intensive – is reaching its limits and showing strain under modern requirements. By contrast, the Physical Internet paradigm represents a holistic solution that can unlock an order-of-magnitude improvement in performance. It is a paradigm shift, analogous to the shift from isolated computer networks to the Internet, or from break-bulk shipping to containerization in the 20th century. Such shifts are challenging, but history teaches us that the long-term gains far outweigh the pains of transition.

Realizing the Physical Internet will be a journey requiring collaboration across industry, government, and academia on a global scale. Key challenges – standardization, cooperation, investment, governance – must be proactively managed. Early successes in pilot projects and incremental adoption will build momentum. Encouragingly, the movement has already begun, with initiatives in Europe and North America exploring elements of the PI. The task now is to scale up these efforts, align them, and maintain unwavering commitment to the end vision. the Physical Internet can be seen as the logistics community's collective project for the coming decades – a project to build a smarter, greener, and more inclusive logistics infrastructure for the world. The benefits in efficiency, sustainability, and resilience make it a worthy ambition. Much as the architects of the Digital Internet rallied around common protocols to interlink the world's computer networks, we call upon stakeholders in logistics and supply chains to rally around the Physical Internet vision. By doing so, we can usher in a new era in which the movement of goods is as seamless and democratized as the movement of information, delivering enormous economic and societal benefits. The time to lay the foundations for this new paradigm is now, so that the Physical Internet becomes not just an idea, but the backbone of global trade and commerce in the years to come.

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Logistics Optimization in Smart Cities Improving E-Commerce Delivery

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Abstract

The rapid growth of e-commerce in urban areas, particularly after the pandemic, has made last mile delivery processes increasingly complex and unpredictable due to increased demand. Traf- fic congestion, limited parking, variable weather conditions and increasing environmental im- pacts have rendered traditional models based solely on short distances inadequate for man- aging logistics operations. This study focus on optimizing courier delivery routes by integrating parameters such as traffic density, weather conditions and parking availability the model aims to optimize routes not only in terms of distance but also in term of operational efficiency and sustainability. A case study using selected neighborhoods from Gaziantep , Turkey demonstrates that real time and data driven routing in urban logistics offers more practical and flexible solutions com- pared to traditional models. A distance matrix modeled with multipliers takes into account traffic flow , weather conditions and parking area to determine optimal routes. The findings suggest that integrating smart city data not only reduce delivery times also provide benefits such as lower emissions improved traffic flow and increased costumer satisfaction. This ap- proach represents an effective model for developing data driven also flexible and sustainable strategies in urban logistics.

Keywords: Smart cities, E-commerce logistics, Route optimization, Traveling Salesman Prob- lem (TSP), Last-mile delivery, Traffic weather and parking integration

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1. Introduction

With the continuous growth of urban populations and e-commerce, coupled with the increasing variety of products offered for sale and the ability to easily view all options on mobile devices, cities are experiencing a significant increase in daily delivery activities. Smart cities, leveraging information and communication technologies to increase urban efficiency and sustainability must implement new strategies to quickly respond to the growing demand for e-commerce deliveries. Among the most critical challenges are traffic congestions, high fuel consumption, delivery delays and limited parking availability.

To address these issues this study proposes the optimization of delivery routes using the Traveling Sales- man Problem (TSP). The TSP focuses on minimizing the total distance required to visit a specific delivery point once and return to the starting point. In this study, the classic TSP aims to simulate real word conditions by integrating smart city parameters such as real time traffic density, weather conditions and parking availability at delivery points. These factors are incorporated into the model to reflect the challenges couriers face in real world urban environments. This study aims to demonstrate how utilizing smart city data can make logistics planning more efficient than traditional methods. Using ten neighborhoods in Gaziantep as an example, the study demonstrates how smart city data can make delivery routes more efficient and sustainable.

2. Literature Review

The use of smart city technologies improves the quality of life in cities and reduces the negative impacts of the flow of goods and people in urban areas. It supports efficiency in cities by improving logistics processes through digitalization and the integration of information technologies with classical data. Sabina Kauf (2019) mentioned that smart logistics improves the economic and social performance of cities and examined the contribution of digitalization to sustainable development [1]. Himanshu Kumar Shee et al. (2021) analyzed the effects of technology enabled smart logistics on the performance of cities using structural equation modeling [2]. Nowicka (2014) showed that cloud based, interoperable information systems in smart city logistics provide flexible solutions to urban transportation demands and increase operational efficiency [3]. Savin (2020) examined the economic impact of smart logistics on quality of life and resource efficiency and emphasized the strategic importance of logistics in the formation of smart cities [4]. Pan et al (2021) evaluated the concept of smart cities within the framework of sustainable urban freight transport linking to IoT, digital twins and data driven technologies [5]. Korczak and Kijewska (2019) studied the transformation brought about by Industry 4.0 and IoT technologies in urbanization processes and emphasized that smart city logistics is a factor that accelerates and supports the development of smart cities [6].

Shee et al. (2020) showed that the use of IoT and disruptive technologies in smart logistics improves the sustainable performance of cities [7]. Fatorachian et al. (2025) studied a predictive analysis approach based on IoT, digital twins and cybernetic feedback to make last mile deliveries more accurate and sustainable [8]. Xenou et al. (2022) proposed a multi criteria and hierarchical assessment called SCLAF to measure the level of smart city logistics systems in European cities [9]. Lingli (2015) argued that the design of logistics platforms with intelligent transportation efficiency [10]. Bektas et al. (2015) studied the social and economic impacts of urban logistics networks with operations research approaches [11]. Gumzej (2022) presented sustainable operational models for e-commerce logistics and transportation using smart logistics systems and augmented logistics [12]. Kalkha et al. (2023) examined the impacts of IoT, AI, Block chain, 5G and cloud computing technologies on e-commerce logistics in terms of delay avoidance, demand forecasting and route optimization through a systematic literature review [13]. Sun and Fan (2021) developed big data and IoT based systems to improve emergency management and resource coordination thereby increasing operational efficiency [14]. Lin (2023) developed a model to optimize terminal distribution in e- commerce logistics using Dijkstra's algorithm and hybrid tag search method [15]. Fu and Zhuang (2020) improved transportation efficiency with a genetic algorithm-based route optimization approach [16]. Huang (2022) proposed optimization models for faster cost effective and more practical e- commerce logistics distribution routes [17]. Gomes et al. (2021) presented a decision support system using genetic algorithms and m-TSP approach to improve route optimization and reduce environmental impacts in smart city logistics [18]. Baniasadi et al. (2020) transformed the clustered generalized TSP problem into classical TSP model, which provides solutions for logistics applications such as automated warehouse management and drone delivery [19]. Yu et al. (2021) proposed a TSP based pricing model for parcel locker services in last mile deliveries [20]. Arkhipov et al. (2021) studied a framework that demonstrates the parallel applicability of genetic algorithms in transportation and logistics planning [21]. Lie et al. (2022) introduced a genetic algorithm that reduces delivery time and improves solution efficiency in route optimization [22]. Finally, Hussain (2025 proposed a cloud-based system that integrates artificial intelligence, IoT devices, GPS tracking, traffic and weather data to reduce delivery times, optimize vehicle utilization and reduce fuel consumption [23].

3. Methodology

This study integrates a model based on the classic Traveling Salesman Problem (TSP) with smart city data to optimize last mile delivery routes within a smart city. The model simulates a courier visiting 10 different neighborhoods in Gaziantep and returning to the starting point (Emek). The primary objective is to minimize the total delivery time, taking into account both physical distance and external urban conditions.

To create a realistic delivery scenario a 10x10 asymmetric distance matrix was created using real world road data between neighborhoods. This data was then added to traffic, weather and parking conditions serving as real world multipliers to obtain an effective distance matrix. Traffic levels were classified as velar, rainy , snowy and stormy. These were categorized based on on-site access, nearby street options or legal restrictions that impact delivery times due to parking availability, loading and unloading delays. Each combination was assigned a numerical multiplier to simulate delays and risk. The optimization model was implemented using the Python based PuLP linear programming library. A binary decision variable x_{ij} is defined designate whether the route included travel from neighborhood i to neighborhood j. The objective function minimizes the sum of effective distances for the selected route, subject to constraints that ensure each location is visited only once and that no sub-tours occur. Sub-tour elimination was implemented using the Miller Tucker Zemlin (MTZ) formulation.

3.1. Classical TSP Model and Result

The classical model used a 10x10 distance matrix between neighborhoods. Starting from the Emek neighborhood the courier must visit all other neighborhoods once and then return to starting point. The problem is formulated as an integer linear programming model.

$min \sum\sum d_{ij} \times x_{ij}$ (1)

The objective of the classical Traveling Salesman Problem (TSP) is to minimize total distance traveled between a set of locations.

$\sum x_{ij} = 1 \text{ for all } i \in N$ (2)

Each node must be departed from exactly once

$\sum x_{ij} = 1 \text{ for all } j \in N$ (3)

Each node must be arrived at exactly once

$u_0 = 0$ (4)

Fix starting point at Emek (node 0):

$u_i - u_j + n \times x_{ij} \leq n - 1 \text{ for all } i \neq j$ (5)

where u_i are auxiliary variables used to eliminate sub-tours.

Table 1. Distance Matrix Description (10×10)

Neighborhood	Emek	Karataş	Güvenevler	Yeditepe	Beylerbeyi	Binevler	Pancarlı	Osmangazi	Kolejtepe	75. Yıl
Emek	0	9.9	4	9	5.5	5.1	6.9	7.5	6.3	10
Karataş	9.8	0	7.1	4.6	8.2	8.1	7.4	8.7	8	3.5
Güvenevler	4.1	7.2	0	7.9	3	2.8	5.1	4.3	3.2	8.1
Yeditepe	8.9	4.5	7.8	0	7.1	6.8	5.6	7.9	6.8	5.1
Beylerbeyi	5.6	8.1	2.9	7.2	0	3.5	6.2	4	4.5	8.4
Binevler	5	8	2.7	6.9	3.4	0	5.8	4.6	3.6	8.2
Pancarlı	6.8	7.5	5	5.5	6.1	5.7	0	6. 0	5.4	7.2
Osmangazi	7.4	8.8	4.2	8	3.9	4.5	5.9	0	5.2	8.9
Kolejtepe	6.2	7.9	3.1	6.7	4.4	3.5	5.5	5.3	0	8.7
75. Yıl	10.1	3.6	8.2	5	8.5	8.1	7.3	9	8.6	0

The resulting optimal tour for the courier, starting and ending at Emek Neighborhood, is as follows: Emek → Güvenevler → Beylerbeyi → Osmangazi → Pancarlı → Yeditepe → Karataş → 75. Yıl → Kolejtepe → Binevler → Emek

The total distance of the optimized route is 47.5 kilometers

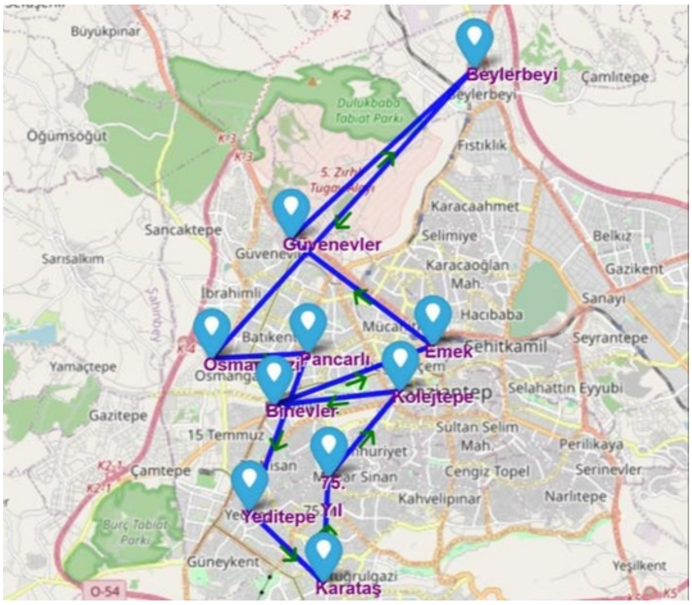

Figure 1. Optimized Delivery Route on Google Maps

3.2. Smart City-Extended TSP Model and Result

In smart cities, realistic route considerations such as traffic, weather and parking availability are incorporated into the TSP and effective distance multipliers are used.

$$c_{ij} = d_{ij} \times t_{ij} \times w_{ij} \times p_{ij} \quad (6)$$

d_{ij} = base distance, t_{ij} = traffic multiplier, w_{ij} = weather multiplier, p_{ij} = parking multiplier

$$min = \sum_{i \in N} \sum_{j \in N} c_{ij} \times x_{ij} \quad (7)$$

The objective of the Travelling Salesman Problem in smart city data computation is to minimize the total distance by considering traffic, weather parking conditions.

Table 2. Traffic Weather and Parking Multiplier

Condition Type	Specific Condition	Multiplier	Description
Traffic	Light Traffic	1	Normal, free-flowing traffic
	Moderate Traffic	1.2	Some congestion, slight delays
	Heavy Traffic	1.5	Significant congestion, slower travel
	Severe Traffic Jam	2	Major traffic jams, very slow movement
Weather	Clear (Sunny)	1	No weather-related delays
	Light Rain	1.1	Slightly slippery roads, minor caution needed
	Heavy Rain	1.3	Reduced visibility and traction
	Snow	1.5	Very slippery roads, major caution needed
	Storm / Severe Weather	2	Hazardous conditions, possible road closures
Parking	On-site Parking	1	Easy and legal parking
	Street Parking Nearby	1.2	Short walk needed
	No Legal Parking	1.5	Risky and slower due to traffic blockage
	Restricted Zone	1.8	Access with permit only or no vehicle allowed
	Underground Garage	1.4	Extra time for entry/exit to garage

To simulate a realistic urban courier delivery scenario, the required conditions were integrated into the distance matrix through three multipliers: traffic, weather, and parking availability.

Simulation Date: May 9, 2025 Time: 4:00 PM to 7:00 PM (peak hour delivery window)

Location: Gaziantep, Turkey

Scope: 10 selected neighborhoods simulated for smart city data calculations.

The data used in the simulation is based on official and open-access sources, as well as reasonable assumptions when local data granularity is limited. Traffic Multipliers are estimated based on proximity to the city center, traffic flow reports published by the General Directorate of Highways, and local traffic observations. Weather Multipliers are derived from hourly meteorological data obtained from the Mynet and Windy weather platforms. They vary across neighborhoods to reflect realistic microclimate scenarios. Parking Multipliers are estimated based on satellite imagery, municipal infrastructure reports, and local news sources on parking availability and density per neighborhood. The ideal tour for a courier, starting and ending in Emek District, is as follows:

Emek → Güvenevler → Beylerbeyi → Osmangazi → Yeditepe → Karataş → 75. Yıl → Pancarlı → Kolejtepe → Binevler → Emek

The total distance of the optimized route is 71.9 kilometers.

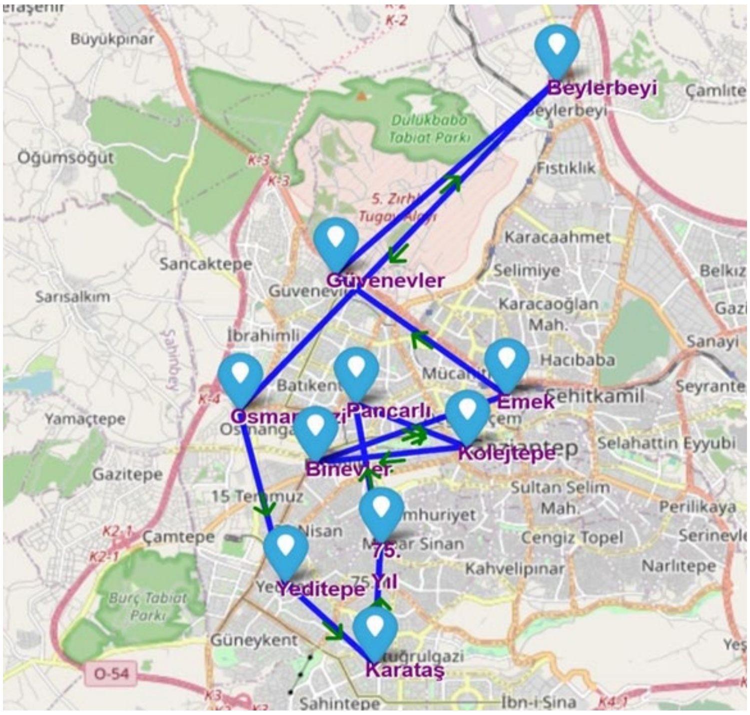

Figure 2. Optimized Delivery Route on Google Maps with Smart City Data

Table 3. Comparison of Classical and Smart City-Enhanced TSP Models

Criteria	Classical Model	Smart City Model
Start/End Point	Emek	Emek
Optimization Method	Pure Euclidean TSP	TSP with Multipliers
Considered Factors	None (only distance)	Traffic. Weather. Parking
Total Distance (km)	47.5	71.9
Route Feasibility	High (theoretical)	Moderate
Operational Realism	Low	High

Calculating the Route Found in Classic TSP by Integrating Smart City Data	Calculating the New Optimum Route by Integrating Smart City Data
72.7 km	71,9 km
Emek → Güvenevler → Beylerbeyi → Osmangazi → Pancarlı → Yeditepe → Karataş → 75. Yıl → Kolejtepe → Binevler → Emek	Emek → Güvenevler → Beylerbeyi → Osmangazi → Yed-itepe → Karataş → 75. Yıl → Pancarlı → Kolejtepe → Binevler → Emek

4. Conclusion

This study examined the optimization of courier last mile delivery routes by comparing two different Traveling Salesman Problem models: a classic distance-based model and an approach integrating smart city data. Both models started and ended point is Emek, aiming to minimize the total travel distance. The classic model based on the calculation of shortest distances, produced a 47.5 km. Route is Emek → Güvenevler → Beylerbeyi → Osmangazi → Pancarlı → Yeditepe → Karataş → 75. Yıl → Kolejtepe → Binevler → Emek. While this route represented the shortest theoretical path, it ignored operational realities such as traffic, weather conditions and parking availability. In contrast, the smart city model incorporated real time urban factors, including traffic density, weather effects and parking area limitations through factoring. This resulted in a revised route of 71.9 km. Route is Emek → Güvenevler → Beylerbeyi → Osmangazi → Yeditepe → Karataş → 75. Yıl → Pancarlı → Kolejtepe → Binevler → Emek. Despite the increase in total distance due to the addition of multipliers, this route offers a more practical and reliable solution by reducing urban bottlenecks and operational delays. The comparison highlights that, while theoretically optimal, classical models may be insufficient to provide operationally viable solutions, while smart city focused approaches provide realistic and feasible logistics strategies. The study also demonstrates that real world data, including key constraints such as sub-tour elimination, fixed start and end points, are effectively integrated with open-source optimization tools such as PuLP, thereby increasing practical applicability.Future work could expand the current model by integrating additional urban factors such as street width, a parking lot occupancy or other local constraints can be added. These factors can be modeled using adjustable multipliers to increase operational realism.

The framework can be expanded to include multi objective optimization for delivery time , fuel consumption and environmental impact, as well as more complex logistics scenarios such as multi courier operations , time constrained deliveries , and priority based routing.

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Appendix

Table A1. Smart City TSP: Effective Distance Table Based on External Factors

From	To	Base Distance (km)	Traffic Multiplier	Weather Multiplier	Parking Multiplier	Effective Distance (km)
Emek	Karataş	9.9	1.5	1.1	1.5	24.5
Emek	Güvenevler	4.0	1.2	1.0	1.2	5.8
Emek	Yeditepe	9.0	1.0	1.0	1.0	9.0
Emek	Beylerbeyi	5.5	1.2	1.1	1.2	8.7
Emek	Binevler	5.1	1.2	1.0	1.2	7.3
Emek	Pancarlı	6.9	1.0	1.0	1.0	6.9
Emek	Osmangazi	7.5	1.2	1.1	1.2	11.9
Emek	Kolejtepe	6.3	1.2	1.0	1.2	9.1
Emek	75. Yıl	10.0	1.5	1.1	1.5	24.8
Karataş	Emek	9.8	1.2	1.0	1.2	14.1
Karataş	Güvenevler	7.1	1.2	1.0	1.2	10.2
Karataş	Yeditepe	4.6	1.0	1.0	1.0	4.6
Karataş	Beylerbeyi	8.2	1.2	1.1	1.2	13.0
Karataş	Binevler	8.1	1.2	1.0	1.2	11.7
Karataş	Pancarlı	7.4	1.0	1.0	1.0	7.4
Karataş	Osmangazi	8.7	1.2	1.1	1.2	13.8
Karataş	Kolejtepe	8.0	1.2	1.0	1.2	11.5
Karataş	75. Yıl	3.5	1.5	1.1	1.5	8.7
Güvenevler	Emek	4.1	1.2	1.0	1.2	5.9
Güvenevler	Karataş	7.2	1.5	1.1	1.5	17.8
Güvenevler	Yeditepe	7.9	1.0	1.0	1.0	7.9
Güvenevler	Beylerbeyi	3.0	1.2	1.1	1.2	4.8
Güvenevler	Binevler	2.8	1.2	1.0	1.2	4.0
Güvenevler	Pancarlı	5.1	1.0	1.0	1.0	5.1
Güvenevler	Osmangazi	4.3	1.2	1.1	1.2	6.8
Güvenevler	Kolejtepe	3.2	1.2	1.0	1.2	4.6
Güvenevler	75. Yıl	8.1	1.5	1.1	1.5	20.0
Yeditepe	Emek	8.9	1.2	1.0	1.2	12.8
Yeditepe	Karataş	4.5	1.5	1.1	1.5	11.1
Yeditepe	Güvenevler	7.8	1.2	1.0	1.2	11.2
Yeditepe	Beylerbeyi	7.1	1.2	1.1	1.2	11.2
Yeditepe	Binevler	6.8	1.2	1.0	1.2	9.8
Yeditepe	Pancarlı	5.6	1.0	1.0	1.0	5.6
Yeditepe	Osmangazi	7.9	1.2	1.1	1.2	12.5
Yeditepe	Kolejtepe	6.8	1.2	1.0	1.2	9.8
Yeditepe	75. Yıl	5.1	1.5	1.1	1.5	12.6
Beylerbeyi	Emek	5.6	1.2	1.0	1.2	8.1
Beylerbeyi	Karataş	8.1	1.5	1.1	1.5	20.0
Beylerbeyi	Güvenevler	2.9	1.2	1.0	1.2	4.2
Beylerbeyi	Yeditepe	7.2	1.0	1.0	1.0	7.2
Beylerbeyi	Binevler	3.5	1.2	1.0	1.2	5.0
Beylerbeyi	Pancarlı	6.2	1.0	1.0	1.0	6.2
Beylerbeyi	Osmangazi	4.0	1.2	1.1	1.2	6.3
Beylerbeyi	Kolejtepe	4.5	1.2	1.0	1.2	6.5
Beylerbeyi	75. Yıl	8.4	1.5	1.1	1.5	20.8
Binevler	Emek	5.0	1.2	1.0	1.2	7.2
Binevler	Karataş	8.0	1.5	1.1	1.5	19.8
Binevler	Güvenevler	2.7	1.2	1.0	1.2	3.9
Binevler	Yeditepe	6.9	1.0	1.0	1.0	6.9
Binevler	Beylerbeyi	3.4	1.2	1.1	1.2	5.4
Binevler	Pancarlı	5.8	1.0	1.0	1.0	5.8
Binevler	Osmangazi	4.6	1.2	1.1	1.2	7.3
Binevler	Kolejtepe	3.6	1.2	1.0	1.2	5.2
Binevler	75. Yıl	8.2	1.5	1.1	1.5	20.3

Pancarlı	Emek	6.8	1.2	1.0	1.2	9.8
Pancarlı	Karataş	7.5	1.5	1.1	1.5	18.6
Pancarlı	Güvenevler	5.0	1.2	1.0	1.2	7.2
Pancarlı	Yeditepe	5.5	1.0	1.0	1.0	5.5
Pancarlı	Beylerbeyi	6.1	1.2	1.1	1.2	9.7
Pancarlı	Binevler	5.7	1.2	1.0	1.2	8.2
Pancarlı	Osmangazi	6.0	1.2	1.1	1.2	9.5
Pancarlı	Kolejtepe	5.4	1.2	1.0	1.2	7.8
Pancarlı	75. Yıl	7.2	1.5	1.1	1.5	17.8
Osmangazi	Emek	7.4	1.2	1.0	1.2	10.7
Osmangazi	Karataş	8.8	1.5	1.1	1.5	21.8
Osmangazi	Güvenevler	4.2	1.2	1.0	1.2	6.0
Osmangazi	Yeditepe	8.0	1.0	1.0	1.0	8.0
Osmangazi	Beylerbeyi	3.9	1.2	1.1	1.2	6.2
Osmangazi	Binevler	4.5	1.2	1.0	1.2	6.5
Osmangazi	Pancarlı	5.9	1.0	1.0	1.0	5.9
Osmangazi	Kolejtepe	5.2	1.2	1.0	1.2	7.5
Osmangazi	75. Yıl	8.9	1.5	1.1	1.5	22.0
Kolejtepe	Emek	6.2	1.2	1.0	1.2	8.9
Kolejtepe	Karataş	7.9	1.5	1.1	1.5	19.6
Kolejtepe	Güvenevler	3.1	1.2	1.0	1.2	4.5
Kolejtepe	Yeditepe	6.7	1.0	1.0	1.0	6.7
Kolejtepe	Beylerbeyi	4.4	1.2	1.1	1.2	7.0
Kolejtepe	Binevler	3.5	1.2	1.0	1.2	5.0
Kolejtepe	Pancarlı	5.5	1.0	1.0	1.0	5.5
Kolejtepe	Osmangazi	5.3	1.2	1.1	1.2	8.4
Kolejtepe	75. Yıl	8.7	1.5	1.1	1.5	21.5
75. Yıl	Emek	10.1	1.2	1.0	1.2	14.5
75. Yıl	Karataş	3.6	1.5	1.1	1.5	8.9
75. Yıl	Güvenevler	8.2	1.2	1.0	1.2	11.8
75. Yıl	Yeditepe	5.0	1.0	1.0	1.0	5.0
75. Yıl	Beylerbeyi	8.5	1.2	1.1	1.2	13.5
75. Yıl	Binevler	8.1	1.2	1.0	1.2	11.7
75. Yıl	Pancarlı	7.3	1.0	1.0	1.0	7.3
75. Yıl	Osmangazi	9.0	1.2	1.1	1.2	14.3
75. Yıl	Kolejtepe	8.6	1.2	1.0	1.2	12.4

Technology Use in the Context of 21st-Century Teacher Competencies

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This study explores the integration of technology within the framework of 21st-century teacher competencies. In today's digital era, teachers are expected not only to possess subject knowledge but also to design, manage, and evaluate learning processes using digital tools effectively. The research focuses on how technology supports pedagogical transformation and enhances the professional competencies of teacher candidates.

A comprehensive literature review and analysis of international practices reveal that successful technology integration requires more than technical skills—it demands digital pedagogical competence. Models such as TPACK and SAMR, as well as UNESCO and ISTE standards, emphasize ethical, creative, and student-centered uses of technology. Examples from Finland, the United States, and Turkey show the potential of digital mentoring, online portfolios, and interactive tools in teacher education.

The study concludes that technology should be considered an inseparable component of pedagogy, not an additional resource. Therefore, teacher education programs must include systematic digital pedagogy training, mentorship models, and performance criteria focused on technology integration.

Keywords: 21st-century skills, teacher competencies, digital pedagogical competence, technology integration, teacher education

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1. Introduction

The 21st century has brought a profound transformation in educational systems. Teachers are no longer merely transmitters of knowledge but facilitators who construct, guide, and integrate technology into pedagogy effectively. This transformation necessitates a rethinking of teacher education programs. The role of technology in education extends beyond facilitating teaching; it has the potential to transform learning environments. The pedagogical use of digital tools directly influences both teacher candidates' professional competencies and students' learning outcomes. Therefore, the active and meaningful use of technology in teaching practice courses is crucial for shaping the profile of the modern teacher.

2. 21st-Century Teacher Competencies

The competencies expected from teachers in the 21st century extend beyond academic knowledge and classroom management. According to OECD (2019), UNESCO (2018), and the Turkish Ministry of National Education (MEB, 2023), a contemporary teacher should be digitally literate, able to foster creative and critical thinking, capable of building collaborative learning environments, and committed to lifelong learning. At the core of these competencies lies not mere technological literacy but digital pedagogical competence. How teachers use technology — in what ways, for what purposes, and through which pedagogical approaches — determines the quality of their professional practice.

3. The Importance of Technology Use

Educational technologies have the potential to make teaching more effective, flexible, and student-centered. Active use of technology in teacher education allows teacher candidates to develop creative instructional designs, gain experience in digital environments simulating real classrooms, and enhance instant feedback and assessment processes. However, research indicates that teacher candidates often perceive technology merely as a presentation or material-preparation tool. This shows that technology has not yet been fully internalized within the pedagogical context. Therefore, technology integration should be addressed not at the level of technical knowledge but at the level of pedagogical awareness.

4. Literature Review and Analysis of Practices

The TPACK model (Koehler & Mishra, 2009) emphasizes that teachers should integrate technology with both content and pedagogy to design effective learning experiences. Similarly, the SAMR model evaluates how technology transforms teaching at four levels: Substitution, Augmentation, Modification, and Redefinition. According to UNESCO (2018) and ISTE (2021) standards, teachers are expected to use digital tools ethically, innovatively, and in student-centered ways. These frameworks highlight that technology use in teacher education should not be considered a mere technical skill but an integral part of instructional design and assessment processes.

An examination of international practices reveals that: In Finland, teacher candidates prepare digital portfolios during practicum courses and receive online feedback from mentors. In the United States, cloud-based systems such as Google for Education help teacher candidates develop digital classroom management skills. In Turkey, joint initiatives by the Ministry of National Education (MEB) and the Council of Higher Education (YÖK) — such as the Digital Teacher Project — expose teacher candidates to smart boards, EBA content, and online assessment tools. These practices demonstrate that experiential technology integration in practicum courses enhances professional confidence. However, in most cases, such integration lacks continuity and remains confined to specific projects.

The literature and practical examples indicate that effective technology integration is only possible through planned, systematic, and reflective instructional approaches. Thus, the development of digital pedagogical competencies should be supported through mandatory digital pedagogy modules in teacher education faculties, digital mentoring programs within university–school partnerships, and performance evaluation criteria that include technology integration in lesson planning.

5. Conclusion and Recommendations

This study highlights the central role of technology in developing 21st-century teacher competencies. Teacher candidates must learn to use technology not merely as a tool but as a constructive element of the learning process.

Recommendations:

1. Incorporate a compulsory 'Digital Pedagogy' course into teacher education curricula.
2. Include technology integration as a performance criterion in practicum evaluations.
3. Establish digital mentoring systems between universities and schools.
4. Encourage teacher candidates to create digital content to promote a sustainable culture of technology use.

In conclusion, achieving the teacher profile required by the digital age demands that technology be viewed not as a supplement to pedagogy but as an inseparable component of it.

Wearable Technologies and Sports: Innovations in Performance Monitoring, Health Tracking, and Athlete Development

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Abstract

Wearable technologies have become an essential component of contemporary sports performance analysis. This study examines their role in monitoring training loads, physiological responses, and recovery status, with examples from popular sports. By integrating data from GPS trackers, HR monitors, and motion sensors, coaches can make data-informed decisions that enhance performance while minimizing injury risk. Beyond performance, wearables support holistic health management by tracking sleep, stress, and metabolic variables. However, data accuracy, privacy, and ethical use remain critical issues. The paper concludes that AI-based analytics and smart textile systems will shape the next generation of personalized, predictive, and adaptive training models.

Keywords: Wearable technology, Performance monitoring, Athlete tracking, Sports science, Data analytics

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1. Introduction

In recent years, wearable technologies have become an integral part of both daily life and the scientific monitoring of human performance. In sports science, these technologies have transformed the way training loads, physiological responses, and biomechanical movements are measured. The ability to collect real-time data from athletes provides coaches and researchers with valuable insights into adaptation processes, recovery status, and potential injury risks. Thus, wearable devices establish a dynamic interface between human physiology and digital analytics, aligning sports practice with the principles of evidence-based performance enhancement (Cardinale & Varley, 2017).

2. Technological Background

Modern wearable systems collect data through sensors that detect acceleration, position, temperature, muscle activity, or cardiovascular responses. These data are wirelessly transmitted to analytical software, where they are converted into performance metrics.

Common categories include:

•GPS and accelerometer systems: measure speed, distance, movement load, and positional data.

•Heart rate (HR) and heart rate variability (HRV) sensors: assess internal load and recovery capacity.

•Electromyography (EMG) and inertial sensors: evaluate muscle activation and joint kinematics.

•Smart textiles: integrate sensors into garments, enabling continuous monitoring without movement restriction (Sperlich & Holmberg, 2017).

These systems are becoming smaller, more accurate, and more affordable, allowing both elite and recreational athletes to benefit from precise feedback.

3. Applications in Popular Sports

Wearable technologies are now widely implemented across major sports disciplines, providing real-time data and analytics for performance improvement, injury prevention, and recovery management.

3.1. Football (Soccer)

GPS vests, accelerometers, and heart rate sensors are used to monitor players' distance, sprint count, and workload profiles. These data are analyzed using the Acute: Chronic Workload Ratio (ACWR) model to balance short-term and long-term training loads (Fullagar, McCunn, & Murray, 2019).

3.2. Basketball

IMU sensors and force platforms track jump height, direction changes, and contact intensity. Load management and HRV monitoring help prevent overtraining. NBA teams widely use Kinexon and Whoop systems.

3.3. Athletics

GPS watches and HR sensors record running mechanics, pace, stride frequency, and energy expenditure. Aerobic capacity (VO_2max) and lactate threshold data guide training intensity adjustments.

3.4. Fitness and CrossFit

Smart bracelets and connected weights provide real-time feedback on calories, HRV, tempo, and metabolic stress. These data optimize recovery cycles and training adaptation.

3.5. American Football and Rugby

Impact sensors and GPS-based shoulder pads measure collision intensity and direction, identifying concussion risks. Zebra MotionWorks provides centimeter-level position tracking.

3.6. Cycling

Power meters measure watt output, cadence, and gradient, while Training Stress Score (TSS) and Normalized Power (NP) calculations guide load management.

3.7. Swimming

Waterproof IMU sensors and smart goggles track stroke rate, symmetry, and lap speed. FORM Smart Goggles project live metrics into the swimmer's field of view.

3.8. Combat Sports (Judo, Boxing, MMA, Taekwondo)

IMU and EMG sensors record speed and force of strikes or throws. HRV and lactate measurements are used to monitor internal load. Catapult OpenField is employed in judo to analyze randori workloads.

4. Ethical and Practical Considerations

Despite their benefits, wearable technologies bring challenges regarding data privacy, ownership, and accuracy. Athletes often have limited control over data sharing, raising ethical concerns. Sensor reliability may vary, and excessive dependence on technology can weaken athletes' self-awareness and decision-making abilities. Addressing these issues requires balancing innovation with ethical responsibility.

5. Future Directions

The integration of wearable technologies with artificial intelligence (AI) and machine learning (ML) enables predictive models for injury prevention, recovery estimation, and individualized training.

Emerging developments include:

- Smart textiles monitoring multiple variables
- Cloud-based athlete management platforms
- Augmented reality (AR) systems for motor learning and tactical training

These advances represent a future where athletes interact continuously with intelligent, adaptive, and data-driven systems.

6. Conclusion

Wearable technologies represent a major advancement in modern sports science. Real-time physiological and biomechanical monitoring has revolutionized how training and competition are analyzed. To fully harness this potential, integration must occur within ethical frameworks that preserve athlete autonomy and encourage critical interpretation of data.

The future of sport lies not merely in data collection but in translating information into actionable human insight. Wearables, when properly implemented, serve not as replacements for human expertise but as scientific extensions of it.

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Disassembly Line Balancing Problem Based on Human-Cobot Collaboration with Ergonomics Constraints In The Industry 5.0 Era

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Abstract

Disassembly line balancing problem which is defined as assigning the tasks to the workstations to minimize the number of workstations and to utilize the available resources as efficiently as possible while meeting the demand for recovered parts. According to the characteristics of the disassembly system, different variants of the problem have been studied for many years. Majority of these problems usually focuses on general restrictions such as precedence relationships, cycle time and assignments of the tasks to satisfy the required performance measure. However, in addition to the general restrictions, specific restrictions considering human factors according to practical cases are important to provide efficient disassembly processes. On the other hand, with the development of the industry 5.0 revolution, it has become evident that human-cobot (collaborative robots) collaboration is inevitable. This is because robots can perform repetitive and dangerous tasks in a superior manner, while humans are skilled at handling more complex and delicate operations. At the same time, it is necessary for humans to collaborate with robots for their health and safety. Therefore, this study extends DLBP considering human factors dependent on human-cobot collaboration and focuses on ergonomics restrictions. A mathematical model is developed for solving the problem. Finally, the model is illustrated and validated using a an illustrative example.

Keywords: Cobots, Disassembly line balancing, Ergonomics constraints, Industry 5.0

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1. Introduction

Industry 5.0 requires a more personalized human-cobot collaboration (HCC) technology that complements the advantages of humans and cobots to protect human physical and mental health as well as well-being during production. However, HCC technology adds many constraints to Disassembly Line Balancing Problem(DLBP), especially the constraints between humans, cobots, and products, which significantly increases the difficulty and complexity of DLBP. Therefore, addressing DLBP by considering HCC constraints is an extremely valuable research topic in the industry 5.0 era (Wu et al. 2023). Based on these areas of interest, this study focuses on modeling and optimizing the single-product and straight DLBP considering ergonomic restrictions (human factors) dependent on HCC and formulate a mathematical model to maximize total net profit (Xu et al. 2020).

2. The DLBP Literature Review

The DLBP was first studied by (Güngör and Gupta, 2001, 2002). Since then, the literature has emerged considering different types of DLBPs. Researchers can find detailed information about the literature in review papers by (Bentaha et al.2015; Özceylan et al.2019; Laili et al. 2020; Güler et al.2024). According to the DLBP literature, it was observed that very few studies have taken human factors into consideration. Guo et al. (2022) have formulated a multi-objective U-shaped DLBP mathematical model which aims to minimize the maximum difference in fatigue between any two workstations and to maximize disassembly profit. Tian et al. (2024) have proposed a multi-objective DLBP model that aims to minimize disassembly line idle rate, improve line smoothness, reduce energy consumption, and balance operator workload. They have considered physical constraints, and mental constraints of the workers. On the other hand, with the development of the industry 5.0 revolution, it has become evident that human-cobot collaboration is inevitable. This is because robots can perform repetitive and dangerous tasks in a superior manner, while humans are skilled at handling more complex and delicate operations. At the same time, it is necessary for humans to collaborate with robots for their health and safety. Some of the DLBP papers focused on DLBP with HCC are summarized as follows: Xu et al. (2020) first proposed a multi-objective human-robot collaboration DLBP. In their study, human and cobot tasks are assigned based on part disassembly difficulty and the objective function is to optimize profit, energy consumption, disassembly difficulty, and the number of workstations. Subsequently, studies incorporating ergonomic constraints were conducted. Compared to previous studies in this field, this study provides the following two contributions: * To the best knowledge of the authors, there are a limited number of studies on task difficulty. One of these studies used the formulation given in the study by Kara et al. (2014) to evaluate task rigidity (difficulty) (TR). Unlike this study, we found the e_i value in this formula according to the disassembly effort index (EI) which is related with the task difficulty. *In the calculation of physical workload, the strain index (SI) value was used for the first time. According to the contributions given above, the authors think that this study provides a different point of view for interested researchers in the area.

3. Evaluation of Ergonomic Restrictions

The psychological and physical health of the human operator is modeled by considering psychological, physical workload, and zoning criteria. These concepts are briefly summarized below.:

***Psychological Workload*:**
Psychological workload represents the overall mental stress, pressure, and challenges experienced by an individual, which can influence attention and task performance. Therefore, in this study, both the physiological workload for each task and total psychological workload for a human are considered (Kara et al., 2014). These parameters are determined based on the weighted rigidity measures of tasks. The weighted task rigidity measure (w_i) of each task, proposed by Kara et al. (2014), is adopted to represent the physiological workload. w_i is calculated by multiplying the task time (t_i) by its subjective rigidity measure (e_i), such that $w_i = t_i \times e_i$. The value of e_i ranges between 1 and 10. As e_i increases, flexibility in work methods and opportunities for individual decision-making decrease. It should be noted that in this study, the value of e_i is determined based on the disassembly effort associated with each task. Since task difficulty is closely related to the Disassembly Effort Index (*DEI*) in terms of the criteria used, assigning the e_i values according to this index is considered appropriate. Various approaches have been proposed in the literature to measure this effort, and in this study, we employ the *DEI* Score Card introduced by Das et al. (2000). The psychological workload (*PW*) of a human operator is defined as the sum of the w_i values of the tasks assigned to that operator.

***Physical Workload*:** It contains discomfort measurement, posture observation, workplace risk analysis, effort and fatigue measurement, lower back disorder assessment, and estimation of upper extremity injury risks. A heavy physical demand at work is a potential risk factor for musculoskeletal systems (Belliappa et al. 2014). Since disassembly tasks primarily require upper body movement, the *SI* is used to quantify physical workload and prevent work-related musculoskeletal disorders (Lou et al. 2023). The *SI* is introduced by Moore and Garg (1995) and it rates six parameters on a scale of 1–5: intensity of exertion (*IE*), duration of exertion (*DE*), efforts per minute (*EM*), body posture (*BP*), and speed of work (*SW*). Each parameter's rating is matched with a corresponding multiplier value. The SI_i value of disassembly task i can be calculated as (Bao et al. (2009)): $SI_i = IE_i \times DE_i \times EM_i \times BP_i \times SW_i$. Moore and Garg (1995) propose the thresholds to predict job safety based on the SI. These thresholds are as follows (Pearce et al. 2018) : SI ≤ 3: Safe; 3< SI < 7: Moderate; SI ≥ 7: Hazardous. The physical workload (*PhW*) of a human operator is defined as the sum of the SI values of the tasks assigned to that operator.

If psychological and physical workloads of each workstation (worker) exceed an individual's coping capacity, it affects the worker's attention and quality of work. The upper limits of psychological (FU) and physical workloads (SU) of each workstation should be acceptable level for human health.

***Zoning Restrictions*:** It is related with hazardous parts. In a disassembly line, some tasks are not allowed to be assigned to the same workstation, and this constraint is called negative zoning constraint. For example, the disassembly of non-hazardous parts and hazardous parts must not be removed at the same workstation to prevent damage to the non-hazardous parts and to minimize the possibility of contamination in the rest of the system (Gungor and Gupta, 2002).

4. Problem Definition and Mathematical Formulation

This research focuses on operator assignments within a workstation (operator mode) is divided into three situations: (1) assigning a worker (om-1), (2) assigning a cobot (om-2), and (3) assigning both a worker and a cobot (om-3). The assignment of task operators requires determining the specific operators responsible for executing each task. A single type of discarded product is disassembled on straight line. Disassembly mode of a part may be reusing (dm-1) or recycling (dm-2). A complete disassembly is done. All parameters are known and deterministic. While revenues of demanded parts are positive; revenues of non-demanded parts are zero. Task costs, task times and part revenues depend on assigned disassembly mode and operator mode. The psychological and physical workload are related to human operators. If possible, having the cobot perform the work done by humans, or performing it together with the cobot, will reduce the value of these workloads. On the other hand, if a cobot is used during the disassembly of a product, there may be a risk of damage to some parts. Therefore, it is necessary for workers to carry out tasks involving these parts. Disassembly of hazardous sub-parts can also cause injuries to workers. To reduce these risks, it is mandatory for cobots to perform tasks involving such parts to maximize worker safety. The SI and w_i are involved in any involvement of human operators in executing a task. These parameters of any task depend on assigned recovery actions and whether the human is alone or with a cobot at the assigned station. The objective function is to maximize the total net profit of the line for one cycle, under ergonomic constraints. We extend the 0-1 integer linear programming formulations by referring the studies of Choi (2009) and Kara et al. (2011). The notation used to describe the proposed formulations are given below:

Indices

i,l,r task (part)
j,v workstation
k disassembly mode (1 = reuse, 2 = recycle)

Parameters and sets

J set of workstations
I set of tasks
I_k set of tasks processed with recovery mode k
H set of hazardous tasks
K set of recovery modes
ZN set of the hazardous tasks
ZP set of non-hazardous tasks
PA_i set of immediate "AND" predecessors of task i
C cycle time
M_{max} maximum number of workstations
t_{ik0} completion time of task i if it is processed with recovery mode k and performed by human
t_{ik1} completion time of task i if it is processed with recovery mode k and performed by cobot
t_{ik2} completion time of task i if it is processed with recovery mode k and performed by human-cobot collaboration
f_{ik0} weighted rigidity measure of task i if it is processed with recovery mode k and performed by human
f_{ik2} weighted rigidity measure of task i if it is processed with recovery mode and performed by human-cobot collaboration
s_{ik0} strain index of task i if it is processed with recovery mode k and performed by human
s_{ik2} strain index of task i if it is processed with recovery mode k and performed by human-cobot collaboration
c_{ik0} cost of task i if it is processed with recovery mode k and performed by human per cycle
c_{ik1} cost of task i if it is processed with recovery mode k and performed by cobot per cycle
c_{ik2} cost of task i if it is processed with recovery mode k and performed by human-cobot collaboration per cycle

r_{ik0} revenue that meets per unit demand of part i, if it is processed with recovery mode k and performed by mode 1
r_{ik1} revenue that meets per unit demand of part i, if it is processed with recovery mode k and performed by mode 2
r_{ik2} Revenue that meets per unit demand of part i, if it is processed with recovery mode k and performed by mode 3
cw cost of a workstation (fixed costs) (per cycle)
cr cost of a cobot (fixed costs) (per cycle)
FU upper limit for the psychological workload (PW)
SU upper limit for the physical workload (PhW)
B a big number

Variables
x_{ij} 1, if task i is assigned to workstation *j*; 0, otherwise
p_{ikj} 1, if task i is processed in work station j with recovery mode k and human; 0, otherwise
q_{ikj} 1, if task i is processed in work station j with recovery mode k and cobot; 0, otherwise
z_{ikj} 1, if task i is processed in work station j with recovery mode k and human-cobot; 0, otherwise
z_{ikj} 1, if task i is processed in work station j with recovery mode k and cobot; 0, otherwise
y_j 1, workstation *j* is utilised; 0, otherwise
u_j 1, if a cobot is assigned to workstation *j*; 0, otherwise

$$Max \sum_{i\in I}\sum_{k\in I_k}\sum_{j\in J} r_{ik0}p_{ikj} + r_{ik2}z_{ikj} - \sum_{i\in I}\sum_{k\in I_k}\sum_{j\in J} c_{ik0}p_{ikj} + c_{ik1}q_{ikj} + c_{ik2}z_{ikj} - cw\sum_{j\in J} y_j - cr\sum_{j} u_j \tag{1}$$

$$\sum_{j\in J} x_{ij} = 1 \qquad \forall i \in I \tag{2}$$

$$x_{ij} \le \sum_{v=1}^{j} x_{lv} \quad \forall i \in I;\ \forall l \in PA_i;\ \forall j \in J \tag{3}$$

$$\sum_{i\in I}\sum_{k\in I_k} t_{ik0}p_{ikj} + t_{ik1}q_{ikj} + t_{ik2}z_{ikj} \le Cy_j \qquad \forall j \in J \tag{4}$$

$$\sum_{k\in I_k} (p_{ikj} + q_{ikj} + z_{ikj}) = x_{ij} \qquad \forall i \in I;\ \forall j \in J \tag{5}$$

$$\sum_{i\in I}\sum_{k\in I_k} (q_{ikj} + z_{ikj}) - B\,u_j \le 0 \qquad \forall j \in J \tag{6}$$

$$\sum_{i\in I}\sum_{k\in I_k} f_{ik0}p_{ikj} + f_{ik2}z_{ikj} \le FU.y_j \qquad \forall j \in J \tag{7}$$

$$\sum_{i\in I}\sum_{k\in I_k} s_{ik0}p_{ikj} + s_{ik2}z_{ikj} \le SU.y_j \qquad \forall j \in J \tag{8}$$

$$x_{ij} + x_{rj} \le 1 \qquad \forall i \in ZN;\ \forall r \in ZP;\quad \forall j \in J \tag{9}$$

$$x_{ij}, p_{ikj}, q_{ikj}, z_{ikj}, y_j, u_j \in \{0,1\} \qquad \forall i \in I,\ \ \forall k \in K,\ \ \forall j \in J \tag{10}$$

The objective function (1) maximizes the total net recovery profit associated with the total revenue earned from released parts, sum of task costs, workstation and cobot cost. Constraint (2) indicates that a task can be assigned to at most one workstation. Precedence relationships among tasks are satisfied by the sets of constraints given in Constraints (3). It allows assignment of task i to station *j* only if its AND predecessors are already assigned to stations 1 through *j*. Constraint (4) ensures that the workload of a workstation does not exceed the predetermined cycle time. Constraint (5) determines the operator mode type (mode-1, mode-1 and mode-3) and disassembly mode (reuse or recycle) allocated to a workstation. Constraint (6) determines whether a cobot is allocated to workstation j. Constraint (7) ensures that total TR of a workstation cannot exceed the upper limit for operators' psychological workload. Constraint (8) ensures that total SI of a workstation cannot exceed the upper limit for operators' physical workload. Constraint (9) guarantees the negative zoning restriction. Hazardous parts cannot be assigned the same station with the non-hazardous parts. Constraint (10) represents the binary nature of decision variables.

5. Illustrative Example

In this section the proposed formulations are illustrated using a 7-task example DLBP. The precedence relationships among tasks are developed randomly and they can be found in Figure 1. Task times that depend on the modes and recovery actions are randomly assigned following a discrete uniform distribution with U(5, 15). The rigidity values are assigned to each task based on DEI of each task. The strain index of each task is randomly assigned following the Table 1. The costs defined in the models are taken as $c_{ik0} = 0.5, c_{ik1} = 0.19, c_{ik2} = 0.35, cw = 0.24, cr = 0.17\ euro/min.$ The revenue value of parts with zero demand is accepted to be zero as well. The revenue of hazardous parts is zero. It is assumed that cycle time is 20 min. The upper limit for the psychological workload of workers (FU) is selected 60. The upper limit of physical workload of workers (SU) is selected 3. All formulations are solved using LP/MIP solver CPLEX (version 10.2) on an Intel Xeon 8 Duo, 3,30 GHz, 8 GB RAM computer. The other data of the example is given in Table 1.

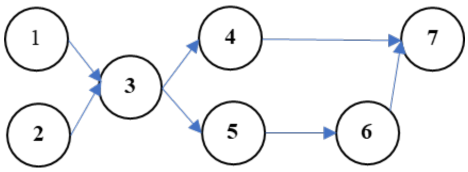

Figure 1. Precedence relationships among tasks for 7-task example

The example assumes that there are two alternative disassembly modes and 2 different operator modes for each task (except for Tasks 2 and 5). Since parts 2 and 5 are hazardous, their disassembly modes are considered as recycling and only cobots disassemble these parts. Task durations, task costs, task rigidity, and strain index vary according to the disassembly mode and operator mode of the task. The reuse revenue of a part is higher than the recycling revenue of the same part, but the task duration and cost are also higher. At the same time, since more meticulous work is required for parts removed for reuse, the task rigidity and strain index are higher. In terms of operator modes, the cost of human labor is lower than that of human-cobot labor, while the task duration, task rigidity, and strain index are higher. It is assumed that the revenue obtained from the reuse of a part is the same for humans and human-robots. The same applies to recycling.

Table 1. Task and worker data of the example problem.

i	*dm*	*om*	*#t*	*#co*	*#re*	w_i	*#SI*	*i*	*dm*	*om*	*#t*	*#co*	*#re*	w_i	*#SI*
1	1	1	9	3.15	13	27	1	5	1	1	0	0	0	0	0
		2	0	0	0	0	0			2	0	0	0	0	0
		3	5	2.5	13	15	0.5			3	0	0	0	0	0
	2	1	6	2.1	11	12	0.5		2	1	0	0	0	0	0
		2	0	0	0	0	0			2	12	2.28	0	0	0
		3	2	1	11	6	0.25			3	0	0	0	0	0
2	1	1	0	0	0	0	0	6	1	1	10	3.5	9	30	3
		2	0	0	0	0	0			2	0	0	0	0	0
		3	0	0	0	0	0			3	5	2.5	9	20	1
	2	1	0	0	0	0	0		2	1	6	2.1	6	12	1.5
		2	9	1.71	0	0	0			2	0	0	0	0	0
		3	0	0	0	0	0			3	2	1	6	6	0.25
3	1	1	13	4.55	10	52	2.25	7	1	1	9	3.15	14	27	3
		2	0	0	0	0	0			2	0	0	0	0	0
		3	7	3.5	10	28	1.5			3	4	2	14	12	0.75
	2	1	6	2.1	7	18	1		2	1	6	2.1	10	18	1
		2	0	0	0	0	0			2	0	0	0	0	0
		3	3	1.5	7	9	0.75			3	2	1	10	4	0.25
4	1	1	10	3.5	15	50	1.5								
		2	0	0	0	0	0								
		3	6	3	15	24	0.5								
	2	1	5	1.75	8	15	1								
		2	0	0	0	0	0								
		3	3	1.5	8	12	0.25								

dm: disassembly mode (1: reuse, 2: recycle); om: operator mode (1: human, 2: cobot, 3:human-cobot) *#t*: time; *#co*: cost; *#re*: revenue; w_i: weighted task rigidity; *#SI*: strain index

The optimal line balance is given in Table 2 and the line layout for the optimal line balance is illustrated in Figure 2.

Table 2. Optimal line balance

Workstation	Tasks assigned	*om-2*	*om-3*	*dm-1*	*dm-2*
1	2	✓			✓
2	1		✓	✓	
	3		✓	✓	
3	5	✓			✓
4	4		✓	✓	
	6		✓	✓	
	7		✓	✓	

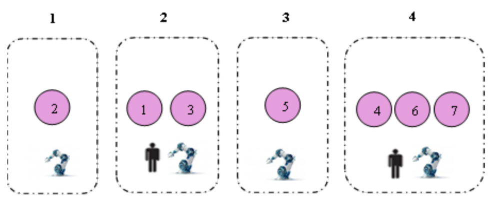

Figure 2. Disassembly line layout of the optimal solution

The optimal line balance result in four workstations with the objective function value of 41.87 dollars for one cycle. Optimal solution is obtained within 1 s CPU time. While tasks 2 and 5 are disassembled by cobots, the other tasks are removed by human-cobot collaboration. It is also observed that no station is exclusively assigned to a human operator ($om - 1$), which reinforces the conclusion that the proposed model exhibits a human-oriented structure. Based on these results, despite the high operational cost of human–cobot collaboration, it can be concluded that this configuration yields the most favorable outcomes for the worker in terms of PW and PhW, making it the healthiest option for human. A scenario analysis is performed to underline the effect of FU and SU on total net profit. Based on the weighted task rigidity values, FU is selected to have the highest value within reuse values (52) and the highest value among return values (18) (18 < FU < 52). Starting from 20, FU values are taken as 20, 30, 40, 50. SU, ranging from 1 to 6 ($1 \ <= \ SU \ < \ 6$), is considered for values 1, 2, 3, 4, 5, and 6.

Table 3. The results of scenario analysis

FU	*SU*	*#Z*	*#nw*	*om-2*	*om-3*	*dm-1*	*dm-2*	*FU*	*SU*	*#Z*	*#nw*	*om-2*	*om-3*	*dm-1*	*dm-2*
20	1	34.14	7	2	5	3	2	50	1	39.64	7	2	5	4	3
	2	34.14	7	2	5	3	2		2	41.46	5	2	5	5	2
	3	34.14	7	2	5	3	2		3	41.46	5	2	5	5	2
	4	34.14	7	2	5	3	2		4	41.46	5	2	5	5	2
	5	34.14	7	2	5	3	2		5	41.46	5	2	5	5	2
	6	34.14	7	2	5	3	2		6	41.46	5	2	5	5	2
30	1	39,64	7	2	5	4	3	60	1	39.64	7	2	5	4	3
	2	40.64	7	2	5	5	2		2	41.46	5	2	5	5	2
	3	40.64	7	2	5	5	2		3	41.87	4	2	5	5	2
	4	40.64	7	2	5	5	2		4	41.87	4	2	5	5	2
	5	40.64	7	2	5	5	2		5	41.87	4	2	5	5	2
	6	40.64	7	2	5	5	2		6	41.87	4	2	5	5	2
40	1	39.64	7	2	5	4	3								
	2.	41.05	6	2	5	5	2								
	3	41.05	6	2	5	5	2								
	4	41.05	6	2	5	5	2								
	5	41.05	6	2	5	5	2								
	6	41.05	6	2	5	5	2								

In Table 3, the third and eleventh columns present the objective function value, while the fourth and twelfth columns report the total number of stations. The fiftt, sixth, thirteenth and fourteenth columns show the number of tasks assigned to operator mode 2 and mode 3, respectively. The seventh, eighth, fifteenth and sixteenth columns indicate, in a similar manner, the number of tasks executed under disassembly mode 1 and mode 2. The results of the scenario analysis are presented in Table 3. As shown in Table 3, it was observed that as the FU and/or SU values decrease—meaning that ergonomic constraints related to the human operator are satisfied and prioritized— the total net profit decreases. This is because lower FU/SU values lead to an increase in the number of stations. It is worth noting that, according to the results none of the tasks are performed solely by a human. These results are highly satisfactory, considering that the objective of the problem is profit maximization based on human health and safety.

6. Conclusion and Future Directions

This study focus on DLBP based on human-cobot collaboration with ergonomics constraints. 0-1 integer linear programming formulation is proposed under ergonomics restrictions. These restrictions are related with weighted task rigidity, and strain index which have not been addressed yet in the DLB literature. Balancing disassembly lines considering ergonomics will meet the physical and psychological demands of people and improve quality of works. The purpose of this study is to provide an introduction to the ergonomic assessment of the disassembly lines and a different point of view for interested researchers in the area. The proposed formulation can be extended different assumptions of DLBP. It can be expanded for U-lines, parallel lines, mixed-model disassembly lines or other types of disassembly lines. The used parameters can be obtained from the industry and the formulation can be updated. Development of efficient heuristic procedures can also be considered for further research.

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Identifying Algebraic Thinking Patterns of Graduate Mathematics Teachers

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Abstract

This qualitative case study examined algebraic thinking patterns among 22 in-service mathematics teachers enrolled in graduate programs using a researcher-designed Conceptual Knowledge Form. Participants answered three open-ended items about when algebra appears in the hierarchy of mathematical knowledge, which parts of mathematics they consider algebra, and the three most characteristic questions they frequently ask students when teaching algebra. Responses were analyzed using thematic content analysis. Five themes emerged: procedural/operation-focused definitions and equation emphasis; conceptual/generalizing approaches; representational teaching; relational thinking; and historical/abstract awareness. Frequency analysis indicated that equality/equation and variable/unknown questions were the most common prompts used by teachers, suggesting a classroom discourse leaning toward procedural fluency. Findings underscore the need to strengthen conceptual tasks, model-based instruction, and question design training in pre-service and in-service teacher education. Methodological limitations include reliance on a single data source and limited reporting of instrument validity and inter-coder reliability. Recommendations for practice and research are provided.

Keywords: Algebraic thinking, Conceptual knowledge, Mathematics teacher, Qualitative research

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1. Introduction

Algebra holds a central position in mathematics education at every level. It plays a key role in developing students' abstract thinking, problem-solving, and logical reasoning skills. Algebraic thinking is essential for understanding advanced mathematical concepts and scientific disciplines. The applications of algebra in mathematics appear in abstract structures such as groups, rings, fields, and vector spaces; in applied sciences such as physics, computer science, cryptography, and coding theory; and in education as a means of enhancing abstract thinking, problem-solving, and logical reasoning skills. In other words, algebra is the universal language and the foundational structure of mathematics. It is indispensable both for the development of theoretical mathematics and for its applications in the sciences.

In algebra instruction, the types of questions and teaching approaches used by teachers critically affect students' conceptual understanding, motivation, and achievement. Deep, open-ended questions posed by teachers foster higher-order and lasting learning, while superficial questions may improve basic skills but do not contribute to permanent learning or metacognitive thinking. Questions containing intentional errors can help students recognize conceptual misunderstandings and provide teachers with insights into their students' misconceptions.

Teacher-designed questions tailored to students' needs increase both motivation and success. Easy questions tend to yield higher achievement and motivate students, yet teachers' approaches to teaching algebra and the questions they pose often remain procedural, failing to emphasize the conceptual dimension of algebra sufficiently (Kieran, 1992; Sfard, 1995).

Teachers' algebraic thinking skills directly affect students' learning processes, making it necessary to examine teachers' algebraic thinking patterns. Therefore, this study aims to reveal and thematically classify the algebraic thinking patterns of mathematics teachers through the Conceptual Knowledge Form.

2. Proposed Method

This study was conducted using a qualitative research approach and was designed as a case study. The participants consisted of twenty-two mathematics teachers who were pursuing graduate studies and had varying years of teaching experience. The data collection tool was the Conceptual Knowledge Form, which was developed by the researcher and consisted of five open-ended questions. Three of these questions were selected for analysis. The obtained data were grouped and thematically categorized. The questions addressed to the teachers were as follows:

1. Within the hierarchy of mathematical knowledge, when does algebra emerge?
2. Which parts of mathematics do you consider as algebra?
3. While teaching algebra, what are the three most common questions you ask your students that differ from other learning areas?

Teachers' responses to these questions are presented in the table below. To facilitate data analysis, teachers were coded as "T" followed by a number (e.g., T1, T2...). The questions aimed to reveal teachers' perceptions of the concept of algebra, its position within mathematics, and the types of questions they use in teaching. The obtained data were analyzed through content analysis, and similar expressions were grouped to form themes.

3. Findings

3.1. Thematic Analysis and Frequency Tables

Table 1. Themes, Participants, and Explanations

Themes	Participants	Frequency (f)	Explanation
Procedural Definition and Equation-Oriented Thinking	T1, T2, T5, T7, T10, T11, T15, T18, T20, T22	10	Defined algebra through operations, equations, and symbols. Their questions focused on equality, finding unknowns, and solving equations.
Conceptual / Generalizing Approach	T3, T8, T9, T13, T17	5	Explained algebra through patterns, generalizations, functions, and proofs. Their questions emphasized relationships between concepts and the development of generalization skills.
Representation-Based Teaching	T3, T4, T6, T19	4	Explained algebra using concrete models, real-life examples, and symbolic representations.
Relational Thinking	T6, T8, T9, T10, T13	5	Addressed algebra through real-life connections, multiple solution strategies, and relationships among mathematical concepts.
Historical / Abstract Awareness	T14, T16, T19, T21	4	Explained algebra in the context of its historical development and abstract mathematical structures.

This table thematically categorizes teachers' ways of conceptualizing algebra. More than half of the participants (10 out of 22) were classified under the "Procedural Definition and Equation-Oriented Thinking" theme, indicating that most teachers define algebra through operations, equations, and symbolic expressions. Meanwhile, those under the "Conceptual/Generalizing Approach" and "Relational Thinking" themes explained algebra through conceptual relations, generalization, and functional connections, reflecting deeper mathematical reasoning. The distribution shows that while procedural understanding still dominates, a gradual shift toward conceptual thinking is emerging among some teachers.

Table 2– Theme, Frequency, Participant Codes

Theme	Frequency (f)	Participant Codes
Procedural Definition & Equation Orientation	10	T1, T2, T5, T7, T10, T11, T15, T18, T20, T22
Conceptual / Generalizing Approach	5	T3, T8, T9, T13, T17
Representation-Based Teaching	4	T3, T4, T6, T19
Relational Thinking	5	T6, T8, T9, T10, T13
Historical / Abstract Awareness	4	T14, T16, T19, T21

This table quantitatively presents the distribution of teachers across identified themes. The highest frequency once again appears under "Procedural Definition and Equation Orientation" (f = 10), followed by "Conceptual/Generalizing Approach" (f = 5) and "Relational Thinking" (f = 5). The relatively lower frequencies of "Representation-Based Teaching" (f = 4) and "Historical/Abstract Awareness" (f = 4) indicate that teachers find it challenging to connect algebra with concrete models or its historical development. Overall, the table suggests that most teachers remain within a symbolic and procedural framework, while a smaller group is beginning to develop a more multidimensional, conceptual understanding.

3.2. Interpretation of Findings

Five teachers demonstrated a conceptual and generalizing approach, highlighting higher-order concepts such as pattern formation, generalization, functions, and proof. Their questions encouraged reasoning about conceptual relationships and generalization. Four teachers exhibited a representation-based approach, using real-life contexts, concrete materials, and symbolic representations to make algebra more accessible for students. Five teachers demonstrated relational thinking, connecting algebra to real-life situations, alternative solution paths, and interdisciplinary relationships among mathematical ideas. Four teachers expressed historical and abstract awareness, situating algebra within its historical context and theoretical structures of mathematics.

3.3. Thematic Analysis of Teachers' Frequently Asked Questions Themes Identified:

1. Equality and Equation-Oriented Questions
2. Variable and Unknown Concepts
3. Generalization and Pattern Recognition
4. Real-Life Context and Modeling
5. Conceptual Relationships
6. Shortcuts and Alternative Solutions
7. Historical / Conceptual Awareness

Table 3- Thematic Analysis of Teachers' Frequently Asked Questions

Question Theme	Frequency (f)	Example Questions
Equality and Equation	9	"What is equality?", "Is 3 + 5 an equation?", "What is an equation?"
Variable and Unknown Concepts	8	"What is a variable?", "What is an unknown?", "Are variable and unknown the same?"
Generalization and Pattern	5	"If we were to generalize a pattern or rule, how would we do it?", "Can we make a generalization?"
Real-Life and Modeling	6	"How should we proceed when baking a cake using 1.5 measures?", "In a balance activity, how many balls should be added?"
Conceptual Relationships	4	"What is the relationship between these two?", "How are they connected?"
Shortcuts and Alternative Solutions	3	"Did anyone find a shortcut?", "Can someone find another method?"
Historical / Conceptual Awareness	2	"What is computational capability?", "I assume it dates back to Al-Khwarizmi's time."

This table presents the thematic categorization of questions teachers frequently pose to students. The prominence of "Equality and Equation" (f = 9) and "Variable and Unknown Concepts" (f = 8) shows that teachers mostly focus on symbolic manipulation and equation-solving in algebra instruction. In contrast, themes such as "Generalization and Pattern," "Real-Life and Modeling," and "Conceptual Relationships" indicate engagement with higher-order cognitive processes. However, their lower frequencies suggest limited diversity in question design with respect to conceptual and modeling-oriented tasks. This finding highlights the need for professional development that emphasizes conceptual questioning and model-based instructional strategies in teacher education.

4. Interpretation

Equality and equation-based questions (f = 9) were the most frequently used by teachers, focusing on the nature of equality, the definition of equations, and solving for unknowns. Variable and unknown (f = 8) questions ranked second, addressing distinctions between variable and unknown and their symbolic representations. Generalization and pattern-based questions (f = 5) encouraged rule formation, general expression development, and functional thinking. Real-life and modeling (f = 6) themes showed teachers' attempts to contextualize algebra through tangible, everyday examples such as balance activities or measurement scenarios. Conceptual relationship (f = 4) questions sought to link algebraic ideas with other mathematical domains but were relatively rare.

Shortcut and alternative solution (f = 3) questions appeared in fewer cases, revealing limited focus on flexible thinking. Historical/conceptual awareness (f = 2) was the least frequent, showing that few teachers incorporated the historical or philosophical background of algebra.

5. Discussion and Conclusion

The findings of this study indicate that most teachers' algebraic thinking patterns are predominantly procedural in nature. This result shows that algebra is generally defined by teachers through symbols, unknowns, and equations. Only a limited number of teachers demonstrated conceptual-level algebraic thinking, focusing on higher-order processes such as pattern formation, generalization, and representation.

Within representation-based thinking, teachers explained algebra through concrete models that students could understand. This approach is pedagogically valuable for the development of algebraic thinking, as it bridges abstract concepts with tangible representations. Teachers who demonstrated historical awareness placed algebra within its historical context, potentially supporting students' disciplinary understanding and appreciation of mathematics as a human construct

Teachers' practices were found to be mostly oriented toward equality/equation and variable/unknown questioning patterns, revealing a predominantly procedural classroom discourse (Kieran, 1992; Sfard, 1995). While conceptual-generalizing and modeling-based question types were less frequent, these approaches contribute significantly to the deepening of algebraic thinking (Blanton & Kaput, 2005; Mason, 1996). The imbalance in question design may limit students' abilities to internalize concepts, generalize, and transfer knowledge. Therefore, increasing the variety of question types could enhance learning outcomes (Hrastinski et al., 2019; Kuang et al., 2024).

In conclusion, to foster teachers' algebraic thinking, teacher education programs should emphasize conceptually based activities, modeling tasks, classroom modeling materials, and generalization-oriented applications. Furthermore, short professional development modules focusing on the historical perspective of algebra may strengthen teachers' disciplinary knowledge. The Conceptual Knowledge Form proved to be an effective tool for analyzing teachers' algebraic thinking patterns and can be further utilized in future studies on teacher cognition and professional growth.

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From Cave Walls to Artificial Intelligence: The Historical Evolution of Educational Technology

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Abstract

This study aims to examine the definition and historical development of educational technology. Educational technology emerged from humanity's need to transfer knowledge. From the first visual drawings on cave walls to today's artificial intelligence-supported systems, the role of technology in this process has been redefined in parallel with changes in philosophical and theoretical approaches. The study first examines the historical development of educational technology, then explores key milestones from the philosophical foundations in Ancient Greece to the invention of the printing press, the audiovisual movement, and the digital revolution. It then examines the transition from objectivist knowledge to constructivist systematic knowledge, the most fundamental transformation in the field. In the objectivist sense, technology is seen as a "transmission tool" through which knowledge is conveyed to students as an external reality, while in the constructivist sense, it is positioned as a "cognitive tool" or "learning environment" where students construct their own meaning. Finally, it discusses why technological innovations have not had the expected revolutionary impact on education, through the concepts of teacher resistance and inadequate planning. The study concludes that the successful integration of today's educational technologies (virtual reality, artificial intelligence, etc.) must be supported by a pedagogical perspective.

Keywords: Educational technology, Instructional technology, Objectivism, Constructivism

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1. Introduction

Although educational technology is often associated with physical hardware or digital tools, it has a broad and deep meaning at its core. The etymological origin of the concept is based on the Greek words "techne" (the art of making things functional) and "technologia" (a systematic approach to art). Therefore, instructional technology can be defined as "a systematic approach to art and craft for imparting any kind of knowledge." This approach is expected to be rational, aesthetic, and functional. From a broader perspective, educational technology is a system comprising personnel, tools, processes, and methods for transforming theories related to education theories related to education into the most effective applications.

The history of this discipline can be traced back to the first moment humans asked the question, "How do I teach this?" This development, ranging from drawings on cave walls to the invention of the printing press, from radio to artificial intelligence, reflects not only the evolution of the tools used but also the fundamental philosophical assumptions about the nature of knowledge, learning, and teaching. The purpose of this paper is to summarize the historical development of educational technology with its main turning points and to analyze how the transformation between objectivist and constructivist systematic knowledge, the most fundamental driving force behind this development, has reshaped the role of technology in education.

2. The Historical Development of Instructional Technology

2.1. Early Applications and Philosophical Foundations (Before 1900)

Before the invention of writing, teaching was based on oral culture. The primary tool was the teacher themselves. Remains on cave walls are the earliest examples of technology showing that early humans used models and pictures for educational purposes. With the advent of written history, teaching methods became systematized. In Ancient Greece, the Great Philosophers systematically used methods such as lectures and group discussions. Socrates developed the Socratic method, which accepted knowledge as innate and brought it out through questioning. In the 15th century, the invention of the printing press enabled the dissemination of books and knowledge to the masses, initiating the dominance of textbooks in education. In the 17th century, Comenius emphasized the importance of the senses and real objects in learning with his first illustrated textbook, "Orbis Pictus," and argued that teaching should be done in sequential steps from simple to complex.

2.2. From Visual-Auditory Movement to System Approaches (20th Century)

At the beginning of the 20th century, the use of visual materials in addition to textbooks became widespread through "School Museums." During this period, films, slides, and photographs were seen as complementary tools. Thomas Edison's prediction that "films will fundamentally change education" symbolized the beginning of the Audiovisual Teaching Movement. The movement gained momentum with the use of radio, sound recordings, and talking pictures in education. Edgar Dale's "Cone of Experience" model provided a theoretical framework for material selection by ranking learning experiences from concrete to abstract.

The 1950s and 1960s saw the rise of B.F. Skinner's "programmed instruction" approach. In this approach, learning begins in small steps and led to the development of teaching machines and early Computer-Assisted Instruction (CAI) applications that reinforced correct feedback.

2.3. The Digital Age and the Rise of the Internet

The proliferation of personal computers in the 1980s and the internet in the 1990s opened a new chapter in educational technology. Access to information became globalized, and distance learning gained popularity. Initiatives such as the FATİH Project and the Education Information Network (EBA) in Turkey are reflections of this digital transformation on a national scale. The recent COVID-19 pandemic has accelerated this process irreversibly by making distance and online education widespread throughout the world.

3. Systematic Knowledge Transformation and the Changing Role of Technology

The most profound change in educational technology stems not so much from innovations in tools as from a shift in philosophical assumptions about the nature of knowledge. This transformation has fundamentally altered the function of technology in education.

3.1. Objectivist Approach: Technology as a "Transmission Tool"

According to the objectivist approach, which dominated much of the 20th century, knowledge is an objective reality that exists independently of the individual's mind. According to this view, the human mind is a blank slate ("tabula rasa") at birth. Learning is the process of transferring this external knowledge into the mind.

Behaviorism and early cognitive approaches were built upon this approach. This philosophical foundation positions educational technology as a "transmission or distribution tool." Technology is used to efficiently deliver structured content to students, control their responses, and reinforce correct behaviors. Skinner's teaching machines and early drill-and-practice computer-assisted instruction software are the most concrete products of this understanding.

3.2. Objectivist Approach: Technology as a "Transmission Tool"

The constructivist approach, which gained strength in the 1980s, argues that knowledge is not passively acquired from outside, but rather actively constructed mentally through the individual's experiences and social interactions. Knowledge is not something to be discovered, but something that exists. This radical change has transformed the impact of educational technology from a content producer to a "cognitive tool" that supports the student's process of accessing knowledge. Technology should provide flexible environments that enable students to explore, form hypotheses, see different perspectives, and collaborate. Technologies such as projections, simulations, and the internet, where content is constantly changing and interpreted by the student, are the results of this approach.

4. Discussion: Reasons for Slow Change and Technological Advancement

When examining the historical process, there are high expectations that each new technology, such as film, television, or computers, will fundamentally change education. However, this has often not been the case. Looking at the underlying reasons for this, the effects on learning have been limited because technology has generally been seen as an "add-on" to existing teacher-centered methods, has been met with resistance by teachers, and has not been addressed with a pedagogical approach. Teachers' distant approach to new technologies and the fact that their ideas were not taken into account in the planning processes also led to the failure of the applications. Structural problems such as the high cost of technology, lack of infrastructure in schools, and scarcity of qualified software have also hindered the widespread adoption of technology.

At this point, the concept of "technological formation" becomes important. This view argues that technology is the main driving force behind social change and that institutions must adapt to technological developments. However, experiences in education show that this approach is misleading. It is clear that technology is not an

autonomous force independent of the social and pedagogical context. Success lies not only in the development of technology but also in determining the learning theory and pedagogical strategy within which it will be used.

5. Conclusion and Outlook

The evolution of educational technology is a story of exploration. It carries the human purpose of sharing knowledge and facilitating learning. While this process progresses from simple tools to complex systems, the most meaningful transformation has been observed at the philosophical level. In short, the role of technology role is shifting from being a channel for the passive transfer of knowledge to an environment where knowledge is actively constructed.

Today, technologies such as virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) aim to make learning experiences more personalized, interactive, and multi-sensory. Advancing technology has given rise to new professions such as "artificial intelligence counseling," "artificial intelligence hosting," or "drone piloting." Therefore, it necessitates the transformation of educational programs. However, considering the lessons learned from the past, the success of these new technologies must be based on a solid pedagogical foundation that focuses on learning. Ultimately, it would be appropriate to use technology not as an end in itself, but as a powerful tool that enables students to develop 21st-century skills.

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Inverse Spectral Analysis of Zero-Diagonal Jacobi Matrices with Double Asymmetry via the Parseval-Type Equality

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Abstract

In this study, a discrete inverse spectral problem is investigated for a Jacobi-type tridiagonal matrix with a zero main diagonal and symmetry broken at two interior points. The main objective of the study is to obtain a Parseval-type equation for this structure and, using this equation, to define the orthogonality properties of the system. While the zero main diagonal simplifies the system, asymmetry at two different points creates local breaks in the spectral structure. Furthermore, it is shown that the matrix elements can be reconstructed singularly using two spectra. The obtained results present a new Parseval-based solution approach for zero-diagonal and multi-point asymmetric discrete systems.

Keywords: Parseval-type equality, Zero-diagonal matrix, Double asymmetry, Inverse spectral problem, Two spectra

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1. Introduction

The spectral analysis of Jacobi-type tridiagonal matrices continues to play a central role in modern mathematical physics, orthogonal polynomial theory, and inverse problems associated with discrete dynamical systems. A Jacobi matrix

$$J=\begin{bmatrix} a_0 & b_0 & 0 & \cdots & 0 & 0 & 0 \\ b_0 & a_1 & b_1 & \cdots & 0 & 0 & 0 \\ 0 & b_1 & a_2 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & a_{N-3} & b_{N-3} & 0 \\ 0 & 0 & 0 & \cdots & b_{N-3} & a_{N-2} & b_{N-2} \\ 0 & 0 & 0 & \cdots & 0 & b_{N-2} & a_{N-1} \end{bmatrix}$$

serves as a discrete analogue of Sturm–Liouville operators and arises naturally from second-order difference equations of the form

$$b_{n-1}y_{n-1}+a_n y_n+b_n y_{n+1}=\lambda y_n,\ \ b_{-1}=b_N=1,\ \ n\in\{0,1,...,N-1\} \tag{1}$$

with the boundary conditions

$$y_{-1}=y_N=0, \tag{2}$$

where $y=\{y_n\}_{n=0}^{N-1}$ is column vector which is solution of the second order difference equation.

The study of inverse problems for Jacobi matrices originates from the seminal works of Hochstadt, who provided the systematic reconstruction procedures for tridiagonal systems. He formulated inverse matrix problems based solely on spectral information (Hochstadt, 1967). This line of research was further developed in (Hochstadt 1974), where he established explicit conditions under which a Jacobi matrix can be uniquely constructed from its full eigenvalue set. Subsequently, Hochstadt extended the framework to include mixed or partially specified spectral data, thereby laying the foundation for two-spectra reconstruction techniques (Hochstadt, 1979).

Following the classical contributions of Hochstadt, substantial progress in the theory of inverse spectral problems for Jacobi operators has been achieved, particularly through the works of Gasymov and Guseinov. They initiated the study of inverse problems for infinite Jacobi matrices in the limit–circle case and demonstrated reconstruction techniques based on spectral data in this setting (Gasymov and Guseinov, 1990). Building upon these ideas, Guseinov developed a comprehensive framework for the determination of infinite non-selfadjoint Jacobi matrices via generalized spectral functions (Guseinov, 1978a) and extended this approach to second-order non-selfadjoint difference equations on the whole axis (Guseinov, 1978b). In subsequent years, he made major contributions to the inverse spectral theory of complex Jacobi matrices, establishing reconstruction procedures from one-spectrum and two-spectra (Guseinov, 2010, 2011, 2013). His results include explicit algorithms for constructing finite complex Jacobi matrices from two distinct spectra and characterizing the uniqueness of such reconstructions. Moreover, Guseinov formulated and solved discrete inverse problems involving two spectra for a broad class of finite Jacobi matrices (Guseinov, 2012a, 2012b), and further extended the analysis to tridiagonal complex Hamiltonians, highlighting the structural properties of their spectral data (Guseinov, 2009).

Further developments in the field have been significantly influenced by research on complex Hamiltonian systems, Sturm–Liouville operators with discontinuous coefficients, and discrete spectral problems involving generalized function potentials. Manafov and Bala introduced reconstruction techniques for tridiagonal $N \times N$ complex Hamiltonians in which the spectral parameter appears in the initial conditions, thereby extending classical inverse spectral methods to a broader class of non-selfadjoint systems (Manafov and Bala, 2013). In parallel, Akhmedova and Huseynov studied eigenvalue asymptotics and eigenfunction properties for Sturm–Liouville operators with discontinuous coefficients (Akhmedova and Huseynov, 2003) and later established inverse problem results for such operators, showing how coefficient discontinuities affect recoverability from spectral data (Akhmedova and Huseynov, 2010). Contributions to discrete systems with generalized function potentials were provided by Bala et al. who analyzed both direct and inverse spectral problems for discrete Sturm–Liouville equations (Bala et. Al, 2016). Huseynov also examined finite-dimensional inverse problems and described reconstruction procedures for matrix systems with structural constraints, enriching the algebraic theory of inverse spectral analysis (Huseynov, 2021). More recently, Bala et. al. developed inverse spectral methods for tridiagonal almost-symmetric matrices using both spectral data and two-spectra approaches (Bala et al., 2019), while Manafov et. al. established Parseval-type identities for discrete Sturm–Liouville equations with periodic generalized function potentials, providing new tools for spectral expansions in discrete settings (Manafov et al., 2018).

In light of these developments, the aim of the present study is to investigate a discrete inverse spectral problem for a Jacobi-type tridiagonal matrix whose main diagonal is identically zero and whose symmetry is broken at two distinct interior points. This structural configuration produces a deviation from the classical symmetric setting and requires a analytical treatment. Our primary objective is to derive a Parseval-type equality adapted to this double-asymmetry framework and, on the basis of this equality, to establish the corresponding orthogonality relations for the eigenfunctions. We further demonstrate that the entire set of matrix entries can be uniquely reconstructed from two distinct spectra generated by different boundary conditions. In this way, the paper extends the existing inverse spectral theory to a new class of zero-diagonal and locally asymmetric discrete systems.

Studying perturbed, asymmetric, or locally modified Jacobi matrices has become more popular in recent decades. These structures can be found in wave propagation on discontinuous networks, lattice models in quantum mechanics, numerical analysis, and the investigation of localized impurities in crystal lattices. Significant modifications in the spectral distribution, such as interlacing patterns, spectral shift functions, and altered orthogonality relations, are introduced by even minor deviations from symmetry.

The present study concerns a special class of almost-symmetric Jacobi matrices characterized by a zero main diagonal,

$$a_n = 0, \quad n \in \{0, 1, ..., N-1\} \tag{3}$$

and double asymmetry introduced at two interior points. The resulting matrix takes the form

$$J_1 = \begin{bmatrix} 0 & {}^0b_0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ {}^0b_0 & 0 & {}^0b_1 & \dots & 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & {}^0b_1 & 0 & \dots & 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 0 & {}^0b_{M_1} & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & \dots & {}^1b_{M_1} & 0 & \ddots & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & \ddots & 0 & {}^1b_{M_2} & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & {}^2b_{M_2} & 0 & \dots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots & 0 & {}^2b_{N-3} & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots & {}^2b_{N-3} & 0 & {}^2b_{N-2} \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots & 0 & {}^2b_{N-2} & 0 \end{bmatrix} \tag{4}$$

which preserve the tridiagonal structure but break the symmetry in a controlled manner. Systems of this type arise in discrete Dirac operators, alternating-mass chains, and optical waveguide arrays with phase defects. The matrix J_1 is $N \times N$ tridiagonal matrix and the entries of J_1 are the coefficients of the equation system

$$\begin{aligned} &{}^0b_{n-1}y_{n-1} + {}^0b_n y_{n+1} = \lambda y_n, && n \in \{0,1,\dots,M_1\}, && {}^0b_{-1} = 1, \\ &{}^1b_{n-1}y_{n-1} + {}^1b_n y_{n+1} = \lambda y_n, \ , && n \in \{M_1+1, M_1+2,\dots,M_2\}, && \\ &{}^2b_{n-1}y_{n-1} + {}^2b_{n,1} y_{n+1} = \lambda y_n, \ , && n \in \{M_2+1, M_2+2,\dots,N-1\}, && {}^2b_{N-1} = 1, \end{aligned} \tag{5}$$

with the boundary conditions (2) and where

$$\begin{aligned} &{}^0b_n = b_n / \alpha_0, \quad n \in \{0,1,\dots,M_1\}, \\ &{}^1b_n = b_n / \alpha_1, \quad n \in \{M_1+1, M_1+2,\dots,M_2\}, \\ &{}^2b_n = b_n / \alpha_2, \quad n \in \{M_2+1, M_2+2,\dots,N-1\}. \end{aligned} \tag{6}$$

and $b_n \in \mathbb{R}^+$. we can rewritten the problem (5) and (6),

$$b_{n-1}y_{n-1} + b_n y_{n+1} = \lambda \sigma_n y_n, \ \frac{b_{-1}}{\sigma_0} = \frac{b_{N-1}}{\sigma_{N-1}} = 1, \ n \in \{0,1,\dots,N-1\} \tag{7}$$

with the boundary conditions (2) and where σ_n is constant

$$\sigma_n = \begin{cases} a_0, & 0 \le n \le M_1 \\ \alpha_1, & M_1 < n \le M_2 \\ a_2, & M_2 < n \le N-1 \end{cases}, \quad \alpha_0 = 1, \quad \alpha_j \in \mathbb{R}^+ - \{1\}, \quad j = 1,2, \tag{8}$$

where numbers α_1, α_2 are different from each other and $b_n \in \mathbb{R}^+$.

So, the eigenvalue problem $J_1 y = \lambda y$ is equivalent problem (7) - (8) which is discrete form Sturm-Liouville problem with discontinuous coefficients

$$\frac{d}{dx}\left[p(x)\frac{d}{dx}y(x)\right]+q(x)y(x)=\lambda\rho(x)y(x),\quad x\in[a,b],$$
$$y(a)=y(b)=0, \tag{9}$$

where and $\rho(x)$ is a piecewise function

$$\rho(x)=\begin{cases}\alpha_0^2, & a\le x\le c_1\\ \alpha_1^2, & \mathrm{c}_1<x\le c_2, \qquad \alpha_j^2\ne 1,\ j=0,1,2.\\ \alpha_2^2, & \mathrm{c}_2<x\le b\end{cases}$$

Since the entries of main diagonal of the matrix J_1 are zero, the potential function $q(x)$ in the Sturm Liouville equation (9) is also equal to zero. Specifically, the lack of a potential improves the model's structural clarity: any departures from the conventional symmetric case are solely caused by localized discontinuities in the diffusion coefficient $p(x)$. Consequently, this approach improves the formulation of the related inverse spectral problem by streamlining the analysis and highlighting the fundamental relevance of the double asymmetry.

2. Direct Spectral Problem

Denote eigenvalues of Jacobi-type matrix J_1 by $\lambda_1,\lambda_2,\ldots,\lambda_N$ and let $v_1,v_2,\ldots,v_N$ be the corresponding eigenvectors, which form an orthonormal basis.

Assuming that all eigenvalues of J_1 are real, we recall the classical structure of the spectral decomposition of J_1 and summarize the basic formulation of the direct spectral problem for this matrix.

Let $P_n(\lambda)$ be a solution of equation (7)

$$b_{n-1}P_{n-1}(\lambda)+b_nP_{n+1}(\lambda)=\lambda\sigma_nP_n(\lambda),\qquad n\in\{0,1,\ldots,N-1\} \tag{10}$$

with initial conditions

$$P_{-1}(\lambda)=0,\quad P_0(\lambda)=1, \tag{11}$$

where σ_n is defined by (8) and the degree of polynomial $P_n(\lambda)$ is n.

Lemma 2.1 *The following equality holds:*

$$\det(J_1-\lambda I)=(-1)^N\left(\prod_{i=0}^{M_1}{}^0b_i\right)\left(\prod_{j=M_1+1}^{M_2}{}^1b_j\right)\left(\prod_{k=M_2+1}^{N-2}{}^2b_k\right)P_N(\lambda).$$

According to Lemma 2.1, the roots of the equation $P_n(\lambda)$ are equal the eigenvalues of J_1, and eigenvectors corresponding eigenvalues $\lambda_k,\ k=\overline{1,N}$ will be

$$\Re\left(\lambda_k\right)=\left(P_0\left(\lambda_k\right),P_1\left(\lambda_k\right),\ldots,P_{N-1}\left(\lambda_k\right)\right)^T.$$

Assuming that $v_k=\frac{\Re\left(\lambda_k\right)}{\sqrt{\beta_k}}$, where $\beta_k=\sum_{j=0}^{N-1}P_j^2\left(\lambda_k\right)$. Thus, we have the complete orthonormalized system of eigenvectors of the matrix J_1. The numbers β_k are called normalized numbers of the problem (10) - (11).

Lemma 2.2 *Eigenvalues of matrix J_1 are different.*

Proof. Because of eigenvalues $\lambda_k,\ k=1,2,\ldots,N$ are the roots of polynomial $P_N\left(\lambda\right)$, we must show that $P_N'\left(\lambda_k\right)\neq 0$. Firstly, take the derivative equation (10) by λ, we have

$$b_{n-1}P_{n-1}'\left(\lambda\right)+b_nP_{n+1}'\left(\lambda\right)=\lambda\sigma_nP_n'\left(\lambda\right)+\sigma_nP_n\left(\lambda\right). \tag{12}$$

Now, if the equation (12) is multiplied by $P_n\left(\lambda\right)$ and the equation (10) is multiplied by $P_n'\left(\lambda\right)$, the second result is substracted from the first, for $n\in\{0,1,\ldots,N-1\}$ we obtain:

$$b_{n-1}\left(P_{n-1}'\left(\lambda\right)P_n\left(\lambda\right)-P_n'\left(\lambda\right)P_{n-1}\left(\lambda\right)\right)-b_n\left(P_n'\left(\lambda\right)P_{n+1}\left(\lambda\right)-P_{n+1}'\left(\lambda\right)P_n\left(\lambda\right)\right)=\sigma_nP_n^2\left(\lambda\right) \tag{13}$$

For $\lambda=\lambda_k$ and summing n from 0 to $N-1$, pay attention to (8), (11), and $P_N\left(\lambda_k\right)=0$ we have

$$b_{N-1}P_N'\left(\lambda_k\right)P_{N-1}\left(\lambda_k\right)=\sum_{j=0}^{M_1}\alpha_0P_j^2\left(\lambda\right)+\sum_{j=M_1+1}^{M_2}\alpha_1P_j^2\left(\lambda\right)+\sum_{j=M_2+1}^{N-1}\alpha_2P_j^2\left(\lambda\right). \tag{14}$$

As a result, $P_N'\left(\lambda_k\right)\neq 0$. ■

According to Lemma 2.2, we can assume that $\lambda_1<\lambda_2<\ldots<\lambda_N$. The following Lemma is about Parseval equality.

Lemma 2.3 *The expansion formula, which is equivalent to equality of the Parseval type, can be expressed as follows:*

$$\sum_{j=1}^{N}\frac{\gamma}{\beta_j}P_m\left(\lambda_j\right)P_n\left(\lambda_j\right)=\delta_{mn},\quad m,n=\overline{0,N-1} \tag{15}$$

where η is defined by

$$\gamma=\begin{cases}\alpha_0, & m \text{ or } n\leq M_1\\ \alpha_1, & \mathrm{M}_1< m \text{ or } n\leq M_2,\\ \alpha_2, & M_2<m \text{ or } n\end{cases} \tag{16}$$

and δ_{mn} is the Cronecker delta.

For $n=m=0$ in the equality (15) and from conditions (11) we obtain following equality

$$\sum_{j=1}^{N}\frac{\gamma}{\beta_j}=\frac{1}{\alpha_0}=1. \tag{17}$$

Thus, we get eigenvalues $\{\lambda_k\}_{k=1}^{N}$ and eigenvectors v_j, $j=1,2,\dots,N$ corresponding $\{\lambda_k\}_{k=1}^{N}$. So, we can say that the direct spectral problem of spectral analysis is solved.

Now let's try to answer the following question:

If the eigenvalues $\{\lambda_k\}_{k=1}^{N}$ and the corresponding eigenvectors $\{v_k\}_{k=1}^{N}$ of the matrix J_1 are known, one may attempt to reconstruct the matrix J_1 through the representation

$$J_1u=\sum_{k=1}^{N}\lambda_k\left(u,v_k\right)v_k,\quad u\in l_2\left(0,N-1\right)$$

where $\left(u,v\right)=\sum_{j=0}^{N-1}u_j\overline{v}_j$ scalar product.

However, it is evident that the eigenvalues of J_1 alone are insufficient for reconstructing the matrix J_1 . Therefore, additional information regarding the eigenvectors is required in order to achieve a unique reconstruction.

Definition 2.4 *The collection of quantitites $\{\lambda_k,\beta_k\}$ are called spectral data for the matrix J_1*

Additional we will need the presentation of entries of the matrix J_1 by the polynomial $P_n\left(\lambda\right)$. For $\lambda=\lambda_j$ the equation (10) is multiplied by $\frac{\gamma}{\beta_j}P_m\left(\lambda_j\right)$, then summing by j from 1 to N and using Lemma 2.3, we have

$$b_n=\sum_{j=1}^{N}\frac{\gamma^2\lambda_j}{\beta_j}P_n\left(\lambda_j\right)P_{n+1}\left(\lambda_j\right),\qquad n=\overline{0,N-2}-\{M_1,M_2\},$$

where γ is defined by (16). It is clear that $\sigma_n=\gamma$ for m or $n>M$. Then, we can write these equalities as below:

$${}^0b_n=\sum_{j=1}^{N}\frac{\alpha_0\lambda_j}{\beta_j}P_n\left(\lambda_j\right)P_{n+1}\left(\lambda_j\right),\qquad n=\overline{0,M_1-1}, \tag{18}$$

$${}^0b_{M_1}=\sum_{j=1}^{N}\frac{\alpha_1\lambda_j}{\beta_j}P_{M_1}\left(\lambda_j\right)P_{M_1+1}\left(\lambda_j\right),\qquad {}^1b_{M_1}=\sum_{j=1}^{N}\frac{\alpha_1\lambda_j}{\beta_j}P_{M_1}\left(\lambda_j\right)P_{M_1+1}\left(\lambda_j\right), \tag{19}$$

$${}^1b_n=\sum_{j=1}^{N}\frac{\alpha_1\lambda_j}{\beta_j}P_n\left(\lambda_j\right)P_{n+1}\left(\lambda_j\right),\qquad n=\overline{M_1+1,M_2-1}, \tag{20}$$

$${}^1b_{M_2}=\sum_{j=1}^{N}\frac{\alpha_2\lambda_j}{\beta_j}P_{M_2}\left(\lambda_j\right)P_{M_2+1}\left(\lambda_j\right),\qquad {}^2b_{M_2}=\sum_{j=1}^{N}\frac{\alpha_2\lambda_j}{\beta_j}P_{M_2}\left(\lambda_j\right)P_{M_2+1}\left(\lambda_j\right), \tag{21}$$

$$ {}^{2}b_n = \sum_{j=1}^{N} \frac{\alpha_2 \lambda_j}{\beta_j} P_n(\lambda_j) P_{n+1}(\lambda_j), \quad n = \overline{M_2+1, N-2}, \tag{22} $$

3. Inverse Problem of Spectral Analysis

The inverse problem of spectral analysis is reconstruct matrix J_1 by using the collection quantities $\{\lambda_k, \beta_k\}$.

Theorem 3.1 *Let an arbitrary collection $\{\lambda_k, \beta_k\}$ of matrix J_1. In order for this collection to be spectral data for some matrix which have form J_1, it is necessary and sufficient that the following conditions be satisfied:*

$$ (i)\ \ \lambda_k \neq \lambda_j, \qquad (ii)\ \ \sum_{j=1}^{N} \frac{\gamma}{\beta_j} = 1, \qquad (iii)\ \ b_n > 0, \quad n = \overline{0, N-2}. $$

Lemma 3.2 *Let λ_k, $k = \overline{1,N}$ are distinct real numbers and for the positive numbers β_k, $k = \overline{1,N}$ be given that $\sum_{j=1}^{N} \frac{\gamma}{\beta_j} = 1$. Then there exists unique polynomials $P_k(\lambda)$, $k = \overline{0, N-1}$ with $\deg P_j(\lambda) = j$ and positive leading coefficients satisfying the conditions (15).*

We will now present the Gelphand-Levitan-Marchenko method, which is a different approach to solving the inverse spectral problem.

Let $R_n(\lambda)$ be a solution of the equation (7) satisfying the conditions

$$ R_{-1}(\lambda) = 0, \quad R_0(\lambda) = 1, $$

in the case ${}^{i}b_n \equiv 1, \quad i = 0,1,2$.

Recall that $P_n(\lambda)$ is a polynomial of degree n, so it can be expressed as

$$ P_n(\lambda) = \eta_n \left(R_n(\lambda) + \sum_{k=0}^{n-1} \chi_{n,k} R_k(\lambda) \right), \quad n \in \{0, 1, \ldots, N\}, \tag{23} $$

where η_n and $\chi_{n,k}$ are constants. There is a connection between coefficients ${}^{0}b_n, {}^{1}b_n, {}^{2}b_n$ and $\eta_n, \chi_{n,k}$. Then we can write the equalities

$$ \begin{aligned} {}^{0}b_n &= \frac{\eta_n}{\eta_{n+1}} \quad (0 \le n \le M_1), \qquad \eta_0 = 1, \\ {}^{1}b_n &= \frac{\eta_n}{\eta_{n+1}} \quad (M_1 < n \le M_2), \quad {}^{1}b_{M_1} = \frac{\eta_M}{\alpha_1 \eta_{M+1}}, \\ {}^{2}b_n &= \frac{\eta_n}{\eta_{n+1}} \quad (M_2 < n \le N-2), \quad {}^{2}b_{M_2} = \frac{\alpha_1 \eta_M}{\alpha_2 \eta_{M+1}} \end{aligned} \tag{24} $$

Now, we can write from (23)

$$\sum_{j=1}^{N}\frac{\gamma}{\beta_j}P_n\left(\lambda_j\right)R_m\left(\lambda_j\right)=\eta_n\left[G_{nm}+\sum_{k=0}^{n-1}\chi_{n,k}G_{km}\right], \tag{25}$$

Where where γ is defined by (16) and

$$G_{nm}=\sum_{j=1}^{N}\frac{\gamma}{\beta_j}R_n\left(\lambda_j\right)R_m\left(\lambda_j\right). \tag{26}$$

Since the expansion

$$R_j\left(\lambda\right)=\sum_{k=0}^{j}w_k^{(j)}P_k\left(\lambda\right)$$

holds, then from (15) we have

$$\sum_{j=1}^{N}\frac{1}{\beta_j}P_n\left(\lambda_j\right)R_m\left(\lambda_j\right)=\frac{1}{\eta_n\gamma}\delta_{nm},\ \ n\geq 0,\ \ s=\overline{0,n}.$$

Considering the equality (25) we get

$$G_{nm}+\sum_{k=0}^{n-1}\chi_{n,k}G_{km}=0,\quad m=\overline{0,n-1},\ \ n\geq 1, \tag{27}$$

$$G_{nn}+\sum_{k=0}^{n-1}\chi_{n,k}G_{kn}=\frac{1}{\eta_n^2\gamma},\quad n=\overline{0,N-1}. \tag{28}$$

Equations (27) play a critical role in solving the inverse spectral problem. First, the values G_{nm} are determined by means of (26), and subsequently the quantities $\chi_{n,k}$, $k=\overline{0,n-1}$ are obtained from the system of equations (27). Hence, using the functions $\chi_{n,k}$ we can determine the unknowns η_n through equations (28).

Lemma 3.3 *For any fixed n the system of equations (27) is identically solvable.*

Lemma 3.4 *Let G_{nm}, $m=\overline{0,n-1}$ be a solution of the system (27). Then*

$$G_{nm}+\sum_{k=0}^{n-1}\chi_{n,k}G_{km}>0,\quad n=\overline{0,N-1}.$$

Therefore we can determine the entries of the matrix J_1 from the formulas (24).

4. Inverse Problem for Two Spectra

Consider the boundary value problem

$$b_{n-1}y_{n-1} + b_n y_{n+1} = \lambda\sigma_n y_n, \quad n = \overline{1, N-1}, \tag{29}$$

with the boundary conditions

$$y_0 = y_N = 0, \tag{30}$$

where σ_n is defined in (8). Now, the matrix of coefficients of (29) is denoted by J_2 which has the same form with matrix J_1. If we delete the first row and the first column of the matrix J_1, then we have $N-1 \times N-1$ tridiagonal matrix J_2 which has $N-1$ number eigenvalues μ_k, $k = \overline{1, N-1}$. Assume that eigenvalues of matrix J_2 are distinct and real. Thus we can write

$$\mu_1 < \mu_2 < \ldots < \mu_{N-1}.$$

The solution of equation (29) is denoted by $\{Q_n(\lambda)\}$ provided that $Q_0(\lambda) = 0, Q_1(\lambda) = 1$. It is clear that the eigenvalues μ_j, $j = \overline{1, N-1}$ are zeros of the polynomial $Q_N(\lambda)$. While we determine entries of J_1, we will use eigenvalues of matrices J_1 and J_2.

Now we will give an important lemma for the inverse spectral problem according to the two spectra.

Lemma 4.1 *The eigenvalues of matrices J_1 and J_2 alternate, i.e.*

$$\lambda_1 < \mu_1 < \lambda_2 < \mu_2 < \ldots < \lambda_{N-1} < \mu_{N-1} < \lambda_N.$$

Additionally, we can find the normalized numbers β_k by aid of two spectrums $\lambda_1, \lambda_2, \ldots, \lambda_N$ and $\mu_1, \mu_2, \ldots, \mu_{N-1}$ of the matrices J_1 and J_2 respectively. Assume that

$$f_n(\lambda) = Q_n(\lambda) + m(\lambda)P_n(\lambda), \tag{31}$$

and require that $f_N(\lambda) = 0$. $m(\lambda)$ is a meromorphic function,

$$m(\lambda) = -\frac{Q_N(\lambda)}{P_N(\lambda)} \tag{32}$$

its poles and zeros coincide with the eigenvalues of the problem (7)-(8) and (29)-(30) respectively. We see that the function $f_n(\lambda)$ satifies the equation

$$b_{n-1}f_{n-1}(\lambda) + b_n f_{n+1}(\lambda) = \lambda\sigma_n f_n(\lambda).$$

Now, if the above equality is multiplied by $P_n\left(\lambda_k\right)$ and the equality (10) (for $\lambda=\lambda_k$) is multiplied by $f_n\left(\lambda\right)$ then the second result is substracted from the first and sum by n, we obtain:

$$\left(\lambda-\lambda_k\right)\sum_{n=1}^{N-1}\sigma_n f_n\left(\lambda\right)P_n\left(\lambda_k\right)=\sum_{n=1}^{N-1}\begin{Bmatrix} b_{n-1}\left(f_{n-1}\left(\lambda\right)P_n\left(\lambda_k\right)-P_{n-1}\left(\lambda_k\right)f_n\left(\lambda\right)\right)\\ -b_n\left(f_n\left(\lambda\right)P_{n+1}\left(\lambda_k\right)-P_n\left(\lambda_k\right)f_{n+1}\left(\lambda\right)\right)\end{Bmatrix}$$

or

$$\left(\lambda-\lambda_k\right)\sum_{n=1}^{N-1}\sigma_n f_n\left(\lambda\right)P_n\left(\lambda_k\right)=-b_0,$$

and then for $\lambda\to\lambda_k$, we have

$$\beta_k=\frac{{}^0b_0 P_N'\left(\lambda_k\right)}{Q_N\left(\lambda_k\right)}.$$

On the other hand from Lemma 2.1, we get

$$\det\left(J_1-\lambda I\right)=\left(-1\right)^N\left(\prod_{i=0}^{M_1}{}^0b_i\right)\left(\prod_{j=M_1+1}^{M_2}{}^1b_j\right)\left(\prod_{k=M_2+1}^{N-2}{}^2b_k\right)P_N\left(\lambda\right)$$

$$\det\left(J_2-\lambda I\right)=\left(-1\right)^{N-1}\left(\prod_{i=1}^{M_1}{}^0b_i\right)\left(\prod_{j=M_1+1}^{M_2}{}^1b_j\right)\left(\prod_{k=M_2+1}^{N-2}{}^2b_k\right)Q_N\left(\lambda\right)$$

and from these equalities we can find

$$P_N\left(\lambda\right)=\frac{\left(\lambda-\lambda_1\right)\ldots\left(\lambda-\lambda_N\right)}{\left(\prod_{i=0}^{M_1}{}^0b_i\right)\left(\prod_{j=M_1+1}^{M_2}{}^1b_j\right)\left(\prod_{k=M_2+1}^{N-2}{}^2b_k\right)},\qquad Q_N\left(\lambda\right)=\frac{\left(\lambda-\mu_1\right)\ldots\left(\lambda-\mu_{N-1}\right)}{\left(\prod_{i=1}^{M_1}{}^0b_i\right)\left(\prod_{j=M_1+1}^{M_2}{}^1b_j\right)\left(\prod_{k=M_2+1}^{N-2}{}^2b_k\right)}.$$

As a result

$$\beta_k=\frac{\prod_{\substack{j=1\\ j\neq k}}^{N}\left(\lambda_k-\lambda_j\right)}{\prod_{j=1}^{N-1}\left(\lambda_k-\mu_j\right)}.$$

Theorem 4.2 *Let the collections $\left\{\lambda_k\right\}_{k=1}^{N}$, $\left\{\mu_k\right\}_{k=1}^{N-1}$ to be real numbers. These collections are spectrums of the $N\times N$ and $N-1\times N-1$ tridiagonal almost-symmetric matrices J_1 and J_2, respectively, it is necessary and sufficient that they are alternate as below:*

$$\lambda_1<\mu_1<\lambda_2<\mu_2<\ldots<\lambda_{N-1}<\mu_{N-1}<\lambda_N.$$

1. Conclusion

In solving the inverse spectral problem based on two distinct spectra, we first determine the normalized numbers β_k of the matrix J_1 by using the $\{\lambda_k\}_{k=1}^{N}$, $\{\mu_k\}_{k=1}^{N-1}$ associated with the auxiliary matrices J_1 and J_2, respectively. Thus, we reduce the problem from two spectra to spectral analysis, and then we determine the values G_{nm}, $\chi_{n,k}$ and η_n from the formulas (26)-(28) by aid of the eigenvalues λ_k and the normalized numbers β_k of the matrix J . Thus, the entries ${}^0b_n$, ${}^1b_n$, ${}^2b_n$ are found from the equalities (24) Thus, the matrix J_1 is reconstructed by using Parseval-type equality.

The findings verify that reconstructibility is not hindered by the matrix's double-asymmetry structure; rather, it results in a richer spectral configuration from which all coefficients can still be uniquely identified.

This technique relies heavily on the Parseval-type equality, which connects the reconstruction formulas to the orthogonality properties of the eigenfunctions. Thus, the work offers an explicit and constructive method for recovering the complete set of matrix parameters in addition to extending the standard two-spectra inverse spectral theory to a new class of zero-diagonal and locally asymmetric Jacobi matrices.

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Comparative Analysis of ByteTrack, YOLOv11n, SAM2 and RF-DETR in Multi-Human Tracking

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Abstract

In recent years, multi-human tracking in videos has become an essential research area, especially for applications in surveillance, sports analysis, and behavior monitoring. This study presents a comparative analysis of four modern algorithms—ByteTrack, YOLOv11n, SAM2, and RF-DETR—evaluated under varying video conditions. The evaluation was conducted using four videos sourced from the internet, each representing a different real-world scenario: a distant football match under daylight, a close-up nighttime football match with rapid camera movement, an indoor basketball game with good lighting, and a street scene in rainy daylight. Results indicated that ByteTrack demonstrated strong tracking capabilities across all scenarios but occasionally misidentified background elements such as audiences or umbrellas. RF-DETR and YOLOv11n offered similarly robust performance, with RF-DETR showing slightly better consistency during fast camera motion and crowded scenes. SAM2, which requires manual initialization of tracking targets, showed high accuracy when the targets were clearly visible in the first frame but struggled in scenes where not all objects appeared initially. The study highlights the strengths and limitations of each algorithm, suggesting that RF-DETR and ByteTrack are the most versatile in diverse environments, while SAM2 is best suited for controlled scenes with known initial object positions.

Keywords: Multi-human tracking, computer vision, ByteTrack, YOLOv11n, SAM2, RF-DETR, video analysis, Object tracking algorithms.

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1. Introduction

In recent years, the task of tracking human movements in video sequences has gained substantial attention in the field of computer vision. This process is particularly critical in applications such as security surveillance, sports analytics, human-computer interaction, and behavioral monitoring in both public and private settings. As emphasized by Anne and Brindha (2025), maintaining consistent object identity across video frames—particularly under challenging conditions such as occlusions—is a key component in achieving accurate person counting and ensuring continuity in multi-object tracking systems.

Despite notable advancements, Multi-Person Tracking (MPT) remains a complex and unresolved challenge. The difficulties stem from a range of real-world factors, including dynamic lighting conditions, varying camera angles, dense crowds, rapid object movements, and frequent changes in direction. These conditions demand the development and implementation of highly adaptive and robust tracking algorithms that can deliver consistent performance across a variety of environments and scenarios.

Although numerous state-of-the-art MPT algorithms have been introduced, a gap still exists in comparative studies that assess their effectiveness under different environmental and contextual settings using real-world video footage.

Most evaluations are either conducted in controlled settings or focus on a limited range of conditions, making it difficult for researchers and practitioners to determine which algorithms are most suitable for specific real-world use cases.

This study aims to address this gap by conducting a comprehensive qualitative evaluation of four state-of-the-art MPT algorithms—ByteTrack, YOLOv11n, SAM2, and RF-DETR—applied across four diverse video scenarios obtained from publicly available online sources. Each video was selected to represent a distinct tracking challenge:

1. **Video 1:** A wide-angle, daylight football match where both players and a distant crowd are visible. This scene presents challenges related to object density and visual clutter due to the presence of multiple players and partial visibility of the audience.
2. **Video 2:** A nighttime football match shot with a closer camera angle, capturing fast player movements and rapid camera motion. Despite good artificial lighting, the scene introduces difficulties in maintaining identity due to motion blur and limited frame stability.
3. **Video 3:** A rainy daytime outdoor scene with two pedestrians walking at a regular pace amidst various static and moving background elements like cars and umbrellas. The camera is relatively close to the subjects, testing the algorithm's ability to isolate individuals from complex urban environments.
4. **Video 4:** An indoor basketball game involving four players in a stable, well-lit environment. This video represents a controlled scene with minimal distractions and consistent lighting, allowing for a clear assessment of each algorithm's baseline tracking performance.

All four algorithms were evaluated based on visual observation only; no quantitative metrics (e.g., MOTA, IDF1) were applied. The objective was to observe each algorithm's qualitative tracking accuracy, identity preservation, and robustness under different scene conditions.

The primary objective of this study is to identify which algorithm performs best under each of the four video scenarios and to explore their adaptability in practical, real-world MPT tasks. By offering this comparative evaluation, the study seeks to contribute valuable insights into the strengths and limitations of modern tracking algorithms, thereby informing future development and deployment of MPT systems across varied application domains. The remainder of this paper is structured as follows: Section 2 reviews related literature and previous work in MPT, section 3 describes the methodology used for algorithm evaluation, Section 4 presents and discusses the experimental results, and Section 5 concludes the study with a summary of key findings and directions for future research.

2. Literature Summary

Recent advancements in multi-object tracking (MOT), particularly within the scope of multi-person tracking (MPT), have led to the development of numerous tracking-by-detection frameworks that aim to balance tracking accuracy with computational efficiency. Akola (2023) conducted a comparative analysis between two prominent algorithms—SORT and Tracktor++—using the MOT17 dataset. The study highlighted notable limitations of SORT, especially its inability to manage occlusions and preserve object identities across frames. In contrast, Tracktor++, which incorporates a re-identification (Re-ID) module, demonstrated enhanced performance in complex and densely populated scenes, emphasizing the importance of dynamic motion modeling and robust detection techniques in achieving reliable tracking outcomes.

In a comprehensive survey, Ciaparrone et al. (2020) categorized MOT methodologies into classical and deep learning-based approaches. Their analysis underlined essential elements such as detection accuracy, feature representation, and data association, all of which collectively influence the robustness of a tracking system. A key observation in their work was the reduced effectiveness of many tracking algorithms under real-world conditions, where factors like occlusions, target similarities, and camera motion present significant challenges. This observation reveals a gap in the literature concerning the qualitative evaluation of tracking algorithms in diverse environmental settings.

Expanding upon these findings, Premanand and Kumar (2023) proposed a hybrid framework that integrates a Modified Recurrent Neural Network (MRNN) with a Pearson Similarity-based Kuhn-Munkres (PS-KM) algorithm. Their model achieved an accuracy of 97% with a false positive rate of only 2.3% on MOT datasets, demonstrating the advantages of advanced data association strategies and feature extraction mechanisms. The study underscores the importance of adaptive tracking systems capable of addressing real-time variations in lighting, motion blur, and partial occlusions.

Further contributions to this field include BoT-SORT, introduced by Aharon et al. (2022), which offers a refined tracking-by-detection framework tailored for multi-human tracking scenarios. This approach incorporates camera motion compensation (CMC) and an enhanced Kalman filter formulation, effectively addressing key shortcomings observed in traditional SORT-based algorithms. BoT-SORT achieves state-of-the-art results on MOT17 and MOT20 benchmarks, outperforming existing methods across various evaluation metrics such as MOTA, IDF1, and HOTA. Similarly, Ghodake et al. (2024) presented a framework that combines YOLO-based object detection with DeepSORT tracking. Their model emphasizes the use of Non-Maximum Suppression (NMS) and Intersection over Union (IoU) techniques to mitigate the impact of overlapping detections and occlusions. The proposed system demonstrated robust performance in real-world scenarios such as surveillance and traffic monitoring, highlighting the effectiveness of integrating strong feature extraction and motion prediction techniques to address issues like occlusion, scale variation, and environmental noise.

While these studies offer valuable contributions to the field of MOT, the majority focus on quantitative evaluations using controlled datasets. The present study evaluates four state-of-the-art MPT algorithms—ByteTrack, YOLOv11n, SAM2, and RF-DETR—using publicly available video footage, aiming to provide practical insights into their strengths and limitations in realistic deployment environments.

3. Materials and Methods

The video datasets used in this study were obtained from publicly available online sources. The dataset consisted of four real-world scenarios: (1) a wide-angle football match in daylight, (2) a close-up football match at night with fast motion, (3) an indoor basketball game with stable lighting, and (4) a rainy outdoor pedestrian street scene with both people and vehicles. The evaluation process was qualitative, focusing on visual inspection and subjective judgment of each algorithm's tracking consistency and reliability. Quantitative metrics such as processing speed or frame-per-second performance were not recorded.

3.1. ByteTrack

ByteTrack is a multi-object tracking algorithm introduced by Zhang et al. (2022) that improves the tracking-by-detection paradigm by incorporating both high and low-confidence detection boxes into the association process. Unlike traditional methods that discard low-score detections, ByteTrack retains them and uses motion-based matching to recover true targets that may be occluded or difficult to detect.

3.2. YOLOv11n

YOLOv11n is a lightweight and efficient variant of the YOLO (You Only Look Once) object detection family, designed for real-time applications. In this study, it was used as the detection backbone for the tracking pipeline.

3.3. SAM2

SAM2 is a segmentation-based tracking method derived from the Segment Anything Model (SAM) (Ravi et al., 2024). It allows manual selection of target objects in the first frame, enabling user-guided tracking. SAM2 was implemented using the SAM2VideoPredictor library, and the bboxwidget tool was employed for designating the individuals to be Tracked. Each frame of the video was processed sequentially to track the selected targets.

3.4. RF-DETR

RF-DETR (Real-time Fast-DEtection TRansformer) is a transformer-based real-time object detection model developed by Roboflow (2024), based on Deformable DETR and LW-DETR. It employs a pre-trained DINOv2 backbone and deformable attention mechanisms for efficient global context modeling. The model supports two configurations—RF-DETR-Base and RF-DETR-Large—and removes the need for anchor boxes and Non-Maximum Suppression (NMS), enabling end-to-end training. In this study, RF-DETR was applied across the selected video scenarios.

4. Results and Discussion

This section presents the qualitative evaluation results of the four multi-person tracking algorithms—ByteTrack, YOLOv11n, SAM2, and RF-DETR—across four distinct real-world video scenarios. The assessment was conducted through visual inspection of tracking behavior in each video, focusing on identity preservation, robustness to occlusion, background confusion, and stability under different environmental conditions. No quantitative metrics were employed; instead, the evaluation emphasizes practical performance in realistic deployment settings. Each scenario corresponds to a publicly available video source listed in the References section. The comparison results are shown in Table 1.

4.1. Video 1: Daylight Football Match (Wide-Angle View)

The first scenario consists of a wide-angle daylight football match broadcast, characterized by a large number of players on the field and visible spectators in the background (Video Source 1). This environment presents challenges related to object density, scale variation, and background clutter.
ByteTrack demonstrated strong tracking performance by successfully maintaining trajectories for nearly all players throughout the video. However, the algorithm occasionally misclassified spectators in the front rows as players, resulting in background-related tracking noise. RF-DETR also tracked the majority of players effectively, though it experienced minor tracking loss for some individuals in certain frames. Compared to ByteTrack, RF-DETR exhibited fewer instances of spectator confusion.
YOLOv11n showed similar behavior to RF-DETR, providing generally stable tracking with rare misidentification of background elements. SAM2 achieved high tracking accuracy due to manual target initialization, which allowed it to focus exclusively on selected players and avoid tracking spectators. Nevertheless, during periods of fast motion or player overlap, SAM2 occasionally lost track of some individuals and exhibited brief identity switches. Despite these limitations, SAM2 delivered the most precise tracking in this scenario when manual initialization was feasible.

.2 Video 2: Nighttime Football Match (Close-Up, Fast Motion)

The second scenario involves a nighttime football match recorded with a closer camera angle and rapid camera motion, introducing motion blur and frequent viewpoint changes (Video Source 2). This scenario tests the robustness of tracking algorithms under fast movement and unstable visual conditions.
RF-DETR and YOLOv11n performed exceptionally well, maintaining stable tracking and consistent identities despite rapid camera pans and player movements. ByteTrack initially tracked players accurately but experienced occasional tracking loss during abrupt camera transitions. SAM2 was not effectively applicable in this scenario, as its reliance on manual initialization conflicted with the partial visibility of players at the beginning of the video. As a result, SAM2 was excluded from meaningful evaluation in this context.

4.3 Video 3: Rainy Street Scene (Pedestrians)

The third scenario features two pedestrians walking at a steady pace in a rainy urban environment, with various background elements such as vehicles and umbrellas present (Video Source 3). This setting

evaluates the ability of algorithms to distinguish humans from visually similar objects under adverse weather conditions.
ByteTrack, RF-DETR, and SAM2 all demonstrated excellent performance, accurately tracking both pedestrians without identity confusion or loss. YOLOv11n also tracked the pedestrians reliably; however, it occasionally misidentified parts of the umbrellas as additional human targets, leading to minor tracking inaccuracies. Overall, this scenario highlighted the effectiveness of all algorithms in low-density scenes, with slight limitations observed in detection-based approaches when confronted with visually ambiguous objects.

4.4 Video 4: Indoor Basketball Game

The final scenario consists of an indoor basketball game involving four players in a stable, well-lit environment (Video Source 4). This controlled setting provides an opportunity to assess baseline tracking performance with minimal environmental complexity.
ByteTrack, RF-DETR, and SAM2 maintained highly accurate tracking throughout the video, consistently preserving player identities and avoiding confusion with surrounding objects. In contrast, YOLOv11n occasionally misclassified static objects, such as plastic cones on the court, as players in a few frames. Despite this limitation, YOLOv11n still delivered generally reliable tracking performance.

Table 1. Qualitative comparison of tracking algorithms across video scenarios

Video	ByteTrack	RF-DETR	YOLOv11n	SAM2
1 – Football Daylight	Excellent tracking of players, but mistakenly tracked spectators	Good tracking of players with minor spectator confusion (less than ByteTrack)	Good tracking of players, rare spectator confusion	Excellent tracking of players only (manual target selection), but occasional identity confusion and loss of tracking in some frames
2 - Football Night Fast Motion	Good tracking, minor loss during fast motion	Excellent tracking, stable during fast motion	Excellent tracking, stable during fast motion	Not applicable (manual initialization issue)
3 – Rainy Street	Excellent pedestrian tracking	Excellent pedestrian tracking	Good tracking, occasionally mistook umbrella parts as persons	Excellent pedestrian tracking (manual target selection)
4 - Indoor Basketball	Excellent tracking, no confusion	Excellent tracking, no confusion	Good tracking, mistakenly tracked plastic cones	Excellent tracking, no confusion (manual target selection)

5. Conclusion

This study aimed to evaluate and compare the performance of four state-of-the-art multi-person tracking algorithms—ByteTrack, YOLOv11n, SAM2, and RF-DETR—under diverse and challenging real-world video scenarios. The objective was to identify which algorithm performs best in each specific context, helping researchers and practitioners make informed decisions when deploying tracking systems in real environments. The qualitative results showed that ByteTrack and RF-DETR performed most reliably across different conditions, with RF-DETR slightly outperforming ByteTrack in fast-moving and crowded scenes due to its robustness in identity preservation. YOLOv11n offered competitive performance, although it occasionally misclassified static objects as human targets. SAM2, while highly accurate when initial target selection was possible, and was limited in its practicality for dynamic scenes where not all persons are visible from the start. These findings are important for real-world applications such as surveillance, sports analytics, and human behavior monitoring, where scene conditions vary and consistent identity tracking is crucial. The results suggest that RF-DETR and ByteTrack are well-suited for dynamic, uncontrolled environments, while SAM2 is preferable for static or semi-controlled settings. Future research should include quantitative evaluations using standard tracking metrics such as MOTA, IDF1, and HOTA. Additionally, testing on larger datasets with annotated ground truth and experimenting with hybrid approaches may further enhance tracking performance and generalizability.

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Video Source 2. Nighttime football match with fast camera motion. Available at: https://drive.google.com/file/d/1OT7r46Fw952gbc56XjI6zunz_eH5BV8z/view?usp=drivesdk

Video Source 3. Rainy pedestrian street scene. Available at: https://drive.google.com/file/d/15rTaeVuHC-VrVqFM0a0kHqDqlPw3CeGL/view?usp=drivesdk

Video Source 4. Indoor basketball game video. Available at: https://drive.google.com/file/d/16R8OUpW6hTlItBTkW5ZeMxrob3va8tVc/view?usp=drivesdk

ABSTRACTS

Design Science and Applied Mathematics in Smart Manufacturing and Logistics: Toward a Big Data-Driven System

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Abstract

Continuous Improvement (CI) remains a foundational element in business strategy, increasingly reinforced by the emergence of Industry 4.0 and 5.0 paradigms, wherein automation, digitalization, and cyber-physical integration reshape operational systems. In this data-intensive context, information serves both as an analytical tool and a mechanism for enabling evidence-based process optimization. This research, conducted under the Design Science Research methodology, presents two primary contributions. First, it introduces four novel, data-driven models designed to identify latent improvement opportunities in manufacturing and logistics environments: (1) a Bottleneck Detection Model operable under minimal data conditions - proposal of a novel Queue-directed graph; (2) a Process Performance Analysis Model, grounded in Operations Research, which captures both static and variation-oriented versions of performance metrics; (3) a Root Cause Analysis Model employing supervised Machine Learning and eXplainable AI to extract influential variables in(in)efficiency patterns; and (4) a Human Performance Variation Prediction Model focusing on individual-level performance dynamics. Second, this work proposes ImproveXpert4.0, a digital platform that operationalizes CI through two supporting artifacts: a DMAIC-PDCA Structural Flowchart aligning strategic and operational KPIs via model integration, and a High-Level Architecture defining the system's computational and data infrastructure. Together, these contributions advance CI from traditional descriptive analytics toward proactive, model-driven, and mathematically driven diagnostics, facilitating the discovery of hidden inefficiencies and enabling data-centric performance enhancement.

Keywords: Big data, Continuous improvement, Operations research, Smart manufacturing and logistics

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Joint Optimization of Disassembly Line Balancing and Vehicle Routing in a Green Supply Chain Context

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Abstract

This study addresses the joint optimization of Disassembly Line Balancing (DLB) and Vehicle Routing Problem (VRP) within a green supply chain framework. The research integrates reverse logistics and sustainable production considerations by focusing on the efficient recovery, disassembly, and distribution of end-of-life (EOL) products. Two different mathematical model are proposed to simultaneously balance disassembly tasks across workstations and optimize vehicle routes for component distribution under CO_2 emission consideration. The mathematical models consider the single-component and multi-component distribution conditions and aim to minimize total disassembly cost and CO_2 emission. The proposed models are tested on an illustrative examples, and the results are analyzed. The analyses provide a quantitative assessment of the benefits associated with incorporating environmental impacts.

Keywords: Disassembly line balancing, vehicle routing problem, sustainability, CO_2 emission

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Facility Location Optimization for Fire Stations in the Central District of Gaziantep

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Abstract

Rapid response to emergencies and disasters is critical to urban safety. Strategic placement is therefore necessary to ensure timely intervention in critical situations. In this study, the p-median model is applied to determine the most suitable fire station locations in the neighborhoods of the Gaziantep Central District, and the results are compared with the existing fire station locations. The results show that the p-median solution achieved a more balanced distribution and reduced distances for a larger share of the population. Accessibility improvements were particularly observed in densely populated neighborhoods. These findings indicate that the p-median approach can serve as an effective tool in municipal disaster management planning. Furthermore, since the model outperforms the current station configuration in terms of service coverage, it has the potential to provide practical recommendations for decision-makers.

Keywords: P-median, Fire Station, Location Allocation

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A Decision Support Model for the Optimal Placement of Smart Benches

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Abstract

Today, as mobile phone usage duration increases, the demand for charging simultaneously rises. The availability of charging points in public areas without charging access is crucial for emergency situations. In this context, smart benches are practical solutions for open areas. This study addresses the location selection problem for smart benches. Strategic placement of smart benches will ensure their optimal utilization. Accordingly, location allocation models are used in this study, which investigates suitable locations for smart benches. A case study is being conducted to examine different scenarios. The results obtained provide decision support for decision makers.

Keywords: Smart bench, Decision support, Location allocation

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Disassembly Line Rebalancing under Robot Failures and Preventive Maintenance: A Human–Robot Collaboration Based Mixed Integer Programming Model

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Abstract

In today's world, where consumption rates are steadily increasing, the effective management of disassembly lines, which are an important part of the recycling process for end-of-life (EOL) products, is of great importance for sustainable waste management. Line balancing problems are used to address this situation. However, certain situations that arise after the initial line balancing cause the existing solution to fail. These situations cause production to stall and, consequently, reduce its efficiency. Rebalancing is necessary to avoid the damage caused by these situations. As in many industries, failures and periodic maintenance of robots frequently used in production lines are among the situations that disrupt production and require rebalancing. This paper addresses the problem of rebalancing the line for situations caused by robot failures and maintenance in disassembly lines that operate with human-robot collaboration. A new mixed integer programming (MIP) model is proposed for the problem addressed. The results obtained reveal the potential of the proposed model while highlighting the necessity of meta-heuristic approaches for solving large-scale problems.

Keywords: Disassembly line rebalancing, Human–robot collaboration (HRC), Robot failure and preventive maintenance, Mixed integer programming (MIP)

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An AI-Based Decision Support System for Multi-Dimensional Sustainability in Logistics Operations

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Abstract

Achieving sustainability in logistics requires a comprehensive approach that considers environmental, economic, and social dimensions simultaneously. However, most current studies focus primarily on one aspect—particularly carbon emissions—while neglecting the holistic nature of sustainable logistics. This study proposes a conceptual framework for an Artificial Intelligence (AI)- Based Decision Support System (DSS) designed to integrate and evaluate the three pillars of sustainability within logistics operations. The proposed framework emphasizes the development of a composite sustainability score, combining environmental indicators (e.g., CO_2 emissions, energy use), economic indicators (e.g., cost efficiency, time utilization), and social indicators (e.g., driver workload, service reliability). Each criterion can be normalized and weighted according to organizational priorities or sustainability policies. The AI component is envisioned to analyse operational data, learn patterns, and assist in estimating sustainability performance under different planning scenarios. Subsequently, an optimization layer can be applied to identify the most balanced and sustainable operational alternatives. This conceptual study does not rely on empirical data but establishes the theoretical foundation for future implementation and testing. It aims to contribute to the literature by introducing a structured approach to multi-dimensional sustainability assessment in logistics and by highlighting the potential role of AI-based systems in enhancing sustainable decision-making. The proposed framework will guide future research phases focused on model formulation, data integration, and real-world validation.

Keywords: Sustainable logistics, Artificial intelligence, Decision support systems, multi-dimensional sustainability, Conceptual framework

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Supplier Selection in the Context of Twin Transformation

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Abstract

Emerging technologies and climate change have recently taken a prominent place on the global agenda. Along with new technologies, the digital transformation process is seen as an inevitable element for improving industrial activities and ensuring global competitiveness. In addition, the contributions of digital transformation to green transformation and the increase in green transformation activities have revealed the need to evaluate these two processes in an integrated manner in many areas, which has been termed "twin transformation" in the literature. This study aims to determine the extent to which companies value twin transformation criteria in their strategic supplier selection. To this end, twin transformation criteria were defined in the literature as 5 main criteria and 9 sub-criteria associated with them. The identified criteria were scored on a 5-point Likert scale by participants who met the criteria included in the scope of the study. In addition, two questions containing qualitative assessments were directed at the participants to measure the expectations of field experts in twin transformation and to contribute to future studies. Based on the scoring results, the ENTROPY method was preferred to determine the weights of the relevant criteria, as it is based directly on data distribution and produces more objective and mathematically grounded results. As a result of weighting using the entropy method, it was concluded that the criterion with the highest weight among the six main criteria in the survey was green transformation and sustainability, while the criterion with the lowest weight was operational performance. Furthermore, it was observed that the criterion with the highest weight among the nine sub-criteria was transparency in production. One of the issues that purchasing specialists conducting the evaluation considered most important was the ability to monitor production in real time. The supplier's capacity to provide innovative tools and activities and R&D investments was identified as the sub-criterion with the least weight as a result of the participants' evaluation. Studies on the evaluation of suppliers in the context of green and digital transformation, targeting purchasing experts in the same sector, will help observe companies' expectations from their suppliers on a sectoral basis.

Conducting the study on a sector-by-sector basis will serve as a guide for procurement specialists working in the same sector by enabling the evaluation of common suppliers preferred by companies in that sector. However, in areas where intra-sector differentiation is high, it will be difficult to follow common policies in terms of supplier selection. For this reason, evaluations made by procurement specialists working in areas where intra-sector differentiation is low will make the study more objective.

Keywords: Digital transformation, green transformation, twin transformation, supplier selection, multi-criteria decision making, entropy

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Nonlinear Optimization Model for Container and Operational Planning

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Abstract

This work settle the theoretical foundation of prescriptive analytics through a system designed to enable proactive, data-driven decision-making via a data-agnostic, scenario-based optimization framework. It combines quantitative variables from any dataset to compute three high-level assessment metrics (KPIs, dimensions, and deviations), leading to prescriptive recommendations tailored to specific operational contexts. The modular architecture of the system allows for adaptation beyond port container terminals, with potential applications in manufacturing, healthcare, and other sectors. It provides a basis for future research into adaptable performance management systems. For prescriptions to be practically useful, managers must be able to influence the analyzed variables—e.g., in healthcare, they can affect the number of surgeries performed. However, some limitations exist. The system's effectiveness relies on the availability and quality of input data. The integration of 21 predictive models with high-dimensional optimization poses computational challenges, especially for real-time or large-scale applications. The model assumes that relevant operational variables can be modeled as time series, thus excluding qualitative factors. User interpretation of outputs is critical for adoption, and calibration of scenario parameters, such as change capability, can be subjective. Future work will develop algorithms to estimate these values based on past decision-makers' actions. Field experts tested the system positively, and further tests are planned within the NEXUS project. Its full implemention could improve container terminal efficiency at the Port of Sines by 2–5%, potentially generating an extra 2–6 million euros in gross income within a year.

Keywords: Nonlinear optimization, Container planning, NEXUS project

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Integrated parallel machine scheduling and AGV routing: A constraint programming approach

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Abstract

Synchronizing production and intralogistics is crucial in modern factories where finished jobs must be evacuated from machines without delaying downstream operations. We study an integrated parallel machine scheduling and automated guided vehicle (AGV) routing problem in which multiple identical machines process jobs and a single AGV performs multiple tours to transfer completed jobs to a depot. The objective is to minimize the overall makespan, defined as the completion time of the last AGV delivery. We formulate the problem as a Constraint Programming (CP) model that jointly decides: (i) job–machine assignments and processing sequences on identical parallel machines; (ii) the AGV's visit order and tour structure; and (iii) synchronized pickup times that cannot precede job completion. The proposed CP formulation features a new cumulative-function technique that tightly couples production and intralogistics. Also, the model uses interval and sequencing variables with no-overlap constraints for machines and for the AGV, considering precedence constraints that couple production completion times with transport start times. Travel times, computed from distances between machines and the depot, are explicitly embedded, allowing the AGV to wait, overtake completed jobs, and form multiple tours when beneficial. At each pickup, a positive pulse increases the AGV load by the job size; at delivery, a negative pulse decreases it, enforcing an upper bound equal to the AGV's capacity by ensuring feasibility across dynamic batching and multi-tour plans. This integrated model captures key trade-offs among machine release times, routing, and batching without resorting to explicit subtour constraints.

Keywords: Parallel Machine Scheduling, AGV Routing, Intralogistics, Makespan Minimization, Constraint Programming

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Simulation of electric vehicle charging stations with lateral transshipment

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Abstract

The rapid growth in the number of electric vehicles has made energy demand and capacity management in charging stations increasingly critical. Conventional stations rely solely on the power grid, which often leads to higher costs, increased carbon emissions, and reduced customer satisfaction during peak demand periods. In recent years, battery energy storage systems have been introduced to mitigate sudden load fluctuations on the grid and to support the integration of renewable energy sources. This study investigates the performance of battery-supported charging stations under lateral energy transshipment strategies. In the model, vehicle arrivals are represented by a Poisson process, while energy requirements follow probabilistic distributions. Energy sharing between stations is governed by (s,S)-type threshold policies, where transfer costs and efficiency losses are explicitly considered. Through simulation, the impact of different transshipment strategies on average waiting times, customer rejection rates, total energy costs, transshipment costs, and carbon footprint is evaluated. The findings indicate that lateral energy transshipment reduces imbalances across stations, improves customer experience, and lowers both grid dependency and associated emissions.

Keywords: Electric vehicles, energy storage, lateral transshipment, simulation, sustainability

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Comparative Analysis of Repetitive Movements in Videos Using Various Methods

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Abstract

This study presents a comparative analysis of repetitive human movements based on video-derived, skeleton-based keypoints. Using skeleton keypoints extracted via a YOLOv11-based pose estimation framework, we apply Discrete Fourier Transform (DFT), Principal Component Analysis (PCA), and Matrix Profile analysis to characterize and compare repetitive human movements. The DFT provides frequency-domain characterizations of motion, PCA attenuates noise to yield more salient patterns, and the Matrix Profile enables precise detection of recurring motifs in the time series. Empirical findings indicate that Fourier-based analyses are more effective for capturing global structural similarities, whereas the Matrix Profile serves as a strong complementary tool for fine-grained examination of repeated segments. This study demonstrates that integrating PCA and Fourier analysis yields a robust and interpretable framework for quantifying similarity in repetitive motions by capturing both dominant spatial variations and underlying temporal frequency patterns. The Matrix Profile further complements this approach by accurately delineating repetition boundaries and detecting recurring motion segments, together forming a reproducible, multi-resolution pipeline for skeleton-based motion analysis across varying movement types and execution speeds.

Keywords: Motion analysis, Fourier transform, Matrix profile, Dynamic time warping

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The full version of this work will be published in a journal.

Smart Waste Management Using EGrab-Bot 2.0: An AI and Robotics-Based Approach

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Abstract

EGrab-Bot is a developed and designed robot with four-wheeled, autonomous robot with a gripper that is powered by a servo motor. Its main purpose is to pick up and segregate plastic bottles using artificial intelligence (AI) technology. At first, the robot will use obstacle avoidance to find its way around and use a camera as input to look for plastic bottles. In the event that YOLOv5s identify the presence of a plastic bottle, the robot will use centroid alignment to monitor the object's location in real time. Furthermore, when the robot navigates linearly to the real place of the object, the frontal infrared sensor will continuously check for the bottle. An Arduino Development Board will be used by the robot to pick up the bottle in a predefined order once it is within the gripper's range. With the YOLOv5s framework, the suggested design methodology produced a 94% detection accuracy rate for plastic bottles.

Keywords: AI, Robotics, Computer vision, EGrab-bot

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A Comparative Analysis of Machine Learning Algorithms for Predicting Fire Radiative Power

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Abstract

As climate change increases the frequency and severity of forest fires, forecasting Fire Radiative Power (FRP) has become crucial for efficient emergency response and resource distribution. Although physical models tend to be slow, numerous contemporary artificial intelligence methodologies operate as "black boxes," causing trust concerns for decision-makers. This research employs 25,478 high-quality records obtained from NASA MODIS/VIIRS satellite data to create a transparent, high-performance predictive system. The methodology encompasses essential preprocessing procedures, such as log transformations and feature engineering to capture seasonal and daily cycles. The study provides a model derived from an optimized weighted voting approach after testing six distinct algorithms. By allocating a weight ratio of 1:5:1 to Random Forest, XGBoost, and CatBoost, the model attained an enhanced performance with an R2 of approximately 0.45 and an RMSE of 24.80 MW. Additionally, SHAP analysis was incorporated to guarantee explainability, demonstrating that the model adequately represents physical fire dynamics, including a positive connection with temperature and a negative correlation with humidity. These findings indicate that optimized hybrid structures serve as a dependable and comprehensible instrument for forecasting fire intensity.

Keywords: Explainable AI (SHAP), Fire Radiative Power (FRP), Machine Learning, XGBoost, Weighted Voting, Wildfire Forecasting

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Study in Compound-Gaussian Lognormal Texture Modeling

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Abstract

Accurate estimation of clutter parameters plays a crucial role in the performance of modern radar detectors, particularly under heavy-tailed non-Gaussian environments. This paper examines the robustness and statistical consistency of moment-based estimators applied to the Compound-Gaussian model with Lognormal Texture (CG-LNT). The considered estimators include the Higher Order Moment (HOME), Fractional Order Moment (FOME), Zlog(z), and Fractional Negative Order Moment (FNOME) techniques. Through extensive Monte Carlo simulations, the sensitivity of each estimator to the texture variability and fractional order selection is analyzed. Results highlight that the FNOME maintains stable estimation accuracy across a broad range of clutter spikiness, outperforming other methods in terms of mean-squared error (MSE) and bias behavior. These findings emphasize the suitability of fractional negative-order formulations for reliable modeling of non-Gaussian sea clutter in high-resolution radar applications.

Keywords: Sea clutter, parameters estimation, CG-LNT distribution

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Examining the Effect of Artificial Intelligence-Based STEAM Activities on Middle School Students' Mathematics Achievement

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Abstract

This study aims to investigate "The Effect of Artificial Intelligence (AI)-Based STEAM Activities on Middle School Students' Mathematics Achievement and Attitudes Toward Mathematics." The research employs a quasi-experimental design with pre-test and post-test control groups to evaluate the impact of AI-supported STEAM (Science, Technology, Engineering, Arts, and Mathematics) activities on 6th-grade students. In the 21st century, individuals are expected to possess skills such as critical and analytical thinking, creativity, problem-solving, and adaptability to the needs of the era. STEAM education supports these skills by integrating the arts into science, technology, engineering, and mathematics, thereby promoting interdisciplinary learning and creativity. Artificial intelligence, a rapidly developing technology, also plays a significant role in education today. AI personalizes learning by offering individualized learning paths tailored to each student's needs and assists teachers through data analysis and feedback. Furthermore, AI contributes to education by automating material creation, accelerating assessment processes, and enriching learning experiences through virtual tutors—thus increasing both efficiency and accessibility in education. Integrating AI into educational practices is expected to foster an innovative and technology-enhanced learning environment. The purpose of this study is to implement AI-based STEAM activities with 6th-grade students and examine their effects on students' mathematics achievement and attitudes toward mathematics. The experimental and control groups will be established while keeping other variables (age, grade level, class size, teacher, etc.) constant; random selection will not be used. The research will be conducted with 6th-grade students at a public middle school located in the Şahinbey district of Gaziantep. The Mathematics Attitude Scale developed by Önal (2013) and a mathematics achievement test prepared by the researcher will be used as data collection tools. For data analysis, multiple regression and correlation analyses will be employed.

The study aims to determine whether AI-based STEAM activities have an effect on students' mathematics achievement and attitudes toward mathematics, as well as the direction of this effect. The findings are expected to provide a concrete foundation for future educational policies and material development processes that integrate technology into student-centered learning approaches. Moreover, the results are anticipated to guide the Ministry of National Education's Board of Education and Discipline in the development of future curricula.

Keywords: Artificial intelligence, STEAM education, STEAM activities

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Research Trends on Drone Applications in Humanitarian Aid Logistics

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Abstract

The integration of drone technology in disaster operations is rapidly increasing, particularly as an innovative vehicle in humanitarian aid logistics. This study provides a framework of the relevant literature that relates to the integration of drones in this field. In this context, the examination of studies was published between 2015 and 2025, as well as the analysis of publication trends and collaboration networks using VOSviewer. The findings indicate that drone technologies constitute a crucial study domain, as demonstrated by a notable rise in the number of publications within the literature. It highlights that concepts such as "humanitarian logistics," "disaster response," "drone delivery," and "emergency management" are particularly prevalent in this field. It highlights that future research trends will prioritize the integration of fuzzy logic and machine learning methodologies to enhance operational efficiency and decision support processes.

Keywords: Humanitarian aid logistics, Drone application, Bibliometric review

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Kicking Ahead: Ball Trajectory Prediction with Recurrent Neural Networks in Soccer

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Abstract

Accurate prediction of ball trajectories in soccer provides valuable insights for tactical analysis, coaching support, and sports analytics. This study presents a data-driven framework for forecasting the future positions of a soccer ball using deep learning. Real match footage was processed using the SAM2 segmentation model to extract frame-by-frame ball coordinates. To improve prediction efficiency and quality, two frame reduction strategies were evaluated: motion-based thresholding and keyframe extraction via PySceneDetect. The resulting datasets were used to train Bidirectional Long Short-Term Memory (BiLSTM) and Gated Recurrent Unit (GRU) models. GRU consistently outperformed BiLSTM, achieving a one-step-ahead average Euclidean error of 26.18 pixels and MAPE of 0.03 with thresholding and 37.46 pixels and MAPE of 0.03 with keyframe extraction. Despite this, keyframe extraction yielded more stable and accurate results overall across the full prediction horizon (1–10 steps ahead). The proposed method achieves high accuracy while operating directly on real-world match footage, highlighting its practical utility for sports analytics.

Keywords: Ball trajectory prediction, BiLSTM, GRU.

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The full version of this work will be published in a journal

Trend Analysis and Machine Learning-Based Forecast Method of Climatic Parameters and Evapotranspiration for Southern Turkey

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Abstract

This study analyzed changes in evapotranspiration, temperature, precipitation, and relative humidity between 1981 and 2024 for the provinces of Adana, Mersin, Hatay, and Osmaniye in southern Turkey. Various machine learning models were tested for evapotranspiration prediction. Meteorological data were obtained from the Turkish State Meteorological Service. Daily data were aggregated to monthly and converted into anomaly series. Temperature, humidity, and precipitation anomalies, along with 1–3-month lags of evapotranspiration and seasonal harmonics, were used as explanatory variables. Forecast models were trained using a time-aware, 5-fold cross-validation approach. According to statistical and trend analysis findings, temperature values showed an increasing trend in all provinces. The highest average temperature trend was calculated for Mersin with 0.065 °C $year^{-1}$. Precipitation showed an increasing trend in all provinces. The highest increase occurred in Hatay with 31.67 mm $year^{-1}$. Relative humidity increased in Adana and Osmaniye, while it decreased in Hatay and Mersin. Evapotranspiration trend increased in Adana and Hatay, while decreasing in Mersin and Osmaniye. Among the tested methods, the ridge regression model demonstrated the highest performance with a mean absolute error of 19.7 mm $month^{-1}$, RMSE of 39.5 mm $month^{-1}$, and R^2 = 0.64. In the study area, mean temperature tended to increase (+0.036 °C $year^{-1}$) and relative humidity tended to decrease (−0.14 % $year^{-1}$). These findings are consistent with increasing evapotranspiration (+0.03 mm day^{-1} $year^{-1}$). Feature importance analysis showed that temperature anomalies and short-term evapotranspiration memory terms were the primary variables for evapotranspiration anomalies, while relative humidity and seasonality were the secondary variables. This machine learning-based approach can be used as a reference in irrigation management planning.

Keywords: Climate change, evapotranspiration, machine learning, trend analysis

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Real-time anomaly detection in the fog computing architecture of the internet of things

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Abstract

The use of Internet of Things (IoT) applications is rapidly increasing and becoming widespread in every area of our lives. The proliferation of IoT has given rise to fog computing, which enables devices located in different geographical regions to communicate with each other, store data, perform calculations, and extend the network to more areas. In the IoT network, fog computing enables the processing of distributed data spread across different geographical regions. This way, many edge devices can easily communicate with each other, and data transfer, storage, and simple computing operations take place on fog clouds. The processing of data received from edge devices on fog clouds in the network and its transfer to actuators must be ensured in a healthy manner. Real-time data acquisition and processing are required in many areas, especially in the healthcare area. At this stage, continuous monitoring and verification of data from sensors in the IoT network is crucial. In this study, machine learning IsolationForest will be used to verify data from sensors connected to fog clouds on the IoT network and to detect anomalies. This model will be trained to perform the process of separating data with anomalies. This process provides both the security of data coming from sensors and real-time control in case of abnormal data transmission, providing repair of possible sensor malfunctions and safer operation.

Keywords: IoT, Fog computing, Anomaly detection, Rael-time monitoring.

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Investigation of Digital Laziness in the AI Age

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Abstract

The growing tendency of digital laziness among adult learners is examined in this study, with special focus on how the pervasive use of artificial intelligence (AI) is changing behavioral patterns, cognitive habits, and educational engagement. As AI-powered technologies become more and more integrated into everyday life, helping with learning, writing, decision-making, and information retrieval, worries regarding AI-induced cognitive off-loading and dependency have grown. It is crucial to comprehend these dynamics in order to create educational strategies that are effective and promote digital well-being. Using the Digital Laziness Scale (DLS), we collected data from 296 participants with a range of demographic backgrounds in order to investigate this problem. Three factors—digital reliance, behavioral engagement, and cognitive off-loading—were shown to have a significant internal consistency (Cronbach's α =.83) in an exploratory factor analysis. According to the findings, digital laziness is quite common and strongly correlated with age and daily internet use: younger persons and those who use digital and artificial intelligence technologies more frequently exhibit higher degrees of digital laziness. Regarding gender, academic achievement, and work experience, no significant differences were found. These findings demonstrate the critical necessity for purposeful AI use, mindfulness, and digital literacy in order to prevent cognitive and behavioral disengagement. Through empirical data on digital laziness in the AI era, this study advances theoretical knowledge and provides useful information for developing educational interventions and policies that encourage self-control and active cognitive engagement in learning environments that are increasingly driven by AI.

Keywords: Digital laziness, Artificial intelligence dependency, Cognitive off-loading, Digital literacy.

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How a Magnetic Field Changes the Polarization of Twisted (Radially Polarized) Light

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Abstract

In this study, we examined how a special type of twisted light behaves when it passes through a magneto-optic material under a magnetic field. Twisted light can have different polarizations, such as radial or azimuthal, but in our study we started with radially polarized light. This light has a donut shape, with electric field lines pointing outward like spokes on a wheel. Usually, scientists study the Faraday effect with straight (linearly) polarized light, but we wanted to see what happens with this more complex light. Our study shows that the magnetic field changes the light's polarization. Without a magnetic field, the light keeps its radial polarization. As the field increases, the Faraday rotation angle θ varys from 0 to π/2, and the polarization gradually transforms into azimuthal, where the electric field lines go around in circles, like the threads on a screw or the rings of a tree trunk. This demonstrates that a magnetic field can convert one type of polarization into another. We also studied the light using a regular polarizing filter. It produces a two-lobed pattern on a screen, which rotates as the magnetic field changes. This makes it easy to observe the effect with the naked eye and could help future studies explore light–magnetic field interactions in a clear and direct way.

Keywords: Twisted light, Radial polarization, Magnetic field, Faraday effect, Optical rotation

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Generation of Orbital Angular Momentum (OAM) Beams from Natural Light Sources

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Abstract

Vortex light, or twisted light, refers to optical beams carrying orbital angular momentum (OAM) with a helical phase structure. Unlike conventional plane-wave beams, these light beams contain phase singularities and, due to their OAM content, have found extensive applications in optical communication, microscopic particle manipulation, and advanced imaging techniques. Natural light sources, such as sunlight, inherently produce broadband, spatially incoherent beams. Therefore, the initial step in generating vortex light from natural sources is to render the light spatially coherent. In this study, a pinhole apparatus was employed to achieve partial spatial coherence of sunlight. Subsequently, the coherent light was transformed into a vortex beam using a spiral phase plate. To validate the experimental methodology and assess its effectiveness, the behavior of the generated vortex sunlight beams was compared with computer-based simulations. The results demonstrate that OAM-carrying beams can be successfully produced from natural light sources and that the experimental outcomes closely match the simulated predictions. This work presents a combined experimental and simulation-based approach for generating vortex beams from natural light, offering potential for sustainable and innovative applications in modern optics.

Keywords: Twisted light; Orbital Angular Momentum (OAM); Natural light; Coherence control; Pinhole apparatus; Spiral phase plate; Simulation; Optical applications

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Pre-Service Teachers' Perspectives on AI-Supported Learning: Insights from a Qualitative Study

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Abstract

This qualitative study investigates the pre-service teachers' perceptions and interpretations of artificial intelligence (AI) in educational settings. Understanding how future educators view AI has become an important field of research as AI-based systems such as ChatGPT, Copilot, and Gemini change learning and teaching processes. This research seeks to uncover how pre-service teachers interpret AI in education, what roles they assign to it, and how they assess its potential contributions and limitations in learning contexts. Data were collected from 32 volunteer preservice teachers via a semi-structured interview form. The interview form was designed around three main themes: (1). Defining and perceiving AI in the educational context, (2). Usage patterns and experiences of AI-based tools, (3). Possible impacts of AI on the teaching profession. The questions aimed to elicit both the participants' cognitive definitions, their personal experiences, and their future predictions. The interviews were conducted online in written form, and the data obtained were analyzed using content analysis. During the analysis process, open codes were first extracted from the statements, and similar codes were combined to form themes. The coding process was conducted by the researcher, and opinions were obtained from two field experts to ensure consistency of the themes. The majority of participants use ChatGPT and similar AI tools for educational purposes, particularly for preparing homework, gathering information, and solving problems. Some students have integrated these tools into their daily lives, and one participant used interactive visual learning methods. The findings indicate that participants generally perceive AI as a supportive and facilitating learning tool. However, some participants emphasize that AI cannot fully assume the role of a teacher and may undermine students' thinking skills. Participants believe that AI could impact the teaching profession in the future, both as a supportive and potentially threatening factor. The general perception is that it won't completely replace teachers, but it will assist in areas such as assessment and evaluation, lesson planning, and student monitoring. Opinions are balanced between positive, negative, and neutral.

Keywords: AI-based Learning Tools, Pre-Service teachers, artificial intelligence, teaching profession

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Production of Bioplastics for Waste Management and Sustainable Material Technologies

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Abstract

Nowadays, plastic pollution has become a serious environmental problem. For instance, plastic remains in nature for many years without breaking-down. It also creates a serious problem for marine life. We know that the remains of plastics used in food packaging, in particular, pave the way for cancer, and that invisible micro-plastics enter our cells and cause chemical changes. The purpose of this research is to create bioplastic from organic waste at home in order to provide an alternative to the environmental damage caused by non-biodegradable plastics. It is important to find a sustainable solution to this problem. In this research, bioplastic was produced using a simple method with vinegar, glycerin, and starch obtained from potatoes. First, the potato was grated and strained to remove the starch, then mixed with water and heated. During heating, vinegar and glycerin were added to the mixture. The mixture gained consistency and was poured onto a flat surface to be released, resulting in a transparent and flexible bioplastic sheet. The bioplastic obtained showed a flexible and non-toxic structure that is easily degradable in nature. These results demonstrate that environmentally friendly plastic alternatives can be produced even in the home environment. It is believed that this study may inspire further research in the field of waste management and sustainable material technologies in the future. In addition, the low-cost and accessible nature of the method used increases the educational and social value of the project.

Keywords: Bioplastic, organic waste, eco-friendly, starch

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Time is Life: Artificial Intelligence-Supported Smart Stop Cancellation System in Patient Elevators

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Abstract

This study was conducted to develop an artificial intelligence-based control system aimed at eliminating unnecessary elevator stops during the transportation of stretchers and critically ill patients in hospitals. The problem addressed in the study is the time loss caused by the call remaining active even after the person who made the elevator call has left the area. It is believed that this system will make significant contributions to healthcare services, as this situation causes delays that are critical in patients requiring emergency intervention. In the Methods section, the presence of people in the patient elevator waiting area was analyzed in real time using image processing technologies; the stop cancellation mechanism was modeled using behavior-based decision-making algorithms. The system was experimentally tested at the prototype level using Arduino-based control cards, a USB camera, motor drivers, and relay modules. The findings show that when a person leaves the waiting area, unnecessary elevator stops are prevented by 100% and significant time savings are achieved during the stretcher transport process. These results increase flow efficiency, especially in transfers between intensive care and operating rooms. In conclusion, the study presents a healthcare technology solution that accelerates emergency management, enhances patient safety, and optimizes hospital logistics processes. Furthermore, the behavior-based artificial intelligence approach stands out as a unique component not found in existing elevator systems. Future studies should focus on developing the system with different machine learning models and conducting pilot applications in large-scale hospitals.

Keywords: Artificial intelligence, image processing, patient elevator, behavior analysis, smart hospital technologies

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The Global Cybersecurity Index and Türkiye: An Assessment of Increasing Measures in Digital Transformation

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Abstract

The accelerating pace of digital transformation under Industry 4.0 has amplified the strategic importance of cybersecurity. This study evaluates Türkiye's progress in global cybersecurity readiness through the Global Cybersecurity Index (GCI) and its interplay with digital governance indicators, namely the E-Government Development Index (EGDI) and the E-Participation Index (EPI). Using longitudinal data from 2014 to 2024, the analysis reveals Türkiye's remarkable trajectory from a "Maturing" stage (Rank 43 in 2017) to a Tier 1 "Role-modelling" position in 2024, driven by advancements in legal, technical, and organizational pillars of the GCI framework. Parallel improvements in EGDI underscore a "V-shaped" recovery, with Türkiye climbing from Rank 80 in 2012 to Rank 27 in 2024, supported by robust e-government infrastructure and enhanced human capital. Furthermore, Türkiye's EPI performance (Score: 0.8630; Rank: 22) reflects strong citizen engagement through platforms such as CİMER, though future progress requires transitioning from consultative mechanisms to participatory decision-making tools. Comparative analysis with global benchmarks and simulation-based insights confirms that sustained investment in capacity building, cooperation, and telecommunication infrastructure is essential for maintaining leadership. This study contributes to the discourse on cybersecurity governance by presenting an integrated assessment of national performance across security, service delivery, and citizen participation dimensions, offering strategic recommendations for consolidating Türkiye's role as a regional leader in digital resilience.

Keywords: Global Cybersecurity Index (GCI); Türkiye; Digital Transformation; E-Government Development Index (EGDI); E-Participation Index (EPI); Cybersecurity Governance; Capacity Building; Role-Modelling Tier; Industry 4.0; Digital Resilience

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STAR (Voice Detection and Perception Guide)

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Abstract

In this project, a special system is being developed to help hearing-impaired individuals understand where sounds in their environment are coming from. In daily life, not being able to detect the direction of sounds such as car noises, doorbells, or someone calling out can lead to both communication problems and safety risks. For this reason, a wearable device has been designed that indicates the direction of sound through vibrations.

In this system, four microphones will detect sound and calculate which direction it is coming from. This information will be transmitted via vibration motors in a device worn on the user's wrist or body. For example, if the sound is coming from the right, the motor on the right side of the device will vibrate, and the user will understand that the sound is coming from that direction.

The project will include:

- Microphones and specialized software will be used to determine the direction of sound.
- It will be powered by Arduino.
- A prototype of a vibrating sweatband, wristband, or vest will be produced.
- The device will be tested both indoors and outdoors to ensure it functions correctly.

This project will contribute to hearing-impaired individuals leading safer, more independent, and more confident lives. It will also offer an innovative solution that combines different engineering fields.

Keywords: Hearing-impaired technologies, Sound direction detection, Wearable technology, Vibration alert system, Arduino-based sensor system

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Poincar´e-Friedrichs Inequalities For Broken-Sobolev/Polynomial Spaces

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Abstract

We introduce a novel technique to establish Poincar´e-Friedrichs type inequalities for broken-Sobolev/polynomial spaces. Distinguishing itself from prior works, this method can be applied to all the linear first-order differential operators, including those with infinite-dimensional kernels. Our contributions encompass the re-establishment of previously proven results and the derivation of novel ones.

Keywords: Poincar´e-Friedrichs inequalities, broken-Sobolev/polynomial spaces, discontinuous Galerkin, finite elements, nonlinear PDEs

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