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The Role of Applying Artificial Intelligence in Improving Supply Chain Management and Sustainability: Evidence from Egypt Ports

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Abstract
This study aims to determine to what extent the application of AI could optimize supply chain management and contribute to the sustainability of Egyptian ports? Egyptian ports were selected to serve as an empirical study in this research, assessing their application of AI and their supply chain management. Interviews were conducted with a group of 7 managers from different Egyptian ports. The results of the interviews showed the main potential risks, ethical principles, and sustainability goals of applying AI to optimize the supply chain and thus ensure the sustainability of Egyptian ports. It also put forward suggestions and recommendations for overcoming these challenges and thus to formulate a comprehensive national AI strategy that aligns with both the sustainable development goals and the overarching vision of Digital Egypt (Vision 2030).

Keywords- Artificial intelligence, Supply chain management, Port sustainability, Egypt.

1. Introduction

Supply chain management is seen as an "*integrative philosophy*" for managing the distribution process (flows, suppliers, users, etc.) (Cooper and Ellram, 1993). It represents a strategy of coordination between several business units. This enables us to build a complex and dynamic network (Harland, 1996). Port operations such as vessel, cargo, and passenger operations, require various infrastructure elements such as berths, quays, cranes, and passenger terminals. Efficient coordination and planning are essential for the smooth flow of goods and people through seaports, including vessel scheduling, berth and cargo-handling equipment allocation, and coordination of customs procedures. These operations play a key role in Supply Chain Management (SCM), facilitating the flow of goods through international shipments by sea (Ascencio et al., 2014).

Recently, public authorities have been facing three major challenges in the field of SCM. These challenges are: (i) effective risk management; (ii) ethical practices; and (iii) sustainable development. Effective risk management is essential for port supply chains because it can minimize risks related to geopolitical crises, accidents, and natural disasters (Acciaro, 2008) and also ensures smooth ports' operations. Thus, adopting an efficient risk management would minimize financial losses and enhances the overall the ports performance (Ivanov et al., 2021). With respect to ethical practices, it also enhances ports' sustainability. Adopting ethical practices will result in a resilient supply chain (Torelli, 2020) and guarantees that goods are produced incompliance with the environmental, social, and ethical standards (Kim et al., 2018), thereby meeting consumers' expectations (Lambrechts, 2020). Regarding sustainability development, Governments are seeking to achieve the global goal of sustainable development. To achieve this goal, they are trying to optimize the sustainability of ports, and this could be done by integrating AI into SCM. To do so, these authorities must respect environmental, economic, and social fluctuations (Alamoush et al., 2021; Styliadis et al., 2022).

Due to the globalization and the rapid growth in international trade, SCM and the enhancement of sustainability in ports are of crucial importance (Cheng et al., 2018; Lui et al., 2023; Li et al., 2023). Today, SCM faces several obstacles, these obstacles include strategic sourcing complexities which is due to geopolitical tensions; increased trade restrictions because of the government measures and challenges related to the adoption of generative AI; and the increase in the operational costs, fluctuation of the consumer demand, labor shortages, and higher customer expectations for speed and sustainability. All these obstacles' effects the supply chains negatively. Moreover, the focus on ESG factors, heightened cybersecurity risks and the global conflicts are further disrupting trade routes and operations, presenting a multifaceted landscape of obstacles for companies to overcome (He et al., 2023).

In this context, there are several solutions that were addressed in the prior studies in order to reduce these obstacles. One solution was the integration of Artificial Intelligence (AI) into the SCM (Chu et al., 2020; Wehrle et al., 2022; Xu et al., 2022) due to its positive impact on ports operations. It helps the managers to optimize operations, manage resources efficiently, reduce waiting times, and improve equipment management. It was found that an effective AI integration into port operations developments its process in a way that will enhances cargo flow, lowers operating expenses, and lessens the carbon footprint connected with logistics-related activities. Moreover, it was found that AI improves ports' sustainability. According to Ahmed et al. (2023), Broekhuizen et al. (2023), and Pournader et al. (2021), AI integration not only optimizes port performance but also proactively satisfies the evolving sustainability standards. Because it helps managers manage waste, lower emissions, and limit energy consumption.

Moreover, Ahmed et al. (2023) added that AI enhances safety and reduces risk, which is essential for aligning economic growth with environmental preservation in SCM and port operations. It was observed that AI enhances safety in ports because of its ability to increase the effectiveness of monitoring, which therefore helps in early identification of abnormalities, and facilitate quicker response to incidents. In addition, AI can facilitate collaboration between various stakeholders in the port's ecosystem, such as terminal operators and logistics providers; therefore, port security and efficiency will be improved (Dauvergne, 2020). The increased coordination throughout the port system and procedures, will be positively affect the operation process and hence better SCM. This implies that AI can improve port performance, service quality, safety, and environmental sustainability (Kumar et al., 2021; Tsolakis et al., 2023).

Previous studies asserted that including AI in port systems enhances SCM and optimizes sustainability (see, for example, Othman et al., 2022). On the other hand, some studies have discussed the risks associated with its application. They found that these risks vary from country to country depending on whether the country in which the entitled ports operate in is developed or developing. They argued that each country has its own technological infrastructure, cybersecurity, and governance capabilities (see, for example, He et al., 2023; Kshetri, 2021; Othman et al., 2022). Although recent literature has focused on discussing the application of AI in SCM and its effect on port sustainability, this exploration still remains an important area for research. Indeed, most of these studies have focused mainly on bibliometric and systematic analyses (such as de la Peña Zarzuelo et al., 2020; Munim et al., 2020; Stein and Acciaro, 2020; Toorajipour et al., 2021). This stream of studies focused on investigating the factors that influence port performance, yet they lack an in-depth analysis of the potential impact of AI on MTS and ports' sustainability (for example, Miller and Hyodo, 2022; Park and Dossani, 2020). Accordingly, this gap in the literature indicates that it is important to explore the possibilities and implications of using AI in the port context. Therefore, this study focuses on AI specific applications and the potential benefits that can improve the sustainability of port operations.

In order to achieve this objective, the researcher addresses the following research questions (RQs):

- ***RQ*1**. What are some potential risks associated with the use of AI in supply chain and port operations, such as the potential for bias, errors, or security breaches?
- ***RQ*2**. What ethical concerns do you think arise from the use of AI in supply chain and port operations, and why?
- ***RQ*3**. How does AI adoption in the port supply chain align with sustainability goals?
- ***RQ*4**. What steps can be taken to ensure that the adoption of AI in supply chain and port operations benefits society as a whole, rather than just a select few stakeholders?

To address these questions, a qualitative approach was developed using a semi-structured interview. The qualitative approach was chosen for its ability to explore complex phenomena specific to the impact of AI on SCM and thus sustainability of Egyptian ports. In addition, it is important for the exploratory nature of the study. Indeed, quantifying these types of variables is still difficult. In addition, the choice of ports as an SCM stakeholder since they present a critical point in the supply chain, particularly in the context of sustainability. This allows us to delve deeper into specific strategies and innovations (AI integration), contributing to the optimization of port operations. Furthermore, answering and discussing these questions helps to refine the understanding of AI's potential influence on optimizing SCM and promoting the sustainability of Egyptian ports.

The main result of the qualitative approach showed the main potential risks, ethical principles, and sustainability goals of applying AI to optimize the supply chain and thus ensure the sustainability of Egyptian ports. From this perspective, Egyptian policymakers can better apprehend the risks inherent in the use of AI in this sector, while committing to ensuring the active participation of stakeholders (workers, consumers, local communities, etc.), in the development and implementation of these technologies. In addition, this study extends the research contributions by highlighting the mechanisms needed to harmonize the adoption of AI in SCM and port operations with broader sustainability objectives (e.g., including greenhouse gas emission reduction and waste minimization).

The rest of the paper is structured as follows: In the second section, a literature review on the application of AI, SCM and port sustainability will be discussed, focusing on previous studies carried out in this field on developed and developing countries. Next, the research methodology will be discussed in Section 3. The results will be discussed in Section 4. This paper will conclude with implications, limitations, and future research.

2. Literature Review

According to Mentzer et al. (2001), there are two categories of perspectives on SCM: (i) SCM as a management philosophy and (ii) a set of management processes. The characteristics of SCM as a management philosophy are as follows: "i) A systems approach to viewing the supply chain as a whole, and to managing the total flow of goods inventory from the supplier to the ultimate customer; ii) A strategic orientation toward cooperative efforts to synchronize and converge intrafirm and interfirm operational and strategic capabilities into a unified whole; iii) A customer focus to create unique and individualized sources of customer value, leading to customer satisfaction" (Mentzer et al., 2001). In the same vein, various activities necessary for the successful implementation of a SCM philosophy were proposed, namely integration of processes and partners to establish and maintain long-term relationships, mutual sharing of risks and rewards, integrated behaviour, mutual sharing of information, cooperation, common purpose and focus on serving customers (Mentzer et al., 2001). In addition, Mentzer et al. (2001) suggest that SCM is a well-defined process. Therefore, SCM is defined as "the process of managing relationships, information, and the flow of materials across enterprise boundaries to deliver better customer service and economic value through to the synchronized management of the flow of physical goods and associated information, from supply to consumption" (Mentzer et al., 2001).

Given these considerations, SCM theory represents the theoretical framework for this study. SCM theory integrates procurement, logistics, and distribution, which is a key to understanding AI's role in sustainable port operations. By taking advantage of AI's predictive analytics, port decision-making operational efficiency will be improved. Additionally, AI supports SCM's core integration principle, which makes data sharing easier between port's stakeholders and thus improves the communication among them. Furthermore, AI can reduce ports' ecological impact and increase adaptation and collaborative efforts to meet sustainability goals that align with SCM's environmental focus. Moreover, SCM theory guides the strategic use of AI at ports to meet the evolving demands of international trade and sustainability challenges.

According to the literature review, the studies were categorized, based on different themes and research methodologies. For instance, several studies in developed countries highlighted that the integration of AI technology optimizes port operations and ensures its sustainability. For example, Caldeirinha et al. (2020) conducted a survey targeting senior executives of Portuguese ports to examine the impact of the community system on port performance. The author found that the port's performance is significantly influenced by the various characteristics of the port's community system. Zhou et al. (2023) also investigated the effect of using blockchain for SCM's sustainability disclosure on consumer confidence. The study revealed that implementing blockchain technology has the potential to boost consumer confidence in sustainability related. Yet, they argued that it could also intensify competition between manufacturers and reduce shared benefits. In a similar vein, Jeanneret et al. (2024) investigated the impact of using blockchain on trust within SCM. Through semi-structured interviews and literature reviews, they found that blockchain reduces information asymmetry and strengthens agent control, but it can also cause an agent's trust in the principal to decline. The authors concluded that reducing stakeholders' conflict of interest requires the adoption of blockchain technologies in SCM.

In addition, other studies have examined the environmental impact and sustainability aspects of ports. Using multiple linear regression, Fahdi et al. (2021) found that the introducing machine learning technology in the port of Casablanca reduced CO_2 emissions, highlighting the potential for pollution reduction through technology application. Argyriou et al. (2022) identified poor infrastructure and waste management as hampering the sustainability of the port of Souda in Crete. Othman et al. (2022) conducted semi-structured interviews in Egypt and highlighted significant challenges faced by Egyptian ports in supporting sustainable performance. They called for measures to facilitate the adoption of smart practices and technology in Egyptian ports.

However, few studies have focused on identifying barriers hindering the adoption of AI technologies in SCM. Using, DEMATEL method based on Pythagorean fuzzy sets, Singh et al. (2023) analyzed the barriers to the adoption of blockchain technology in construction SCM. The study identified market risks, high costs, and use in the underground economy as the most influential barriers to blockchain adoption in construction SCM. Furthermore, Kshetri (2021) assessed the impact of blockchain applications on sustainable SCM management in developing countries. The study highlighted challenges faced by developing countries, including an unsupportive institutional framework, high costs, technological limitations, unequal power distribution among supply chain actors, and opaque value delivery networks.

Moreover, several studies have investigated the factors that affect the efficiency and performance of ports. For instance, Miller and Hyōdo (2022) used stochastic frontier analysis to analyze the impact of the Panama Canal expansion on port efficiency, revealing the significance of factors such as quay length and the number of cranes on port performance. They recommended adopting of new strategies to create added value and ensure the dynamics of logistics centers in the maritime sector. Additionally, as per the researcher's awareness, few scholars have investigated the impact of digital adoption and strategic alliances on port sustainability using case study analysis. For example, Utama et al. (2024) used PLS-SEM analysis to investigate the influence of digital adoption, service quality, and strategic alliances on the commercial sustainability of Indonesian ports. They found that digital adoption and service quality positively influence the development of strategic alliances, which, in turn, contribute to improving the sustainability of port companies.

Finally, other studies focused on other question related to IA and SCM. For example, Surucu-Balci et al. (2024) focused on analyzing the correlation between blockchain adoption barriers and the key players identified to foster this adoption within maritime supply chain. Their findings highlight major players such as container shipping lines, ports, beneficial cargo owners, third-party freight forwarders and logistics and customs authorities. This study confirms the validity of the stakeholder theory. In addition, Niu et al. (2021) reported that the effectiveness of machine learning technology in extracting anchor ship positions has simplified and improved the ship tracking process. They also showed that this technology can optimize port resource management, reduce operational costs, and improve the efficiency of maritime operations. Similarly, Kumar et al. (2021) conducted a partial least square to analyze whether environmental dynamics can induce companies to implement I4.0 technologies, while also testing the mediating effect of critical factors on this relationship, based on a survey of Indian manufacturing industries. To categorize the critical determinants of I4.0. The findings showed that environmental dynamics have a positive and statistically significant impact on I4.0 technologies. This translates into its ability to promote I4.0 technologies and, consequently, improve performance (environmental and commercial). In addition, Ferdous et al. (2024) have shown that improving Blockchain technology is necessary to facilitate its successful implementation in supply chain. This, in turn, ensures the sustainability of supply chain. Finally, Liu et al. (2023) reported that machine learning and neural network approaches play a fundamental role in predicting port throughput at the port of Ningbo-Zhoushan in China. This study shows that the application of AI techniques helps to reduce the risks associated with infrastructure investments during the development phase, while ensuring better port throughput prediction in the long term.

3. Research Methodology

This study was conducted to examine the extent to which the application of AI could optimize SCM and contribute to the sustainability of Egyptian ports? Through an empirical investigation focused on Egypt, this research seeks to resolve the following questions:

- ***RQ*1.** What are some potential risks associated with the use of AI in supply chain and port operations, such as the potential for bias, errors, or security breaches?
- ***RQ*2.** What ethical concerns do you think arise from the use of AI in supply chain and port operations, and why?
- ***RQ*3.** How does AI adoption in the port supply chain align with sustainability goals?
- ***RQ*4.** What steps can be taken to ensure that the adoption of AI in supply chain and port operations benefits society as a whole, rather than just a select few stakeholders?

The *RQ*1 focuses on the risks of AI in supply chain and port operations. The importance of this question is essentially focused on certain reasons, namely errors and security loopholes etc. Furthermore, this question is crucial as it contributes to the existing literature by highlighting the challenges facing Egypt. More specifically, the answer to this question helps policymakers and regulators to develop new AI standards (Ali et al., 2023). It also serves to improve understanding of the application of AI in supply chain and port operations. Finally, this question also has practical ramifications that can foster digital innovation in Egypt's supply chain and port logistics.

For the *RQ*2, the ethical deployment of AI in supply chain and port operations is a critically important area of research for Egypt. Accordingly, this research highlights the need for transparency and explicability in AI systems to maintain international trust, addresses the need to mitigate bias and ensure fairness in AI outcomes, and highlights the importance of privacy and data security in the context of increasing digitization (Muldoon et al., 2023). In addition, it also explores the ethical dimensions of human-AI collaboration and the environmental impact of AI in logistics optimization. In this respect, the study aims to contribute to the literature by exploring the ethical implications in Egypt. Additionally, AI urges effective industrial policies and practices to support the sustainability of Egyptian ports.

Regarding *RQ*3, it addresses the alignment of AI adoption in port supply chains with sustainability goals. More specifically, it explores how AI can contribute to achieving global sustainability goals through several measures namely energy efficiency, waste reduction and logistics improvement. In addition, this question also examines the innovative role of AI in SCM, its economic and social ramifications (e.g., changes in the labor market and skills requirements, environmental benefits) (Othman et al., 2022; Tsolakis et al., 2023). With a focus on Egypt, *RQ*3 aims to enrich the academic literature with empirical data from a developing country, and to propose practical recommendations for policymakers and industry professionals to optimize the potential of artificial intelligence for sustainable development. This survey sits at the crossroads of technology, sustainability, and supply chain management, and makes a valuable contribution to academic discourse and practical applications in Egypt's critical economic and ecological framework.

Finally, *RQ*4 addresses the imperative of ensuring that the adoption of AI in supply chain and port operations benefits society, not just a select group of stakeholders. More specifically, it highlights the need for equitable technological progress to avoid disparities, the societal impact of AI on employment and community well-being, and the promotion of economic sustainability through inclusive growth (Ali et al., 2023).

Answering these questions helps the researcher to refine the potential influence of AI on optimizing SCM and enhancing the sustainability of Egyptian ports. From this perspective, Egyptian authorities and policymakers can better apprehend the risks inherent in the use of AI in these sectors, while committing to ensuring the active participation of stakeholders such as workers, consumers, and local communities, in the development and implementation of these technologies. Furthermore, this study extends the research contributions by highlighting the mechanisms needed to harmonize the adoption of AI in SCM and port operations with broader sustainability goals, including the reduction of greenhouse gas emissions and waste minimization, in developing countries, particularly Egypt.

3.1 Research Design

For this research, it was decided to choose a qualitative research approach. The choice of the qualitative approach is based essentially on the following two reasons. First, the application of AI to supply chain management in the context of Egyptian ports involves complex and context-specific phenomena that are best explored by qualitative methods. These methods allow us to capture the nuances with which AI can influence SCM and thus port sustainability. Second, given that AI integration into SCM is still in its infancy, our study is exploratory. Therefore, qualitative research is particularly suited to new areas of inquiry where variables are not yet clearly defined.

An empirical study was conducted to determine to what extent the application of AI could optimize supply chain management and ensure the sustainability of Egyptian ports. The primary data were collected based on data collection, analysis, and evaluation stages. Specifically, this study uses a semi-structured interview. As part of the narrative research, the information gathered was concentrated and summarized. On this basis, the research was completed by semi-structured interviews to converse with experts. Interviews are the most commonly used data collection method in qualitative research, and the most important method in narrative research in particular, as interviewees answer questions based on their narrative schema, which reflects their knowledge and experience. Semi-structured interviews were analyzed using content data analysis methods, in addition to a comprehensive literature review of related theories and approaches, policy regulations and guidelines related to the topic.

In terms of methodological strategy, the application of AI in port SCM could generate three main consequences, namely potential risks, ethical principles, and sustainability goals. As mentioned above, SCM optimization is seen as a mediating role between the consequences of AI application and port sustainability. Consequently, **Figure 1** shows a diagram of the research framework.

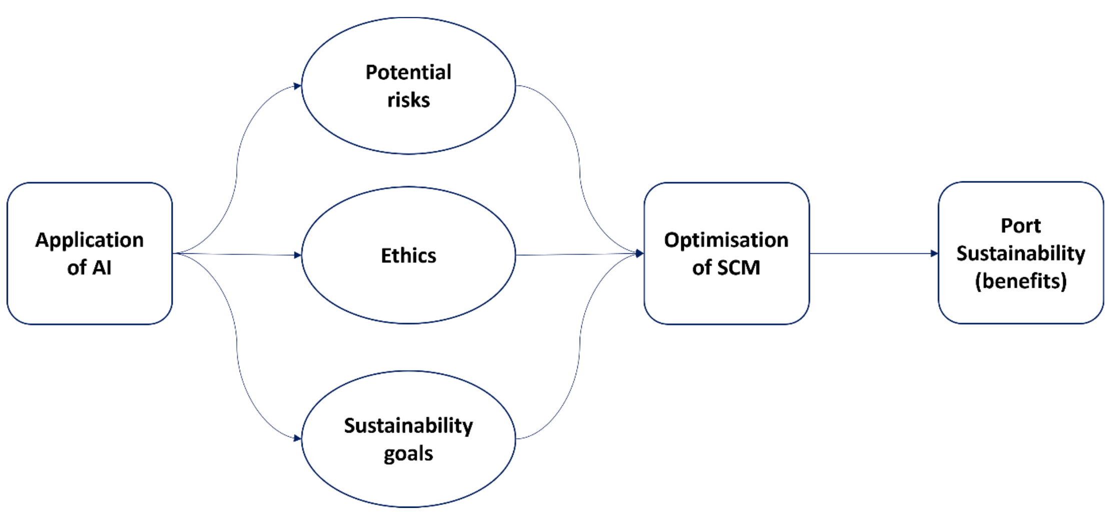

Figure 1. The scheme of the research framework.

Therefore, this study is followed by an in-depth analysis through a semi-structured interview analysis to identify the main challenges related to the use of AI in the port supply chain. More specifically, it is important to focus on the potential risks, the ethical principles, and the main port sustainability goals to optimize the SCM and thus achieve a sustainable port. Therefore, the group of interviewees will be led to conclude certain procedures in order to draw suggestions and recommendations that determine the requirements and prerequisites for a sustainable and intelligent port. **Figure 2** illustrates the research methodology to investigate the research methodology for to assess the extent to which the application of AI could optimize SCM and ensure the sustainability of Egyptian ports.

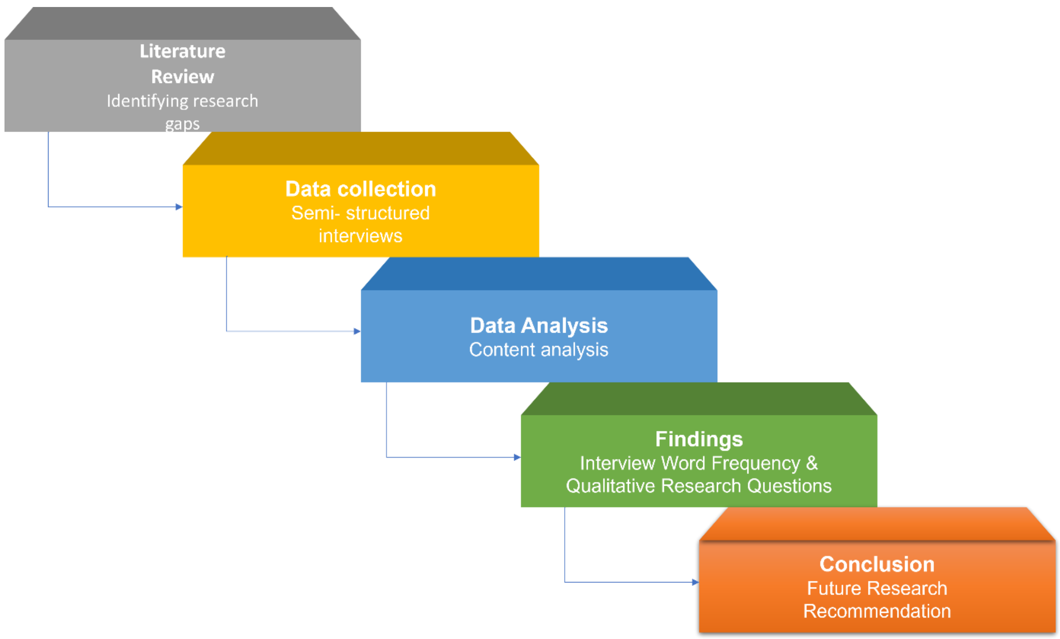

Figure 2. Research methodology.

3.2 Participants

The study involved seven directors who were experts in the domain. Following Thomas and Simerly (1995) method, the directors were chosen deliberately for their roles as decision-makers and their reputation as authorities in the area, having dealt with this particular topic and having applied it in their past work. Accordingly, the participants included in the sample are senior managers from maritime sectors with adequate industry experience.

The choice of seven directors for the interviews reflects a methodical and strategic approach aimed at capturing a representative view of port activities in Egypt. There are seven main ports operating in Egypt, and each selected participant was responsible for managing one of these ports This to ensure that the gathered data covers data cover a significant geographical and operation scope. The diversity of ports is essential, since each port has its unique challenges and dynamics that might impact the performance and the management strategy of the entitled port. Despite the logistical and communication problems, the choice of at least one director per port ensures that the information gathered is balanced and comprehensive, offering an in-depth analysis of Egypt's port infrastructure, which is vital to the country's trade and economy. This deliberate choice strengthens the validity of the study and provides a solid basis for well-informed conclusions.

The **Table 1** shows the profiles of the seven directors who participated in the study as experts in the maritime sector in Egypt. They were selected from different ports along the Mediterranean and Red Sea coasts. They also represent various job roles and professions within this industry. The table also indicates the years of experience that each director had, ranging from 15 to more than 20 years. Based on the directors' knowledge and expertise, it was expected that they will provide a valuable insights and opinions related to this subject area.

Table 1. Interview participants.

Code names	**Participant group**	**Job role/ Profession**	**Sector**	**Years of experience**
Director 1	Alexandria port	Chief Financial Officer	Maritime	15-20
Director 2	Damietta port	Human resources director	Maritime	>20
Director 3	Port-Saïd	Administrative director	Maritime	15-20
Director 4	Suez Port	Production director	Maritime	15-20
Director 5	Adabiya Port	Chief Financial Officer	Maritime	>20
Director 6	Safaga Port	Administrative director	Maritime	15-20
Director 7	Al Sokhna Port	Human resources director	Maritime	>20

3.3 Data Analysis

In order to achieve the objective of the study, the researcher collected data by conducting individual interviews with various stakeholders; each interview lasted 45 minutes. The data also includes a three-hour discussion recorded on tape and audio. Afterwards, these recordings were transcribed and analyzed.

The technique that the researcher employed to analyze the semi-structured interview was content analysis. Content analysis is a widely used method for analyzing qualitative data. This type of analysis allows the researcher to analyze the information that respondents provided and determine the consistency of the data offered.

In light of this, the researcher adhered to the following four content analysis framework steps: First, the data was collected by audio recording with the interviewee's consent and then translated into English to ensure accuracy and clarity. Second, the transcribed data were sorted, categorized, and contrasted for each question to gain a deeper understanding. Third, the categorized data were linked to the relevant concepts from previous studies, and lastly, the researcher analyzed the data and presented the results in an organized way.

4. Empirical Study

This study aims to highlight the potential risks resulting from using AI technology in the Egyptian port business. Additionally, it explores how port companies and policymakers can guarantee that the incorporation of AI into SC and port operations adheres to the port's sustainability goals. Accordingly, this section endeavors to examine the impact of implementing AI technology on the SCM and sustainability of Egyptian ports.

4.1 Interview Word Frequency

Several visualizations were used by the researcher to facilitate the exploration of the most frequently used words by the participants and to visualize the source data by areas of coding similarities. The **Figure 3** show the Word Cloud Map based on MAXQDA analysis of coded nodes. More specifically, the Word Cloud Map provides the frequency of each word.

Figure 3. Word cloud map.
Source: *Word Cloud Based on MAXQDA Analysis of Coded Nodes using interview data by the research.*

4.2 Potential Risks Associated with the Use of AI in SCM

Coding references for the potential risks subtheme by all participants are shown in **Figure 4**. From this graph, we can observe that 7 quotes from the interview address the question of ethical and social implications. Director 1 has the highest number of coded references with 21.21%, followed by Directors 3, 6 and 7 with coded references 18.18%, 18.18% and 15.15% respectively (e.g. sum of the percentages of four participants is equal to 72.72%). Directors 2, 5 and 4 have the lowest numbers of references with references coded 12.2%, 9.09% and 6.06% respectively (27.27%). Thus, the sum of the percentage of all participants is equal to 100%. This percentage is calculated by dividing the number of coded references per director by the total number of coded references for all directors. However, this does not mean that other participants did not have important opinions on the Potential risk's dimensions, but perhaps they focused on other subthemes of ethical and social implications.

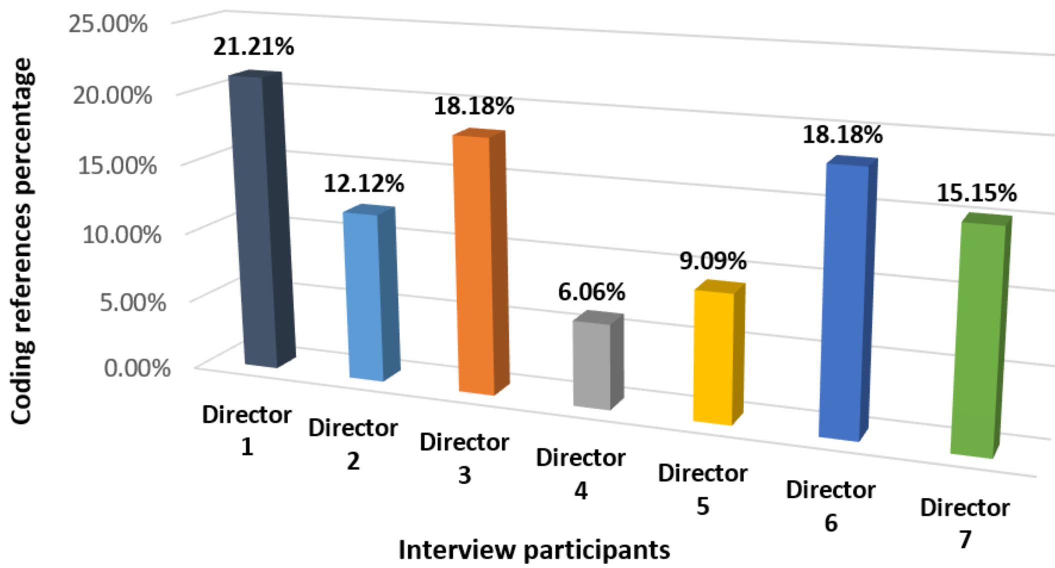

Figure 4. Potential risks sub-theme coding rate.
Source: *Author's work using cross tabulation query result from MAXQDA.*

Directors' responses highlight the economic risks associated with integrating AI into port operations in Egypt. These risks include bias and errors, lack of transparency, workforce displacement, lack of explanation, loss of human expertise, and lack of accountability. In this case, it is important to discuss to discuss each type of risk separately.

AI technologies depend on data for learning and decision-making. However, this data can sometimes be biased. If an AI used to predict market demand is trained on data influenced by personal bias, it may make predictions that unfairly favor certain items, fields, or groups. Such prejudices clash with ethical values (e.g., discrimination). To avoid this type of risk, it is essential to build AI with clarity, responsibility, and ethics. To do this, it is important to share transparently the data, techniques and premises used, as well as to systematically check and review AI decisions to ensure they are free from bias and error.

According to respondents, lack of transparency also presents another important type of potential risk of AI integration. Indeed, some AI algorithms - particularly complex deep learning models - can be difficult to interpret and understand. This lack of transparency can hamper the ability of the user of this technology to identify the root causes of errors. This requires the prioritization of explainability and transparency in AI systems.

The application of AI techniques could create a risk of employee displacement. Indeed, over-reliance on AI can be risky in the absence of human supervision. This is because technical problems can lead to major failures. A balanced integration of AI and human knowledge is therefore essential. Port managers therefore face a major challenge, which hinges on the ease of training to enable the workforce to adapt easily.

Another potential risk arising from the integration of AI is the lack of explanations. Because of its complexity, AI could generate ambiguous conclusions that are difficult to grasp. This could undermine trust and complicate issues that require clear explanations. Finally, lack of accountability could also be one of the main risks. Indeed, poor, diffuse AI decision-making across all port activities could hamper traceability and obscure responsibility in the event of a problem. In this case, it is important to put in place a clear and solid governance framework. This result is in line with the one found by Othman et al. (2022). However, it contradicts those found by Liu et al. (2023), Jeanneret medina et al. (2024) and Utama et al. (2024). It can be noted that the increase in operational costs can impede the use of AI in maritime and ports industries, as demonstrated by Kshetri (2021) and Singh et al. (2023).

4.3 Ensuring Ethical and Response

The coding references of the sub-theme ensuring ethical and responsible seems to be important since only two participants didn't express their opinion on this issue (see **Figure 5**). Among all participants, Director 1 has the highest (45,45%) coding reference to this theme, followed by participant Director 2 with 36,36% of the coding reference. However, Director 6 has the low (18,18%) coding reference to this theme.

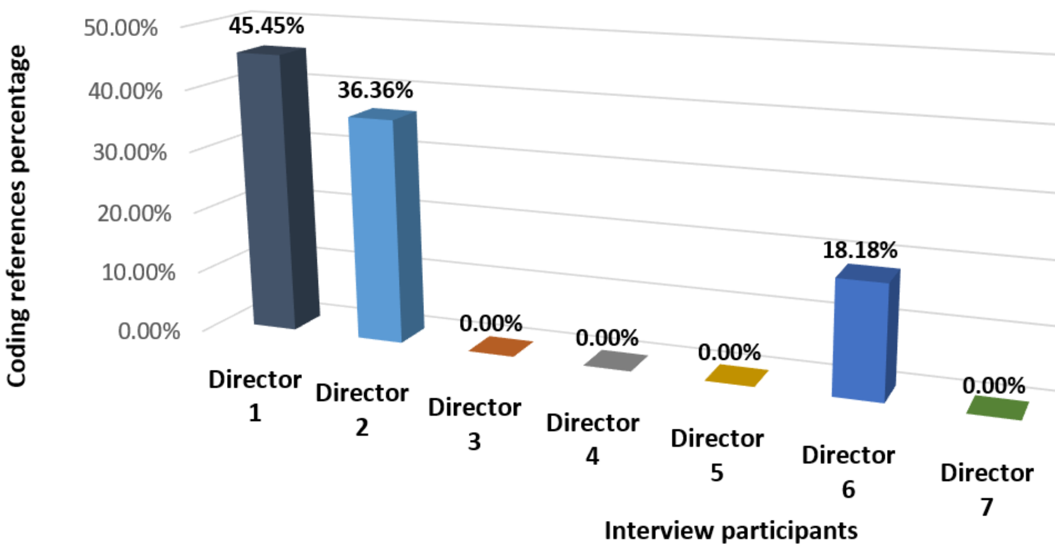

Figure 5. Ensuring ethical and responsible sub-theme coding rate.
Source: *Author's work using cross tabulation query result from MAXQDA.*

The results suggest the importance of ethics and responsibility in integrating AI into port operations. The almost unanimity of directors expresses major economic concern for these questions. Managers' responses focus mainly on three main elements explaining the ethical aspect of integrating AI into SCM. First, the integration of AI into SCM and port operations is based on the implementation of a transparent governance framework with ethical and accountability guidelines. More specifically, the alignment of AI with societal norms and values essentially depends on the commitment of all stakeholders. To achieve this, according to the directors, it would be useful to conduct continuous assessments of AI's societal impact, comply with data management protocols on quality and confidentiality, and have in-depth training on the ethical use of AI. In this case, continuous dialogue, and development between all stakeholders in AI could be driven by promoting a culture of confidence and innovation. Second, the directors also put a great emphasis on data confidentiality and security. Indeed, they indicated that it is crucial to implement strong data privacy and security measures to protect sensitive information. Third, to mitigate the risks, the directors tried to explain another factor relating to the ethical aspect of integrating AI into SCM. By carrying out regular audits and evaluations of AI systems, it is obvious therefore to identify any biases and unintended consequences. This result is consistent with the one found by Surucu-Balci et al. (2024).

4.4 Sustainability Goals

From **Figure 6**, the *Sustainability goals* sub-theme seems to be less important as only three participants (Director 1, Director 4, and Director 7) expressed their opinion. Among all participants, Director 1 has the highest (46,15%) coding reference to this theme, followed by participant Director 7 with 30.77% of the coding reference. However, Director 7 has the low (23.08%) coding reference to this theme. The sum of the percentage of all participants is equal to 100%.

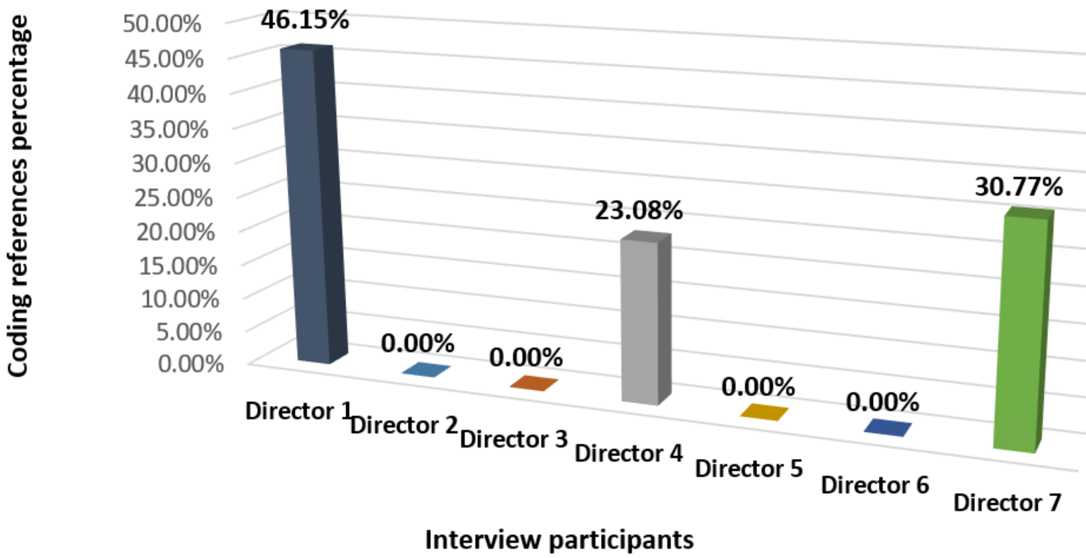

Figure 6. Sustainability goals theme coding rate.
Source: *Author's work using cross tabulation query result from MAXQDA.*

The diversity of managers' perspectives on sustainability goals, as revealed in **Figure 6**, indicates that sustainability priorities within the organization are not uniform. Although only three directors expressed their opinion on this sub-theme, the level of engagement varies considerably. Director 1 shows a strong commitment to sustainability goals, suggesting a desire to promote sustainability. On the other hand, Director 7 seems less engaged. This variation in importance can influence how the organization approaches sustainability initiatives, which can have major economic implications. An increased commitment to sustainability can result in efforts to reduce costs, improve efficiency, and strengthen reputation, while less commitment can result in the status quo. Ultimately, this diversity can influence organizational competitiveness, resilience, and profitability in a sustainability-driven economic landscape. It is therefore essential to balance economic and environmental objectives when developing strategies for a prosperous future. This implies that the Egyptian government is urged to commit to reducing pollution and CO_2 emissions while investing in AI technologies. This finding aligns with the conclusions of Fahdi et al. (2021).

4.5 Inclusive Benefits: Port Sustainability

From **Figure 7**, the Inclusive benefits sub-theme coding rate seems to be important as three of the participants expressed their opinion. The participant Director 2 has the highest (46,15%) coding reference to this theme, followed by Director 3 and Director 4 with 30.77%, and 23,08%, respectively. The sum of the percentage of all participants is equal to 100%. Although all participants gave their opinions on this theme, it is interesting to address only the main responses.

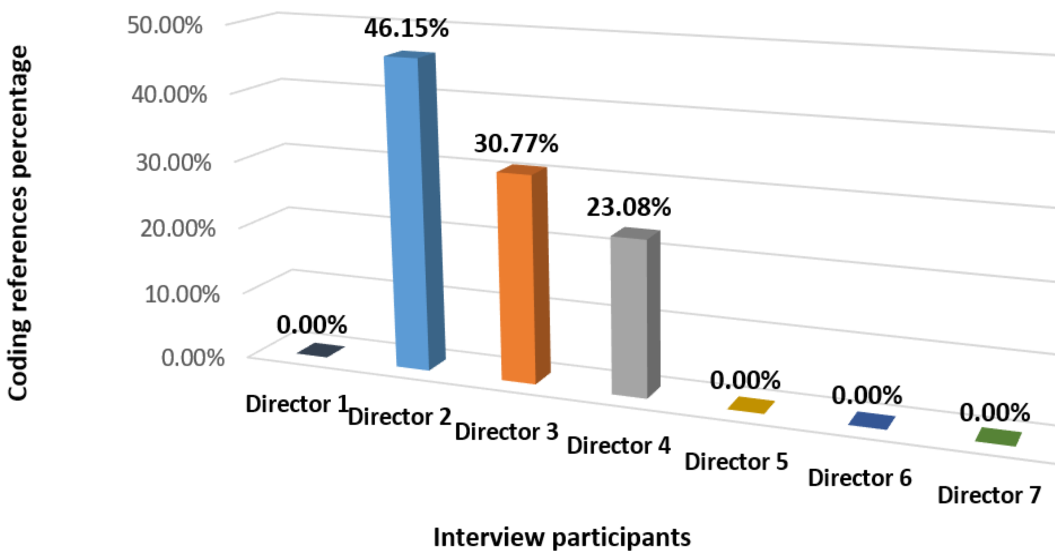

Figure 7. Inclusive benefits sub-theme coding rate.
Source: *Author's work using cross tabulation query result from MAXQDA.*

The directors recognize that the Egyptian market can have a significant impact on the port's economic activities, particularly in terms of imports, exports, cargo flows and revenues. The fact that the directors attach great importance to this stakeholder in the SCM means that the Egyptian market represents a key economic opportunity for the Egyptian economy. More specifically, the integration of AI into port operations can play a crucial role in improving SCM and, thus, the sustainability of Egyptian ports. To this end, according to responses of these directors, the use of AI can help port managers in optimizing shipping processes, decreasing operational expenses, and improving service quality. Consequently, this will lead to a higher level of sustainability inside ports. This finding is consistent with the previous studies (such as Chu et al., 2024; Liu et al., 2021; Jeanneret medina et al., 2024).

5. Conclusion

The objective of this study was to investigate to what extent the AI technology can improve SCM and determine its impact on the sustainability of Egyptian ports. Accordingly, the researcher relied on qualitative approach to gather data using semi-structured interviews. The study's main findings indicate that the use of AI increases ethical challenges and economic risks at Egyptian ports. It can also be concluded that if the approach is reliable and transparent, it will increase stakeholders' trust and guarantee the ethical use of AI. Moreover, the study revealed that there are variations in the sustainability levels among the seven examined ports. This shows that, within a sustainable business environment, these variations can hinder ports' stability, competitiveness, and profitability. Finally, the findings also indicated that using AI has the potential to enhance the overall effectiveness and quality of service provided by Egyptian ports. Consequently, it will boost their economic performance.

5.1 Implications

Based on the findings of this study, the researcher offers some policy implications that can assist managers of Egyptian ports in integrating AI technology into their operations. First, policymakers must develop a strategy clarifying how AI can be applied in Egypt. The proposed strategy should meet Egypt's digital vision (Vision 2030) and the global sustainable development goals. Second, a regulatory framework and set of ethical standards specific to the port industry should also be formed. This framework needs to make sure that when AI technology is being used, the values of accountability, transparency, and fairness are respected. Third, policymakers should prioritize the enhancement of the capacities and expertise of the workforce and other relevant stakeholders in the port industry. Employees and other stakeholders in the port industry will therefore be able to use AI efficiently and benefit from the changes and opportunities that it presents. Fourth, to enhance the port industry, policymakers should encourage collaboration between port entities, government organizations, educational institutions, and private businesses to leverage the benefits of AI technology. Finally, policymakers should integrate port systems into their practices and technologies to boost port efficiency, reduce impact, and enhance customer satisfaction.

5.2. Limitations and Futures Research

This study has three main limitations that needed to be considered in future research. Firstly, the data collected for this study is limited to semi-structured interviews. It may have certain degree of biases and limitations related to the quality and quantity of the data used. Therefore, it is recommended that future research employ other data collection methods, such as surveys, observations, or secondary data. This will complement and triangulate the findings from the interviews. Secondly, although this study focused on AI's current and potential applications in the Egyptian port sector, it did not examine the actual impact or outcomes of AI integration on port performance and sustainability. Therefore, longitudinal or experimental studies are recommended for future research to measure and evaluate the effects of AI on ports' efficiency, quality, resilience, competitiveness, profitability, and environmental and social responsibility aspects. Thirdly, this study explored the perceptions and attitudes of the port managers and employees towards AI but did not investigate the perspectives and expectations of other port stakeholders (such as customers, suppliers, regulators, or the general public). Therefore, future research should analyze the stakeholder's engagement to understand the needs, preferences, and concerns of different port stakeholders regarding AI. This would ensure the alignment and compatibility of the AI integration strategy with the stakeholder interests and values, and enhance the trust and acceptance of AI among the port community.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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