Optimizing Maritime Freight: Digital Technologies for Sustainable and Efficient practices

Thesis submitted in partial fulfilment for the

Award of Degree

Doctor of Philosophy

By

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LIST OF ABBREVIATIONS

CO_2	Carbon dioxide
SOx	Sulphur Oxide
GHG	Greenhouse Gas
SMFT	Sustainable Maritime Freight Transport
MFT	Maritime Freight Transport
IMO	International Maritime Organization
BAP	Berth Allocation Problem
QCAP	Quay crane assignment problem
UNCTAD	United Nations Conference on Trade and Development
MCDM	Multi-Criteria Decision-Making
SEM-ANN	Structural Equation Modeling-Artificial Neural Networks
Grey-DANP	Grey Decision-making Trial and Evaluation Laboratory based on Analytic Network Process
Fuzzy-AHP	Fuzzy Analytic Hierarchy Process
Fuzzy-TOPSIS	Fuzzy Technique for Order of Preference by Similarity to Ideal
PROMETHEE II	Preference Ranking Organization Method for Enrichment Evaluations II
SVM	Support Vector Machines
DT	Decision Trees
ANN	Artificial Neural Networks
RF	Random Forests
ICSO	Improved Chicken Swarm Optimization
BDA	Big Data Analytics
BCT	Blockchain Technology
SSCP	Sustainable Supply Chain Performance
CFA	Confirmatory Factor Analysis
SCM	Supply Chain Management

IoT	Internet of Things
AI	Artificial Intelligence
ML	Machine Learning
GAs	Genetic Algorithms
SIM	Simple Inversion Mutation Operator
TOE	Technology-Organization-Environment
DOI	Diffusion Of Innovation

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 CO_2 emissions based on a range of operational parameters, such as total time spent at sea, total fuel consumption, and CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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; CO_2 emission; Maritime Freight Transportation; Industry 4.0; Digital Technologies; Blockchain; AI & IoT; Bigdata; MCDM; Machine learning; Optimization.