CHAPTER 1

INTRODUCTION

1.1 Background

One of the most interconnected industry in the world, the maritime sector involves the international transit of a wide range of commodities and documents (Papathanasiou et al., 2020). In terms of cost per ton of freight and high-efficiency transportation system, maritime freight is one of the cheapest and most convenient modes of transport. Almost 90% of the commodities that cross international boundaries each year cost more than 16 trillion dollars and are transported by sea (Liu et al., 2021). The compound annual growth of seaborne trade has been 2.9% over the last two decades and is expected to continue growing in the foreseeable future due to the globalisation of manufacturing processes and increased worldwide trade (UNCTAD, 2021). Maritime transportation is generally considered an environmentally favourable mode of transportation. However, coordinating cargo information, managing cash flow among multiple stakeholders, and addressing sustainability-related issues remain challenging for maritime logistics. Despite its efficiency and relatively lower emissions compared to other transport modes, the growing scale of global trade has amplified its environmental footprint.

However, according to previous studies, it is contributing significantly to carbon emissions as international trade and business continue to flourish (Ezinna et al., 2021; Wan et al., 2018). Consequently, it is heavily responsible for air pollution. According to International Maritime Organization (IMO), the estimated value of carbon emissions in the shipping industry is increased by 72 percent in 2020 (Lun et al., 2015). Even a single ocean fleet contributes to an excessive amount of pollution, emitting CO_2 and NO_x equivalent to 70,000 cars (Czachorowski et al., 2019). Globally, there are around 96,295 fossil fuels-based ships in operation (Zincir, & Deniz, 2021). In the year 2019, these ships accounted for 2.2% of CO_2 emissions, 20.98% of NOx, 11.80% of SOx, 8.57% of particulate matter 2.5, and 4.63% of particulate matter 10 (EEA, 2021; Tiller et al., 2022). In this regard, Monteiro et al. (2018) investigated the impact of shipping emissions on air quality in a European context using numerical air quality modelling. The results suggest that shipping emissions partner in the concentration of NO_2 in excess of 20% for the deltas, and less than 10% of PM10, in typical urban areas along the west coast located here. Bagoulla and Guillotreau (2020) assessed the Greenhouse Gas (GHG) emissions (SO_2, NOx, CO_2, PM2.5, PM10) of maritime industries over air pollution. Taking into account the ecological impact of maritime freight transport through air pollution, it can be seen that maritime freight transport is among the top five most polluting industries (Bagoulla and Guillotreau, 2020). Maritime freight transport not only causes environmental issues, but empty container repositioning is also another critical issue for this sector (Kuzmicz & Pesch, 2019). The international trade imbalance among various regions originates from different supply and demand patterns, which accumulate empty containers at demand points. Ultimately, there is a shortage of empty containers to ship cargos to their destination points (Zhou et al., 2009; Zheng et al., 2017). Subsequently, the reallocation of these empty containers accounts for 30% of all container movement and around 20% of worldwide port operations (Yan et al., 2023; Nazafi & Zolfagharinia, 2021). Lee and Moon (2019) proposed the idea of foldable containers as an alternative solution to deal with the Empty Container Repositioning problem. Toygar et al. (2022) identified four main issues along with their sub-issues that arise due to the Empty Container Repositioning problem. To address the environmental and economic issues of sea freight, the concept of sustainability has arisen. Sustainable Maritime Freight Transport (SMFT) is not only a means of providing ecological support, but it also addresses economic and social concerns (Lister, 2015). In the year 2018, the IMO, the United Nations agency specializing in international shipping, released the preliminary IMO strategy to reduce GHG emissions from ships. This strategy sets a target of 50% reduction in emissions by the year 2050. However, compared to 2008, CO_2 emissions from maritime freight transport are set to climb 90 to 130% by 2050, based on economic growth and energy advancements (Serra & Fancello, 2020; Joung et al., 2020). In addition, as per the Paris Agreement, the maritime freight industry and its stakeholders are highly encouraged to submit voluntary reports including strengthening and adhering to sustainable development policies as one of their prime objectives (Johnsson et al., 2021). To meet IMO's expectations, maritime industries need to incorporate stringent policy measures to drive down GHG emissions (Rojon et al., 2021). Policy-makers have devised various measures to make maritime freight transport more environmental-friendly. For example, after 2020, ships passing through European ports must have exhaust SOx levels below 0.5% mm (Hayami et al., 2022). As a result, businessmen who deal with the shipbuilding and shipping industry are increasingly concerned about the development of vessel types that are powered by hydrogen or hybrid concepts (Bach et al., 2020).

Indeed, emissions are generated by both ships and ports (Kuang et al., 2023). Therefore, Gibbs et al. (2014) examined how ports can help reduce GHG emissions by developing policies not only for themselves but also for maritime industries. Port managers can create plans or projects to decarbonize the maritime freight sector and also track performance using Emission Inventory methods (Dai et al., 2019). In order to contribute to port sustainability, various researchers have conducted studies on sustainable maritime freight transport. As such, Cammin et al. (2020) analyses the barriers to building efficient Emission Inventories and highlights some of the key constraints such as poor information systems and data secrecy. Ampah et al. (2021) reviewed the literature on cleaner alternative marine fuels and estimated that around 70% of shipping emissions could be saved by the adoption of alternative marine fuels. Similarly, the shipping emissions inventories between river–sea modes and their mixed modes have been compared by (Ye et al., 2022). They concluded that river-sea vessels operated in river-sea and mixed mode are more efficient ways of reducing emissions.

1.2 Need for Digital transformation

Meanwhile, the main challenges in the maritime supply chain are primarily the result of trust issues between stakeholders, need for interoperable information systems, inefficient document management system, product traceability and process optimization, etc. (Farah et al., 2024; Liu et al., 2023). Thus, policy-makers and business parties are looking to invest in efficient operational and technical improvements to reduce pollution and make the maritime system efficient. To achieve these goals, ports, shipping fleets, and hinterland connections must undergo significant digital transformation to address global disruptions, climate change, and carbon emissions, as highlighted by UNCTAD (2022). Digital innovations play a crucial role in helping industries meet their sustainability and efficiency objectives (Sachs et al., 2019). In this era of digitization, organizations are trying to adopt technologies such as blockchain, big data analytics, artificial intelligence, and the Internet of Things in their processes. These advancements enable them to pursue eco-friendly practices while simultaneously fulfilling their business requirements, striking a balance between operational efficiency and environmental responsibility (Heilig et al., 2017; Yang, 2019).

The digital revolution, often referred to as the "digital age," has reshaped competitive dynamics across various industries, with the maritime logistics sector being no exception (Hofmann & Osterwalder, 2017). While playing a pivotal role in global and regional trade, the maritime logistics industry has been slow to embrace digitalization, facing challenges such as high fragmentation, manual processes, lack of transparency and visibility in logistics operations often results in uncertainties and delays (Raza et al., 2023). The maritime logistics sector, with its network-centric nature involving multiple independent actors in each voyage, suffers from poor predictability, longer transit times, delays, and increased costs due to manual processes and a lack of seamless coordination among stakeholders (Göçer et al., 2023; Raza et al., 2023). In this context, the need for various digital technologies implementation in maritime freight becomes imperative to address these challenges and enhance the efficiency and competitiveness of the industry (Mudra et al., 2023).

1.3 Need for Blockchain Technology Adoption

Blockchain technology has the ability to transform the maritime industry by increasing transparency, reducing fraud, and streamlining supply chain processes. By providing a secure, decentralized ledger for monitoring and verifying transactions, blockchain can enhance transparency, security, and efficiency in information management within enterprises. The effective management of information is critical for maritime freight enterprises to streamline operations, optimize resources, and deliver seamless services to customers. However, the traditional information management systems often face challenges related to data integrity, security breaches, lack of transparency, and inefficiencies in information exchange between several supply chain stakeholders. These shortcomings can lead to delays, errors, disputes, and increased operational costs, ultimately affecting the overall competitiveness of maritime freight enterprises. Blockchain technology enables the creation of cryptographic algorithms, ensuring the integrity of data, standardized auditing processes, and the establishment of formalized contracts for data access (Chen et al., 2019). It serves as a secure archive for past transactions, distributing them across multiple servers, chaining them chronologically, and organizing them into blocks to establish a trustworthy provenance system. Several participants in the marine industry have begun numerous pilot projects for the use of blockchain in maritime logistics. For example, IBM and Maersk have partnered to launch TradeLens, a blockchain-based platform for supply chain visibility and efficiency. Similarly, the Hong Kong Shipping Exchange has launched a blockchain-based platform for shipping finance. To promote creative development, 14 Japanese maritime companies have worked together to create a blockchain-based platform for trade data sharing. Blockchain technology gives the marine sector a way to confirm the accountability of partners, suppliers, service providers, and authorities as well as to boost confidence in the veracity of the data gathered during participant-to-participant transactions (Li and Zhou, 2021). The ability of this technology to retain a certified history of information and the capacity to automate the execution and reporting of participant-to-participant transactions is becoming more and more apparent to the maritime industries (Saberi et al., 2019; Sarker et al., 2021). Smart contracts, a feature of blockchain, can automate the execution of shipping-related transactions, such as the transfer of cargo ownership or payment for services. This can greatly reduce the requirement for intermediaries and increase transaction speed and accuracy. The maritime industry and others could also use smart contracts to exchange information more quickly regarding their production process, maintenance and delivery schedule, delivery status, the status and condition of their boats, and crew changes (Chang et al., 2020; Kern, 2021). Besides this, paperless versions of several important shipping documents, such as the bill of lading, which must be issued for each shipment, can be implemented (Pu and Lam, 2021).

1.4 Need for IoT Adoption

Internet of Things (IoT) is a technological paradigm that holds paramount importance across various industries due to its unique features. Digital technologies have already revolutionized various industries such as; finance (Chen et al., 2021), healthcare (Kraus et al., 2021), manufacturing (Ghobakhloo and Ching, 2019), retail (Pantano and Vannucci, 2019), agriculture (Rijswijk et al., 2021), etc.) and the maritime freight sector stands to benefit significantly from IoT implementation. At its core, IoT is instrumental in providing unparalleled connectivity by interlinking physical devices, enabling them to communicate seamlessly over the internet. This connectivity facilitates the real-time exchange of data, offering a dynamic and comprehensive view of the environment in which these devices operate (Khan et al., 2020; Tran-Dang et al., 2020). A key aspect of IoT lies in its ability to enhance visibility, allowing for a deeper understanding of processes and systems. Moreover, IoT enables remote monitoring, empowering users to keep tabs on the status and performance of devices or systems from a distance. This feature is particularly beneficial in optimizing operations, troubleshooting issues, and making informed decisions based on up-to-the-minute data. Overall, IoT's importance is rooted in its capacity to foster connectivity, provide real-time insights, and enable remote monitoring, thereby revolutionizing how we interact with and understand the physical world (de Oliveira et al., 2023; Salah et al., 2020).

1.5 Need for Bigdata & AI Adoption

Big data technology empowers the management of vast datasets, offering robust analysis capabilities to unveil concealed patterns, correlations, market trends, and valuable insights. Within the maritime freight sector, terminals and vessels generate an estimated 100 to 120 million data points daily (Trelleborg Marine Systems, 2018). Leveraging this data, companies predict optimal routes, with Artificial intelligence (AI)-driven algorithms yielding a notable 5-10% performance enhancement. AI and big data synergize, with AI methodologies such as machine learning and neural networks leveraging the expansive datasets furnished by data-analytics. The maritime industry's need for expedited communication is bolstered by AI and Machine learning (ML) processing capabilities. Investments in AI amplify the efficacy of big data analysis, furnishing significant advantages to early adopters in the shipping domain. Despite automation strides in maritime freight by developed nations like Singapore and Denmark, other regions encounter adoption hurdles.

To the best of the author's knowledge, limited researchers have focused on the implementation of digital technologies in the maritime freight industry to enhance sustainability. Among the published research papers, so far very few studies have established a relevant relationship between digital technologies and maritime freight processes (Yang, 2019; Agrifoglio et al., 2017; Parola et al., 2021). Furthermore, the integration of sustainability factors with maritime freight processes has not yet been explored due to the dearth of research papers. Thus, the integration of digital technologies in developing efficient maritime logistics systems and advancing sustainable development remains in its early stages in several Asian countries. Consequently, a deeper understanding of their adoption process is needed. To bridge this gap, the study utilizes a three-stage approach - descriptive, predictive, and prescriptive analysis - to explore the integration of key digital technologies in maritime freight enterprises.

1.6 Motivational Questions

Here are some key considerations that prompted us to undertake the study in this specific area.

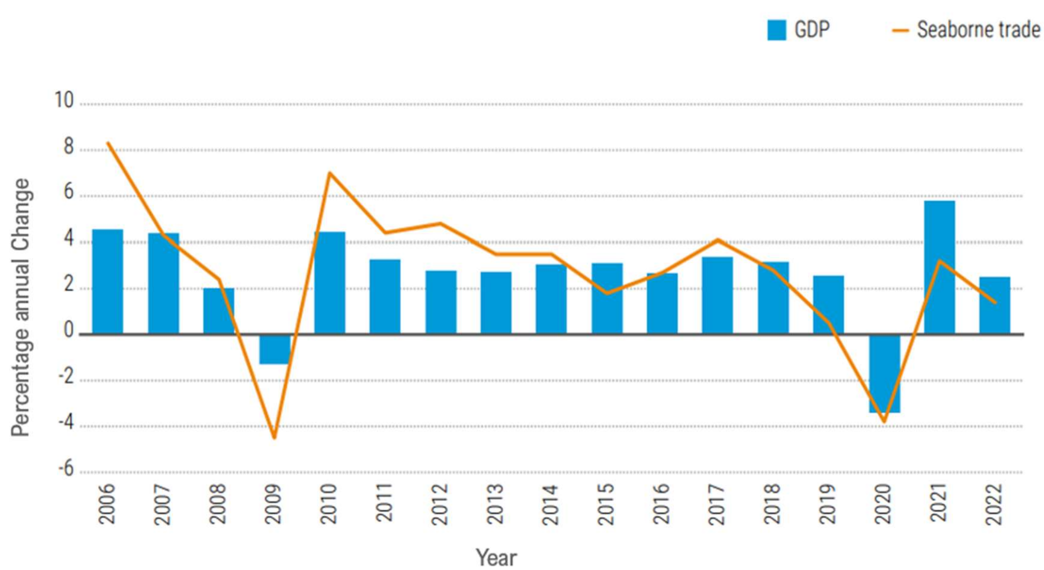

Figure 1:1 International Maritime Trade and World GDP (percentage annual change)
Source: UNCTAD (2022).

- How does the relationship between international maritime trade and world GDP underscore the need for innovative digital solutions to address current and future challenges in the maritime industry?

Understanding the intricate relationship between international maritime trade and world GDP is crucial for developing strategies to enhance both economic and environmental performance. There is a clear correlation among world GDP and Maritime trade, can be seen from Figure 1:1 when maritime trade declines, global GDP tends to decrease, and as maritime trade accelerates, global GDP also increases. This pattern is evident during significant events. For example, in 2020, the COVID-19 pandemic led to a decrease in maritime trade, which was followed by a decline in global GDP. A similar pattern occurred in 2009 during the economic crisis. The data from UNCTAD (2022) highlights the critical role maritime trade plays in the global economy, demanding the innovative digital solutions to address emerging challenges in the industry.

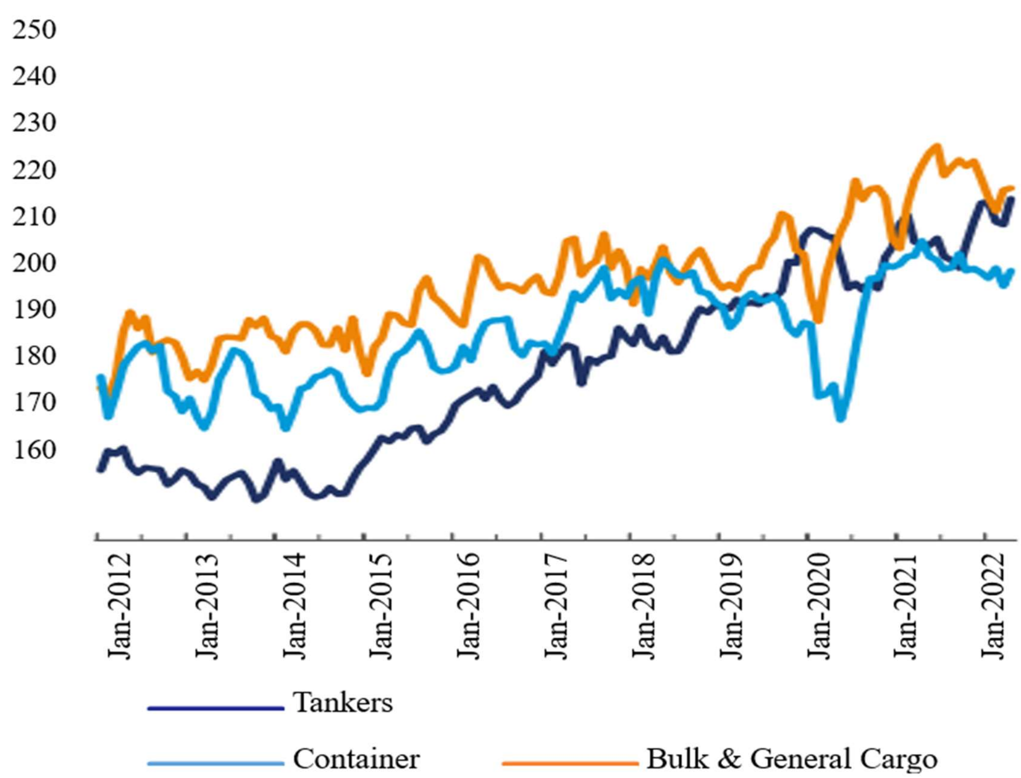

Figure 1:2 Total CO_2 emissions of world fleet by vessel type, million tons.
Source: UNCTAD (2022).

- What are the most significant contributors to CO_2 emissions in the maritime sector, and how can digital technologies target these areas for maximum impact?

Figure 1:2 depicts, the maritime industry accounts for approximately 3% of global greenhouse gas emissions. If no changes are initiated, these emissions could rise to 17% by 2050. In 2022, an estimated total of about 221.5 million metric tons of carbon dioxide were released from global container vessels. Annually, 80,000 ships visit the European ports, which in turn has significantly contributed to air pollution (UNCTAD, 2022; European Commission, 2010). This type of pollution has caused grave health issues, among which lung and heart diseases and cancers have caused about 50,000 deaths in Europe every year. This data brings forth an issue of critical salience pertaining to pollution by ships as there is an acute need to curtail CO_2 emissions from environmental as well as social perspectives. Analysing the total CO_2 emissions by vessel type provides insight into the most significant contributors to environmental pollution, underscoring the urgency for decarbonization initiatives and the adoption of digital technologies to mitigate these impacts.

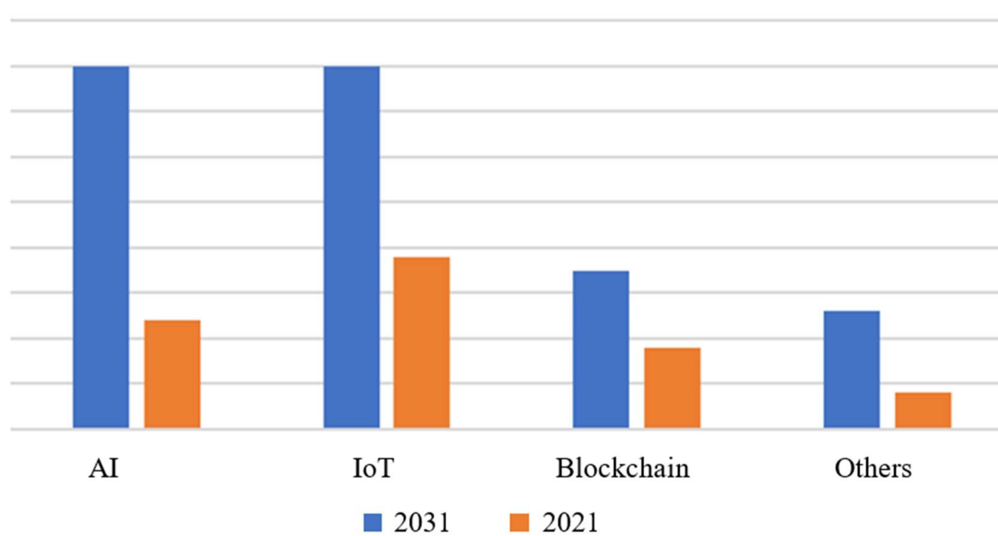

Figure 1:3 Maritime Digitalization Market
Source: Research and markets (2022)

- Given the projected growth of the maritime digitization market, how can port authorities and maritime stakeholders leverage this expansion to enhance connectivity, reduce emissions, and optimize operational processes?

A report by Research and Markets (2022) highlights the significant impact of digital technologies and decarbonization strategies on the maritime industry (refer to Figure 1:3). As per the report, the carbon emission will be reduced up to 38% if digitally-enabled vessels with decarbonization technologies are used. This is a vital approach toward reaching a more sustainable future. Furthermore, increased connectivity among maritime industry could increase profitability by 4 to 17% for the economic benefits as this grows along with the digital transformation in the maritime sector. The significance of these technologies has been expressed in the maritime digitization market. The market size is estimated to be $157.4 billion in 2021 and projected to grow to around $423.4 billion by 2031, with the rate of growth being estimated to be around 10.7% from 2022 to 2031. This extensive growth is a result of rising investment in digital solutions in order to ensure improved both environmental sustainability and profitability.

1.7 Research Objectives

The research addresses a set of critical questions guiding the investigation into integration of digital technologies in the maritime freight sector for enhanced sustainability and efficiency. The objectives are met by raising the following research questions:

- How can digital technologies be effectively integrated into maritime freight operations to enhance sustainability and operational efficiency?
- How can machine learning algorithms utilize data from maritime ports to enhance operational efficiency and achieve sustainability goals?
- What strategies can optimize port operations while balancing sustainability and cost efficiency?

This study tries to address the above research questions by pursuing the following research objectives:

- Identification of digital technologies use cases for sustainable maritime freight system.
- To model the contextual relationship of digital technologies and maritime freight sustainability.

- To predict CO_2 emissions of seaside operations by applying various machine learning models.
- To evaluate the most effective and accurate machine learning technique for predicting CO_2 emissions in the maritime freight industry.
- To formulate a mathematical model that evaluates and optimizes the emissions from seaside port operations, thereby enhancing both operational efficiency and environmental effectiveness.

1.8 Scope of the Research

The scope of this research encompasses the exploration of digital technologies and their role in enhancing sustainability within the maritime freight sector. It aims to explore the key technologies, such as AI, IoT, blockchain, and big data analytics, and analyse their potential applications in maritime freight operations. The study will investigate effective integration strategies for these technologies in operational activities and emissions monitoring. Additionally, it will utilize machine learning algorithms to analyse data from maritime ports, seeking insights that can inform policy and operational improvements. Ultimately, the research will assess how a marine port can optimise efficiency and sustainability, and meet the urgent need for innovative solutions in response to environmental challenges and industry demands. By focusing on these elements, the research contributes to the understanding of digital transformation in maritime freight and its implications for sustainable practices.

1.9 Methodology

The present work employs a holistic, analytical approach by integrating descriptive (SEM-ANN & MCDM), predictive (ML models), and prescriptive (optimization) analytics to provide a structured decision-making framework for maritime freight operations. While MCDM methods are crucial for identifying and prioritizing key factors influencing digital technology adoption, predictive and prescriptive analytics further enhance decision-making by offering data-driven predictions and optimal strategies.

i. *Descriptive Analysis: identifying key factors and their relationships*

Initially, we conducted a descriptive analysis using various SEM-ANN and Multi-Criteria Decision-Making (MCDM) methods to understand the interrelationships among factors influencing the adoption of digital technologies. Methods based on MCDM techniques are frequently considered to address complex problems with multiple conflicting criteria (Jiang et al., 2018). Assessment of these factors often involves considerable uncertainty, particularly concerning subjective judgments and decision-makers' (DMs) characteristics. Decision-makers, driven by a strong aversion to making poor decisions, tend to consider more criteria in the decision process, leading to conservative choices that differ from those of neutral or optimistic DMs. Consequently, decision-making becomes susceptible to risks, as crisp numbers prove inadequate in evaluating such ambiguity (Agarwal et al., 2021). To address these challenges, fuzzy theory and grey theory are integrated into MCDM methods, offering specialized accuracy in handling uncertain data (Liu et al., 2021; Shanker et al., 2022). The descriptive analysis identifies and prioritizes the key factors that influence digital technologies adoption in MFT by employing the following methods:

- Structural Equation Modeling-Artificial Neural Networks (SEM-ANN): This method allows us to model complex relationships among multiple variables, combining the strengths of SEM for structural modeling and ANN for predictive accuracy.
- Grey Decision-making Trial and Evaluation Laboratory based on Analytic Network Process (Grey-DANP): This approach aids in evaluating the influence of various factors in uncertain environments, capturing both qualitative and quantitative data. In this work, grey relational analysis (Julong, 1989) integrated with DANP has been considered for computing the degree of inter-relationships and priority weights of the identified factors. This Grey-DANP method generates the direct influence matrix using the GRA method, and then the DEMATEL-based ANP method is used to provide the final prioritized framework.
- Fuzzy Analytic Hierarchy Process (Fuzzy-AHP) and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (fuzzy-TOPSIS): Fuzzy-AHP helps in prioritizing factors by addressing the vagueness and subjectivity inherent in expert

opinions. And, the TOPSIS approach proves significant by calculating the influencing potential of alternatives based on judging criteria (Goyal et al., 2021).

- Preference Ranking Organization Method for Enrichment Evaluations II (PROMETHEE II): This method facilitates the ranking of alternatives based on multiple criteria, providing a clear decision-making framework.

By capturing both qualitative and quantitative insights, SEM-ANN & MCDM methods bridge the foundation for data-driven decision-making. It identifies the key factors & their inter-relationships for enhancing the sustainability and efficiency of the maritime freight system.

ii. Predictive Analysis:

To make the maritime freight transport system both sustainable and efficient, industries must evaluate the variables contributing to emissions and quantify their impact. Following the descriptive analysis, we implemented predictive analysis to predict the CO_2 emissions from the maritime freight system. To achieve this, the analysis employs four machine learning models, namely; Support Vector Machine (SVM), Decision Tree (DT), Random Forest (RF), and Artificial Neural Network (ANN), to assess their performance using metrics like Mean Square Error, Mean Absolute Error, and Mean Absolute Percentage Error. The analysis was carried out using Python.

iii. Prescriptive Analysis:

The insights gained from both descriptive and predictive analysis play a crucial role in shaping the optimization model for enhancing sea-side port operations. This study develops a mathematical model that seamlessly integrates berth allocation, quay crane scheduling, and emissions reduction into a unified framework. To solve this model efficiently, Elite Genetic Algorithm (Elite GA) and Gurobi Solver are employed, ensuring high-quality, optimal solutions. This approach enables decision-makers to implement cost-effective and sustainable strategies, ultimately reducing emissions and enhancing operational efficiency.

1.10 Contribution of the Research

This study contributes in three phases and collectively addresses a complex maritime freight problem. While there is already existing literature exploring factors influencing the adoption of various digital technologies like Blockchain, Big Data Analytics, AI, and IoT, these studies belong to different domains (Wong et al., 2020; Bhaskar et al., 2021; Rao & Amritha, 2024; Plaza et al., 2021; Aamer et al., 2021). They have either been conducted using surveys or have proposed models to implement these technologies within a system. Such studies provide insights into the challenges managers face when adopting these technologies or, if they have already decided to adopt them, they guide them on how to implement these technologies. However, there is a gap in research when it comes to the initial planning phase - how organizations should plan for the adoption of these digital technologies so that the entire system undergoes a successful digital transformation and fully benefits from these innovations.

The descriptive analysis in this study provides a structured planning process for decision-makers, outlining which factors should be prioritized and how they influence other factors in the process. To achieve this, the study first applies the SEM-ANN approach to model the theoretical framework for the adoption of Blockchain technology in maritime freight, assessing its impact on sustainability and efficiency while testing its influential factors. This approach establishes relationships between key variables and quantifies their impact.

Following this, the descriptive analysis employs MCDM techniques to establish interrelationships among various key digital technologies and their influential factors. By doing so, it identifies the critical factors influencing the adoption of digital technologies in the maritime freight system. Once these key factors and their interdependencies are determined, decision-makers and policymakers can devise strategies and policies to streamline this adoption process for maritime freight industries. Once industries successfully embrace these digital technologies, they move toward the primary objective of adoption: enhancing the system's sustainability and efficiency.

To make the maritime freight transport system both sustainable and efficient, industries must evaluate the variables contributing to emissions and quantify their impact. Machine learning (ML) algorithms play a crucial role in predicting these emissions. Existing literature includes studies that employ various statistical, optimization, simulation, and hybrid models to predict energy consumption, fuel consumption, and CO_2 emissions during routing and other maritime processes (Bassam et al., 2022; Tran, 2021; Hu et al., 2021; Ağbulut, 2022). However, previous studies have not accounted for CO_2 emissions throughout the entire journey of vessels - covering the vessel's departure from the port, transit, docking at the destination port, and other stages. This study aims to fill that research gap.

To achieve this, ML models have been chosen to address the stated objectives. The next challenge is determining which ML model is most suitable for this problem. During the literature review, we found that previous studies have utilized Support Vector Machines (SVM), Random Forest (RF), Decision Trees (DT), and Artificial Neural Networks (ANN) to predict fuel consumption in maritime freight transport (Gkerekos et al., 2019; Wang et al., 2022; Zhou et al., 2022). These studies have demonstrated the effectiveness of these models in solving complex maritime environment problems. Since fuel consumption prediction and CO_2 emission prediction in maritime systems are closely related, this study follows the same approach and applies these four ML models to predict CO_2 emissions within the maritime sector (Ağbulut, 2022). The predictive analysis determines the most effective ML model for predicting CO_2 emissions from maritime freight operations. By assessing the performance of SVM, RF, DT, and ANN models, the study helps decision-makers select the most accurate and reliable option for better forecasting and informed decision-making. Additionally, it identifies key variables influencing total CO_2 emissions, enabling policymakers to implement targeted interventions such as optimizing fuel usage, improving vessel efficiency, and enforcing emission control measures. The predicted CO_2 emission values provide decision-makers and managers with valuable insights for strategic planning and operational improvements.

While CO_2 emissions occur both at sea and in port, our focus on port-side operations is driven by the fact that these emissions are more controllable and can be optimized through prescriptive analysis. A literature review reveals that existing studies have primarily addressed either the Berth Allocation Problem (BAP) (Ribeiro et al., 2016) or the Quay Crane Scheduling Problem (QCSP) (Hu et al., 2019), with very few considering the integrated problem of BAP and QCSP (Wang et al., 2019; Iris et al., 2015). Some studies have also factored in emissions alongside BAP or QCSP (Jauhar et al., 2023; Kenan et al., 2022). In this study, we conduct a prescriptive analysis by developing a mathematical model that optimizes BAP and QCSP while accounting for emissions from both vessels and quay cranes. Previous research has solved this type of models using various optimization algorithms, such as Nested Non-dominated Sorting Genetic Algorithm II (Yu et al., 2023), Lbest and Nbest Particle Swarm Optimization (GLNPSO) (Mogale et al., 2023b), Exact Decomposition Algorithm (Rodrigues & Agra, 2021), and CPLEX, etc. For our study, we employ the Elite GA algorithm, as it demonstrates superior performance in terms of solution quality, stability, and computational efficiency (Jong, 1975). Given that the model is a Mixed-Integer Nonlinear Program (MINLP), we use the GUROBI optimization solver to obtain exact solutions for comparison with our Elite GA algorithm. Prescriptive analysis enables decision-makers and port authorities to take strategic actions to optimize berthing schedules, handling operations, and energy consumption. Additionally, this data-driven model assists policymakers in refining regulations to ensure they are both effective and practical for shipping companies.

1.11 Chapter-wise summary

The study is structured as follows: Section 2 presents the literature review, which explores existing research on descriptive, predictive, and prescriptive analyses related to the key digital technologies' adoption in maritime freight. This review serves as the foundation for understanding use cases, challenges, and adoption trends, offering essential background knowledge for the study. Furthermore, Section 3 outlines the methodology, detailing the structured approach used to achieve the research objectives. The study is conducted in three distinct phases: descriptive analysis, predictive analysis, and prescriptive analysis. Each phase employs specific methods tailored to different aspects of the research problem, collectively contributing to a deeper understanding of how digital technologies can enhance sustainability and efficiency in maritime freight operations. This section provides a detailed explanation of all the methods applied across these three analytical phases. Hereafter, Section 4 focuses on descriptive analysis, where various hybrid decision-making methods are utilized to identify and examine the interrelationships among factors influencing the adoption of key digital technologies in the maritime freight system. This phase lays the groundwork for understanding the critical drivers and barriers to digital transformation in the industry. Similarly, Section 5 delves into the predictive analysis, where various machine learning algorithms were employed to predict CO_2 emissions from vessels in the maritime freight industry. This analysis aimed to identify the most effective and accurate machine learning technique for emission prediction in maritime freight context. The ML models used in this study include Support Vector Machine (SVM), Decision Tree (DT), Random Forest (RF), and Artificial Neural Networks (ANN). Following this, Section 6 explores the prescriptive analysis, in which a mathematical model was developed to optimize both operational and emissions costs associated with sea-side port operations. This section discusses the results of the data analysis, highlighting key findings of the study. Finally, Section 7 concludes the study by summarizing its key contributions, addressing its limitations, and suggesting directions for future research. This chapter also presents the broader research implications, emphasizing how digital technologies have the potential to transform the maritime freight industry by enhancing sustainability and efficiency.