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Editorial

Editorial: Smart Cities, Innovating in the Transformation of Urban Environments

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Abstract: The Special Issue *Smart Cities: Innovating in the Transformation of Urban Environments* presents a collection of original research contributions that employ mathematical modeling, optimization, machine learning, and deep learning techniques to tackle urgent challenges in designing, monitoring, and operating smart urban systems. The articles in this special issue cover a range of topics, including environmental engineering, intelligent transportation, photovoltaic performance assessment, and urban mobility. All manuscripts share a commitment to rigorous quantitative methodologies and data-driven decision support, with results that directly impact ecological integrity, public health, and overall population well-being. Additionally, the articles emphasize the importance of providing context for each contribution within the broader field of smart city research. They highlight their relevance to the Mathematical Biosciences and Engineering journal, which focuses on complex data and information processing at the intersection of mathematics, engineering, and life sciences.

Keywords: smart cities; mathematical modeling; optimization; machine learning; deep learning; urban sustainability; public health; Industry 5.0

1. Introduction

Cities around the world are undergoing significant transformations driven by digitalization, environmental regulations, and the increasing demand for efficient, sustainable, and human-centered services. These changes are not only technological; they also raise important public health and ecological concerns. Urban environments influence air quality, water discharge, physical activity levels, and injury risks, affecting residents. The concept of the smart city has emerged as a key framework for addressing these challenges by leveraging information and communication technologies, real-time data, sensor networks, and advanced analytics to enhance the quality of life. Information fusion and computational intelligence are becoming increasingly important for integrating diverse data sources to support effective decision-making [1]. In this context, the transformation is closely linked to the Industry 4.0 and Industry 5.0 paradigms. While Industry 4.0 focuses on automation and operational efficiency through digital transformation, Industry 5.0 emphasizes societal needs, human-centered approaches, and environmental responsibility across both industrial and urban development [2].

The Mathematical Biosciences and Engineering (MBE) journal is an interdisciplinary Open Access publication that encourages innovative research, technology transfer, and the translation of knowledge related to complex data and information processing at the intersection of mathematics, life sciences, and engineering. Its focus includes general mathematical methods and their applications in biology, medicine, and bioengineering, with particular attention to mathematical modeling, nonlinear dynamics, stochastic systems, and computational intelligence. The study of smart cities fits naturally within this scope. Urban systems are large-scale socio-technical environments, and their performance is evaluated not only in engineering terms but also with respect to ecological integrity, exposure to environmental pollutants, the burden of injury and disease, and population-level behavioral patterns. To convert these dimensions into practical tools, a rigorous, quantitative, and interdisciplinary methodology is required, exactly what the journal promotes, including mathematical modeling, optimization, and computational learning, all grounded in real data and validated against measurable outcomes.

This way, the Special Issue was created to highlight contributions that further this research agenda. It is partly associated with the 7th Ibero-American Congress of Smart Cities (ICSC-CITIES 2024), which brought together researchers from across the Ibero-American region to discuss solutions for urban sustainability and intelligence. This volume includes four peer-reviewed articles that cover complementary domains: *i*) environmental engineering and multi-objective optimization for wastewater treatment; *ii*) deep learning for intelligent traffic sign recognition; *iii*) diagnostics for photovoltaic cells based on convolutional neural networks; and *iv*) machine learning for predictive modeling in bike-sharing systems. Together, the manuscripts illustrate the diversity and methodological rigor that characterize data-driven research in smart cities.

2. Overview of the published articles

The article "Mathematical Optimization for Environmental Management in Smart Cities" by Caro et al. [3] addressed a significant environmental challenge in smart cities: cost-effectively removing phosphorus from industrial wastewater. Excess phosphorus discharged into surface waters is a major contributor to eutrophication, harmful algal blooms, hypoxic "dead zones," and the collapse of aquatic ecosystems. These phenomena have direct consequences for biodiversity and public health in urban watersheds, aligning with UN Sustainable Development Goal 6, which focuses on clean water and sanitation. As discharge regulations become increasingly stringent, wastewater treatment plants face mounting financial pressure, requiring operators to manage a challenging trade-off between ecological compliance and operational sustainability. To assist with this decision-making process, the authors developed a bi-objective optimization framework for chemical dosing in physicochemical phosphorus removal systems, aiming to minimize both operational costs and effluent phosphorus concentration simultaneously. The methodology relied on surrogate modeling. Since the commercial simulator

BioWin functions as a black-box tool, polynomial regression models of varying degrees are fitted to simulation data generated by adjusting the dosages of two coagulants: aluminum sulfate and ferric chloride, along with sodium hydroxide. The resulting surrogate models (degree-4 polynomials for phosphorus concentration and degree-1 for pH, both with $R^2 = 0.99$) were integrated into the optimization problem, which was solved using both the weighted-sum and ε-constraint methods in Pyomo and IPOPT. The estimated Pareto fronts revealed highly nonlinear cost-performance trade-offs: in the case of aluminum sulfate, reducing effluent phosphorus from 3.0 to 1.0 mg–P/L results in a 114% cost increase; for ferric chloride, the increase is approximately 355%. Aluminum sulfate was identified as the more cost-effective option for all phosphorus targets, due to its lower molar dosages and reduced sodium hydroxide demand. The proposed approach demonstrated how mathematical modeling and multi-objective optimization tools can be practically applied in environmental engineering, contributing directly to the smart city goal of resource efficiency and regulatory compliance.

The article ‘Deep Learning for Intelligent Transportation Systems” by Deng et al. [4] addressed traffic sign recognition in the context of autonomous vehicles and intelligent transportation systems, which are crucial components of smart city infrastructure. The significance of this problem extends to biomedical and public health, as road traffic injuries rank among the leading causes of death globally, particularly affecting younger populations. Reliable machine perception of regulatory signage is essential for driver-assistance and autonomous driving systems aimed at reducing this injury burden. However, traffic sign recognition poses several challenges due to high intraclass variability, interclass similarity, occlusion, and complex backgrounds. The authors presented two key empirical findings to motivate their work: *i*) certain invariant features of a sign's appearance, such as color-shape relationships and symbolic patterns, remain consistent under varying viewpoints and lighting conditions; and *ii*) subtle differences between visually similar signs can convey critical semantic meanings. To tackle these challenges, the authors proposed TTSNet, a novel Transformer-based architecture that includes three specially designed modules. The ESIR (Eliminating Spatial and Information Redundancy) module reduces spatial and channel redundancy by separating spatial and channel reconstruction units and using group normalization and gating mechanisms. The DLFI (Attention-based Internal Scale Feature Interaction) module selects and aggregates discriminative feature maps across Transformer stages, employing a cosine-similarity-based scoring method to minimize the impact of noisy, low-rank features. The SSFM (Cross-scale Cross-space Feature Modulation) fusion module combines multilayer feature maps using a top-down hierarchical approach, thereby capturing both fine-grained local and global contextual information. Extensive experiments conducted on the T100K and CTSDB benchmarks showed that TTSNet achieves state-of-the-art mAP@0.5 scores of 89.10% and 89.97%, respectively, surpassing competing methods such as DETR, Deformable-DETR, RepViT, and DINO. Ablation studies confirmed the unique contributions of each module, and qualitative visualization analyses reveal that TTSNet focuses more accurately on sign regions compared to baseline Transformers. Additionally, the proposed Input-IoU loss function, which incorporates auxiliary bounding boxes at multiple scales, enhanced bounding box regression accuracy. The proposed approach aligned with MBE's focus on complex information processing and the development of mathematical tools, specifically deep neural architectures and attention mechanisms, for managing high-dimensional, real-world data. The proposed approach has direct applications in smart urban mobility and road safety.

The article ‘CNN-Based Diagnostics for Photovoltaic Systems” by Mateo-Romero et al. [5] discussed the monitoring and performance assessment of photovoltaic (PV) cells, which are essential components of the renewable energy infrastructure in smart cities. The importance of the proposed approach reached beyond energy economics; replacing fossil-fuel generation with photovoltaic capacity is one of the most effective ways to reduce urban exposure to air pollutants. The reduction had well-documented positive effects on the incidence of respiratory and cardiovascular diseases in densely populated areas. Therefore, accurate, non-destructive monitoring of PV cell health was crucial to ensuring the long-term reliability of these public health benefits. The article proposed a convolutional neural network (CNN) model that estimates the slope of a PV cell's current-voltage (I-V) curve from its electroluminescence (EL) image. The slope, which corresponds to the electrical conductance measured in siemens, is directly related to the cell's series resistance. Series resistance is a critical parameter that affects the fill factor and overall energy conversion efficiency; an increase in series resistance indicates cell degradation or defects. A key methodological contribution was the selection of the target variable. Instead of predicting series resistance directly, which can have an irregular, right-skewed distribution, the authors predicted its reciprocal, electrical conductance. The transformation resulted in a smoother, more regular distribution, which is better suited for regression analysis. The slope values were obtained from the I-V curves using an iterative linear regression procedure that identifies the asymptotic slope near the open-circuit voltage. The CNN architecture consisted of 18 layers, including combinations of 2D convolutional, max pooling, and fully connected layers. It was trained on 852 paired samples of (EL image, slope) using Bayesian hyperparameter optimization and data augmentation techniques. The proposed model achieved a mean absolute percentage error of 4.20% on the test set, outperforming other methods such as Gaussian Process Regressors, Support Vector Machines, and feature-based neural networks. An additional contribution expands on the practical value of the predicted slope. By incorporating it as an extra scalar input to a CNN-based maximum power point (MPP) estimator, the mean absolute error was reduced from 0.0262 to 0.0231, representing a 12% reduction. The authors note that MPP estimation was particularly sensitive to cells with unusually high series resistance, and that the predicted slope provides information that images alone cannot. The proposed approach demonstrated that CNN models, a mathematical tool rooted in signal and image processing, can extract physically meaningful parameters from visual data. The proposed approach supported predictive maintenance and performance optimization of smart energy infrastructure, aligning with the interdisciplinary scope of modern engineering.

The article 'Machine Learning for Smart Urban Mobility" by Ali et al. [6] discussed predictive modeling for bike-sharing systems (BSS), which are a key component of smart urban mobility. Among the technologies considered in the issue, bike-sharing likely has the most direct impact on public health. Engaging in active transportation offers measurable benefits for cardiovascular and metabolic health, mental well-being, and overall physical activity levels, while also reducing exposure to vehicle-related air pollution. To realize these benefits on a larger scale, operational reliability is essential, which depends on accurately forecasting demand, trip duration, and trip distance. The authors argued that the common practice of training a single predictive model on the entire BSS dataset is suboptimal. Different user groups, defined by factors such as gender, age, or trip origin, displayed distinct riding patterns. The variability results from behavioral and demographic differences, and combining the groups could increase noise, reduce interpretability, and lower prediction accuracy. This way, the proposed "divide-and-train" method segmented the dataset based on a selected attribute, such as user gender, age bracket, or departure station, and trained separate models for each resulting subset. Five models were evaluated, i.e., three ensemble machine learning methods (Random Forest, CatBoost, and Bagging) and two recurrent deep learning architectures (GRU and LSTM). The proposed approach was validated using the New York City Citi Bike dataset, which contains over 735,000 anonymized trips. The statistical significance of the sub-dataset partitions was established using the Kruskal-Wallis and Mann-Whitney U tests, both of which show p-values less than 0.001 for trip duration and distance by gender. The results were impressive: the Random Forest model trained on gender-specific sub-datasets achieved improvements of 84.2% (for males) and 87.4% (for females) in root mean square error for trip duration predictions compared to the baseline model trained on the full dataset. A similar level of improvement was noted for trip distance. Consistent gains were observed across all three partitioning strategies and all five models. The proposed methodology was computationally efficient, required no hyperparameter tuning, and its enhancements arose solely from data stratification. It was broadly applicable to other transportation datasets and to any regression scenario involving target-relevant subpopulations. The proposed approach aligns with the tradition of using rigorous mathematical and statistical methods to address complex real-world systems, contributing to data-driven management of urban resource allocation in smart cities.

3. Concluding remarks

The four articles in this Special Issue showcase the diversity and depth of mathematical and computational research addressing smart city challenges. Spanning wastewater treatment, traffic safety, renewable energy diagnostics, and urban mobility, these works share a common methodological theme: the application of rigorous quantitative models that leverage optimization frameworks, deep neural architectures, convolutional networks, and ensemble learning methods. The proposed approaches aim to extract actionable insights from complex, real-world data.

Importantly, the four contributions focused on outcomes that significantly impact life sciences and public health, specifically: aquatic ecosystem integrity; road injury prevention; air pollution-related disease mitigation; and promoting active transportation at the population level. The intersection of advanced mathematical methods with engineering practice, environmental and biomedical effects, and societal benefits is where Mathematical Biosciences and Engineering operates.

Several common themes emerge from this collection. First, all four contributions involve surrogate or learned approximations of complex phenomena: polynomial surrogates for physicochemical simulations, attention-based Transformers for visual feature abstraction, CNNs for parameter inference from images, and ensemble regressors for behavioral prediction. Second, each article addresses the challenge of decision support under uncertainty or data scarcity, presenting practical methods validated on real datasets and accompanied by open code or data. Lastly, three of the four articles are explicitly connected to the ICSC-CITIES 2024 conference, highlighting the vitality of the Ibero-American smart cities research community.

Overall, this collection aims to serve as both a reference and an inspiration for researchers at the intersection of mathematics, engineering, and urban sustainability.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

Diego Rossit, Sergio Nesmachnow, Luis Hernández Callejo and Pedro Moreno are special issue editors for Mathematical Biosciences and Engineering and were not involved in the decision to publish this article. All authors declare that there are no competing interests.

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