

ABSTRACT

Maritime freight has gained popularity among researchers and practitioners due to its cost efficiency and environmentally friendly nature. It was initially developed for cargo transfer, but its widespread adoption has made it the backbone of the global economy. In the existing era, international trade is boosted by maritime freight movement. Despite its favourable nature, some of its serious negative impacts have attracted the attention of researchers and scholars. These emissions not only contribute to global air pollution but also pose a risk to air quality in coastal areas. The maritime freights' emissions are currently rising and are expected to continue increasing due to the expansion of international trade. The resulting pressure of globalization has made the industry more challenging and a highly emitting industry. Due to which academicians and governments are concerned about the environmental pollution caused by maritime freight. At the same time, Industry 4.0 has introduced some key digital technologies such as Blockchain, Big Data, AI, and IoT, which are emerging as solutions to enhance sustainability and maintain competitiveness in the industry. For instance, blockchain technology enables secure transactions, facilitating the efficient and reliable movement of goods. Moreover, it enhances the speed and coordination of loading and unloading operations. As a result, vessels operate more efficiently, reducing harbour time and ultimately lowering emissions. The Internet of Things allows the remote and autonomous operation of machines, improving safety and efficiency while reducing maintenance, interruptions, and energy consumption. This technology facilitates a reduction in carbon emissions by enhancing operational efficiency. Artificial Intelligence and Big Data are employed to oversee ship sensors and do predictive analysis, which is crucial for averting delays and improving the overall operational efficiency of this field.

Therefore, the present work mainly focuses on the integration of key digital technologies in maritime freight processes to make it sustainable and efficient. To achieve this, the study employs three types of analysis: descriptive, predictive, and prescriptive. The descriptive analysis explores the use cases of digital technologies in the maritime freight industry and makes a foundation for predictive and prescriptive analysis. Descriptive analysis encompasses Structural Equation Modeling-Artificial

Neural Networks (SEM-ANN) method and a range of Multi-Criteria Decision-Making (MCDM) methods, including Grey Decision-making Trial and Evaluation Laboratory based on Analytic Network Process (Grey-DANP), Fuzzy Analytic Hierarchy Process (Fuzzy-AHP), and Preference Ranking Organization Method for Enrichment Evaluations II (PROMETHEE II). These methods are employed to identify and analyse the interrelationships among the factors influencing the adoption of digital technologies in the maritime freight system. While MCDM methods help in evaluating and prioritizing these factors, SEM-ANN is used to model complex causal relationships and to statistically validate dependencies.

By utilizing these sophisticated analytical techniques, the study aims to provide a comprehensive understanding of how various factors interact and impact the adoption process, ultimately aiding in more informed decision-making and strategic planning within the industry.

Following the descriptive analysis, the study progressed to predictive analysis, utilizing various machine learning algorithms including Support Vector Machines (SVM), Decision Trees (DT), Artificial Neural Networks (ANN), and Random Forests (RF). The primary aim of this analysis is to predict CO₂ emissions based on a range of operational parameters, such as total time spent at sea, total fuel consumption, and CO₂ emissions both at berth and during travel. By comparing the performance of these algorithms on the maritime dataset, the study identified which algorithm delivers the most accurate and reliable predictions. The results provide detailed projections of CO₂ emissions under different operational conditions, offering valuable insights into the environmental impact of maritime activities. This analysis also explored specific activities where port authorities need to focus their optimization efforts, highlighting processes that can be refined to reduce emissions and enhance efficiency. Furthermore, the study's comprehensive approach to evaluating algorithm performance facilitated the identification of the most reliable and accurate model for practical applications in maritime freight. This information is crucial for stakeholders aiming to implement data-driven strategies to improve sustainability and operational efficiency in the maritime industry.

Hereafter, to provide actionable recommendations based on descriptive and predictive insights, we adopted mathematical model to optimize the process and minimise the CO₂ emissions. Findings of the work includes; identification of key factors influencing the adoption of digital technologies in the maritime sector, namely; Sustainability-Enabled Digital Freight Training, Initial Investment Cost, Trust in Digital Technology, Perceived Benefits, and Government Policy and Support. For predicting CO₂ emissions from various maritime activities, the Artificial Neural Network (ANN) model demonstrates superior performance, achieving an R-squared value of 0.9636, effectively capturing the underlying patterns in CO₂ emissions data. Additionally, a comprehensive mathematical model prescribes several key actions for managers to optimize costs and enhance operational efficiency and sustainability of sea-side operations. Overall, to address operational inefficiencies and promote sustainability in the maritime freight industry, freight managers and policymakers are encouraged to implement strategic approaches and develop supportive policies.

Keywords: Sustainability; CO₂ emission; Maritime Freight Transportation; Industry 4.0; Digital Technologies; Blockchain; AI & IoT; Bigdata; MCDM; Machine learning; Optimization.