Towards AI Driven Environmental Sustainability: An Application of Automated Logistics in Container Port Terminals

Abstract

Artificial intelligence and data analytics capabilities have enabled the introduction of automation, such as robotics and Automated Guided Vehicles (AGVs), across different sectors of the production spectrum which successively has profound implications for operational efficiency and productivity. However, the environmental sustainability implications of such innovations have not been yet extensively addressed in the extant literature. This study evaluates the use of AGVs in container terminals by investigating the environmental sustainability gains that arise from the adoption of artificial intelligence and automation for shoreside operations at freight ports. Through a comprehensive literature review, we reveal this research gap across the use of artificial intelligence and decision support systems as well as optimization models. A real-world container terminal is used, as a case study in a simulation environment, on Europe's fastest-growing container port (Piraeus), to quantify the environmental benefits related to routing scenarios via different types of AGVs. Our study contributes to the cross-section of operations management and artificial intelligence literature by articulating design principles to inform effective digital technology interventions at non-automated port terminals, both at operational and management levels.

Keywords: Intelligent Port Logistics; Artificial Intelligence, Automated Guided Vehicles; Container Port Management; Routing; Environmental Sustainability.

1. Introduction

Ongoing growth in international trade has fuelled the development of port container hubs as critical nodes of global supply networks. Indicatively, global container port throughput increased by 4.7% during 2017-2018, amounting to over 793.26 million 20-foot equivalent units (TEUs), thus reflecting the expansion of manufacturing operations (UNCTAD, 2019, p.14). In addition, the capacity of large container ships has increased above 10,000 TEUs (UNCTAD, 2019, p.69), thus creating challenges in port terminals regarding performance efficiency and service levels (Zhong et al., 2020). From an environmental sustainability viewpoint, international shipping is responsible for 2.2% of global CO_2 emissions and the of the United Nations - International Maritime Organization (IMO) has set a strategic goal to halve greenhouse gas (GHG) emissions by 2050 (GEF-UNDP-IMO GloMEEP Project and IAPH, 2018). Towards this path, academics and practitioners have proposed policies for promoting net-zero GHG emissions in the port sector via technology interventions at the shoreside (GREENPORT, 2019). To that end, automation in ports and terminals on the landside[1] is regarded as a viable option that can promote sustainability (Fenton et al., 2018). One aspect of these interventions is the use of Automated Guided Vehicles (AGVs) as an enabling technology of intelligent logistics. In this context, our motivation is to examine the role of AGVs as a key technological application in next-generation container terminals and investigate how Artificial Intelligence (AI) can improve AGVs' performance and container port management.

Fully automated container hubs are expected to incur reduced operating expenses by 25-55% and increased productivity throughput by 13-35% (Chu et al., 2018). Notwithstanding the proclaimed benefits of automation, only 3% of container terminals around the globe are either semi- or fully-automated (Mongelluzzo, 2019), thus indicating a need for more research as to adoption obstacles and associated cost-benefit outcomes. Similar to other domains, the main reasons for the low penetration of automation in ports refers to the duality of capital-intensive investments as well as the objections from labour unions. The latter expresses the so-called "fear of automation" (Spencer, 2018). In the operations management literature, technology-enabled container handling in port terminals is generally well studied (Gharehgozli et al., 2016); however, two main gaps can be identified. First, the studies on modeling port operations mainly consider conceptual port layouts and myopically focus on performance improvements in specific operations by considering uninterrupted material and process flows. For example, Liu et al. (2004) used simulation modeling to determine the optimal number of AGVs to deploy in common yard layouts and investigated the respective container terminals' operational performance. Second, the challenge of orchestrating real-time collaboration between the different systems, actors, and entities (e.g., port authorities, cargo owners, quayside cranes, yard cranes, vehicles, etc.) is discounted due to the added complexity to the modeling process. Specifically, the literature discussing the use of AGVs in container port terminals focuses on routing and scheduling aspects with the vast majority of modeling efforts investigating performance improvements such as the number of AGVs, the travel distance by vehicles, and/or efficiency and effectiveness of the applied analytic approaches (e.g., computational time and optimality gap).

Furthermore, extant studies on the use of AGVs in real-world container port terminals are limited while the research objectives focus on the operational performance of the vehicle(s) and overlook

[1] Throughout the manuscript the terms shoreside and landside are used interchangeably to denote the port operations taking place in the land, including loading and unloading of cargo containers among other operations that require the vessel to be docked.

any environmental sustainability implications. Indicatively, Gelareh et al. (2013) studied the Dublin Ferry port Terminal to optimize the time required by AGVs to process all tasks before the departure of a cargo vessel. Furthermore, there is a sparsity of studies investigating the use of AGVs powered by non-conventional diesel engines in container port terminals. Notably, Schmidt et al. (2015) assessed the use of electric AGVs at Hamburg's Altenwerder terminal, but the analysis mainly considered economic sustainability aspects. Therefore, research on the environmental sustainability impact of different types of AGVs in real-world container port terminals, in tandem with vehicle routing, is sparse.

In addition, the majority of modeling approaches that seek to address the routing of AGVs in container port terminals focuses on exact solution methods. The drawback of an exact solution method is the computational time requirements to calculate the optimal solution owing to the size or complexity of the constraints (Desrochers et al., 1992). Hence, exact solution methods are unable to tackle dynamic changes and be implemented in real-world problems that require immediate actions/responses. In this regard, AI could support sensor-driven robotic operations in complex environments that entail real-time information gathering and processing for operational efficiency (Selke et al., 1991), such as at automated container port terminals. Heuristic and metaheuristic search, a core area of AI, has flourished during the last years (Pillac et al., 2013), indicating the importance of AI in practical settings (Spanaki et al., 2021). Several heuristic and metaheuristic algorithms have been developed to tackle practical problems by seeking to incorporate strategies to avoid local optima and diversify their search process, hence obtaining high-quality solutions in short computational times. The interest in AI and automation has been rekindled due to the range of organizational operations that could be transformed based on data gathering, sharing and analytics (Spanaki et al., 2018; Sahu et al., 2020). This research focuses on the routing of AGVs at container terminals and the associated environmental implications by adopting AI principles. An interface is required to transition from a simple machine code for operations optimization to high-level application generators combining an AGV's sensory data (Hinde, 1989). To this effect, we claim that AGVs need to have some degree of intelligence to support such an interface to account for any possible error observations experienced at a shop floor level.

More specifically, this research contributes to the ever-growing literature of container port terminals' digitization by investigating the environmental sustainability implications of intelligent logistics operations enabled by AGVs. In particular, a case study is considered via simulation, while at the same time design principles are proposed regarding the introduction of AGVs in extant ports, specifically focusing on the related gaseous emissions' impact and energy consumption. The research objectives that this study seeks to address are: (a) *What are the structural modeling characteristics of routing algorithms of AGVs within the context of container port terminals?* and more specifically (b) *How could such logistics operations be designed and managed in order to contribute to environmental sustainability?*

In this context, this study contributes to the cross-section of the operations management and artificial intelligence fields by studying the relationship between digital technologies and container port design within the prospect of automated operations to inform relevant interventions. Our work promotes the adoption of intelligent logistics in container port operations, following the greater need in the manufacturing domain (Dolgui, 2005; Chien et al., 2020). To address the first research objective, we perform a comprehensive literature review related to the routing of AGVs in container port terminals. Regarding the second research objective, we develop a simulation study that captures the prospect of intelligent container handling operations at a real-world container terminal (Piraeus port). Our results support the articulation of design principles in intelligent port logistics, ensuring operational performance and sustainability. We anticipate our work to be beneficial to stakeholders (including policymakers and local governments) to consider adopting automation at ports.

To this end, the remainder of this study is structured as follows. Section 2 reviews the relevant literature. A simulation model investigating the environmental impact of alternative AGV types and scenarios is developed in Section 3, while Section 4 presents and discusses the results. In Section 5, four design principles for intelligent port logistics are articulated for supporting the transition towards sustainable container terminals and harness competitive advantages, thus highlighting the academic and practical contributions of this study. The paper concludes in Section 6 with a discussion of limitations and future research directions.

2. Literature Review

During the last three decades, there have been several studies about the use of AGVs in the workplace (Qiu et al., 2002; Fazlollahtabar and Saidi-Mehrabad, 2015). Qiu et al. (2002) provided a comprehensive review on AGV routing and scheduling issues in industrial applications. The authors grouped the algorithms into three categories: (i) algorithms for generic path topology; (ii) path layout optimization; and (iii) specific path topologies. In addition, Fazlollahtabar and Saidi-

Mehrabad (2015) performed a literature review on the routing and scheduling of AGVs in business operations, distribution, transhipment, and cargo transportation in the industrial and construction sectors. The study focused on different methodologies that are used to optimize AGVs, indicating the following classification of main approaches to study AGVs: (i) exact and heuristic methods; (ii) metaheuristic techniques; (iii) simulation; and (iv) AI methods. In this research, we focus on the routing of AGVs in container port terminals with regard to shoreside operations and the role of AGVs as an enabling tool of efficiency improvements and effective port management. Our aim is to inform about existing routing algorithms and modeling aspects.

2.1 AGVs' Routing in Container Terminals

To perform a comprehensive literature review and identify all relevant published scientific articles regarding the examined topic, we conduct Boolean-type searches using appropriate keywords in the Elsevier's Scopus database to perform a literature synthesis (Aivazidou et al., 2016). Although there is a range of electronic search engines to retrieve academic contributions, Scopus was selected due to its wide acceptance for systematically mapping and reviewing the extant body of literature (Fahimnia et al., 2019; Pournader, Shi et al., 2020) and the excessive coverage (>90%) of scientific articles in the "Business, Economics & Management", "Physics & Mathematics" and "Engineering & Computer Science" domains (Martín-Martín, 2018). The query involved the terms: "Automated Guided Vehicle", "container terminal", and "rout*" which were matched against the article's title, abstract and keyword field. No specific time horizon was imposed and the results were filtered to include only peer-reviewed articles to ensure access to "*best-quality evidence*" (Tranfield et al., 2003) written in the English language. The results were screened for eligibility, subject to the objectives of this research.

Based on the above criteria, 12 publications on AGVs routing were selected. Since the number of articles was low, we also included studies retrieved from other sources like the Thomson Reuters's Web of Science database, whilst considering conference papers as well. In alignment to Pournader, Kach et al. (2020), our personal experience through investigating the Web of Science database led to the understanding that Scopus provides the plethora of most relevant articles published in the research topic of focus. In particular, for the purposes of this study, we observe that the search outcomes in Scopus completely cover and extend the search results in the Web of Science. The growing publications' trend during the recent years demonstrates the vivid research interest on AGVs' routing at freight ports.

2.1.1 Integrating Routing and Scheduling Decisions

Dkhil et al. (2013) developed a bi-objective model to formulate the scheduling problem of activities in a single 'Quayside Cranes-AGVs-Yard Cranes' system under the objectives: (i) to minimize the container handling and transport time; and (ii) to minimize the AGV fleet size. The main idea was to address the task scheduling problem and decrease the operating cost at an automated container terminal. The study emphasized the formulation of the mathematical models for three alternative traffic layouts at the terminal, seeking to examine different terminal architectures and the impact of these on the scheduling decisions. Regarding the routing problem, the focus was on a tactical level; in particular, the authors' aim was to calculate the sufficient number of AGVs for the optimal schedule rather than the detailed routes of AGVs. Hence, operational routing decisions and the related gaseous emissions and/or energy considerations were overlooked.

In a similar stream of literature, Corman et al. (2016) studied the combinatorial scheduling and routing problem of AGVs in an automated container terminal. The authors proposed a mathematical formulation, based on the alternative graph model, to solve the combinatorial problem in a near-optimal way. Specifically, a hybrid model was deployed to address both discrete (i.e., assign containers to AGVs and then determine the order of containers' movement) and continuous dynamics (i.e., free-range trajectories of AGVs) of the examined setting. Metaheuristic algorithms, such as the Variable Neighbourhood Search and the Tabu Search, were applied to decide the assignment of containers to AGVs, while a truncated branch and bound algorithm was used to solve the scheduling problem. Numerical experimentations were conducted to evaluate the performance of the proposed approach, indicating its applicability in real world problems.

Another recent study from Zaghdoud et al. (2016) examined the problem of containers' assignment to AGVs, incorporating three sub-problems (routing, dispatching, and scheduling) by developing a hybrid approach. The optimization of the operations as a single problem is a complex task; hence, the basic research idea was to decompose the problem into sub-problems. The authors proposed a hybrid solution that composes an exact algorithm for the routing problem, a genetic algorithm about the dispatching problem, and a heuristic algorithm for the scheduling problem. Numerical analysis indicated that the proposed algorithm is effective and computes high-quality solutions regarding the objective while the computational time is not significantly affected. However, the authors did not consider energy consumption along with the related emissions.

In regard to crane operations in port terminals, Yang et al. (2018) investigated the problem of integrated scheduling of quay cranes, AGVs and automated rail-mounted gantry cranes, for simultaneous container loading and unloading operations. The authors developed a two-level programming model to minimize completion time, considering also traffic congestion. The proposed solution combined a heuristic and a genetic algorithm. The idea behind the utilized approach was to develop an algorithm that firstly is effective in global search with the ability to obtain accurate solutions and secondly is flexible and applicable to different problems. The authors' contribution lies in the integrated programming of AGVs, quays and yard cranes to optimize vehicles' route planning at automated terminals while implementing traffic congestion prevention rules. This is also beneficial for terminal managers at an operational level.

Lu and Wang (2019) studied the scheduling of 'twin' yard cranes that interact with AGVs to minimize their waiting time and consequently the loading and unloading times of containers. The problem is NP-hard; hence, the authors developed a metaheuristic algorithm based on graph theory to tackle it. In particular, the proposed solution applied the Particle Swarm Optimization method. The scheduling strategy directly affects the waiting time of AGVs and plays an important role in the terminal's operational performance. The authors evaluated the proposed algorithm and demonstrated the resulting benefits through numerical experimentation.

As regards to container loading, Shouwen et al. (2020) considered the problem of container loading and unloading operations at an automated terminal. The authors studied a combinatorial optimization problem regarding the integrated scheduling of quay cranes, AGVs, stacking cranes, and the conflict-free AGV routing. Their proposed solution was based on a two-level programming model. First, they solved the integrated scheduling problem of the three classes of equipment and then, they determined the route that minimizes the travel distance of the AGV fleet by designing two bi-level genetic algorithms to tackle the combinatorial problem. They also verified the effectiveness of that approach experimentally.

Hu et al. (2020) examined the dispatching and routing problem of AGVs at an automated container terminal, where the objective was to minimize the total travel distance of AGVs and reduce the operations time. The authors proposed a three-stage decomposition approach to tackle the problem, while time windows for the AGVs were considered. The three stages were: (i) task assignment based on quick response; (ii) route planning based on the minimum distance; and (iii) route re-planning based on both conflict type and processing time. Hence, the proposed solution combined elements of pre-planning and real-time planning algorithms.

Zhen et al. (2020) provided a decision framework to address the problem of scheduling and routing AGVs in a time-varying traffic environment. The authors sought to optimize the scheduling and routing of an AGV fleet considering the waiting time caused by traffic congestion. The main study objective was to find the optimal routing plan under the criterion of minimizing the total penalty cost attribute to traffic congestion. Specifically, an integer linear programming model was employed to tackle the examined setting. The latter is realistic since several AGVs are used at automated container terminals. Computational experiments were conducted to validate the proposed decision support framework's efficiency and demonstrate high quality solutions within a (relatively) short computation time. This is also beneficial for both terminal managers at an operational level and port managers to design and schedule dynamic routing plans for AGVs under different traffic conditions.

Finally, Xu et al. (2020) studied the scheduling and routing problem of AGVs in an automated container terminal considering fully loaded mode. The authors examined the case in which an AGV can carry two containers at the same time, seeking to improve efficiency from a transportation perspective. The main idea was to allow a two-way loading between the dock and the container yard, while a quayside buffer exists to ensure coupling between quayside work and AGV routing. The problem was addressed based on a simulated annealing algorithm. The authors compared their proposed solution with two popular algorithms to verify the effectiveness of their approach. However, energy consumption considerations and the related emissions were not contemplated.

2.1.2 Routing Decisions

Zeng and Hsu (2008) employed a mathematical model regarding the routing of multiple AGVs in a mesh topology, extending the idea of conflict-free routing of AGVs (Qiu and Hsu, 2001). Qiu and Hsu (2001) formulated a mathematical model to achieve a conflict-free routing of AGVs, indicating the critical conditions and the key parameters for that. Zeng and Hsu (2008) explored alternative directions and velocities of vehicles to avoid collisions and minimize work completion time. The authors considered discrete time division and presented a mesh routing algorithm that guarantees freedom of conflicts by allowing the selection of suitable vehicles' velocities along different directions. Numerical experiments verified that the proposed routing algorithm achieves high performance; however, carbon emissions and/or energy consumption of the AGVs were not considered.

Jeon et al. (2011) developed an algorithm for AGVs’ routing at port terminals based on machine learning. More specifically, the authors employed the Q-learning technique to achieve the shortest travel time instead of the shortest distance route (which is common in routing problems) for each delivery order. This was feasible since the authors considered the congestion at the container port terminal. The focus on travel time is logical, since one of the most critical aspects for efficient port operations management is to minimize the total time that a vessel is docked to the terminal. Furthermore, a simulation study was performed indicating that travel time for an AGV could be reduced up to 17.3% when the proposed learning-based route is applied.

Li et al. (2011) formulated a routing algorithm and investigated its performance through simulation under the objective to minimize AGVs’ travel distance and cargo transport times. The results showed that the use of multiple intersections in a network can lead to shorter waiting times for vehicles at major intersections, while the total travel distance was significantly longer than that using central junctions. Moreover, the use of alternative routes provides more space for the movement of vehicles which leads to increased travel distances for the vehicles. A routing algorithm for AGVs in a conceptual terminal for the optimal management of containers between the quayside cranes and the stacking area, by allowing the AGVs to use the entire area and not only predefined and/or fixed paths has been developed by Duinkerken and Lodewijks (2015). The proposed method focused on minimizing the routing cost (determined by four factors, namely: vehicle speed, travel time, avoidance of fixed obstacles, avoidance of other vehicles) to improve vehicles’ average waiting time, average trajectory length, and number of moves per hour.

At the same time, Li et al. (2016) presented a traffic control for AGVs to exclude inter-vehicle collisions and system deadlocks. The traffic control approach allows each AGV to select its routes for any finite sequence of transportation tasks avoiding collisions and deadlocks with the occurrence of vehicle breakdowns. Hence, the authors were able to design routing algorithms that guarantee the avoidance of collisions and deadlocks with full freedom of routing. A simulation-based case study at an automated container terminal was developed to demonstrate the applicability of the proposed approach, while the results were compared with cases in which the freedom of routing was not applied.

2.2 Research Gap

The thorough literature review initially reveals that the AGVs' routing problem at a container terminal can be considered either in isolation or part of a more complex setup, involving coordination with other types of equipment. An interesting finding is that the environmental impact of AGVs measured either through carbon emissions and/or energy consumption has not been addressed when the routing problem is examined. The importance of considering energy consumption and related emissions factors is a critical aspect towards the net zero emissions target. Iris and Lam (2019) conducted a systematic review of the energy efficiency in ports, focusing on the business strategies and operations, technology adoption, renewable energy sources, alternative fuels, and energy management systems to improve terminals' environmental performance. There are interesting studies related to the environmental sustainability of AGVs at container terminals, but routing decisions either on a tactical or operational level are not considered. The study by Schmidt et al. (2015) provides an indicative case in that regard, where the use of battery-electric AGVs was assessed based on their economic feasibility regarding capital cost and return on investment. This demonstrated that terminal operators could achieve more than 10% of cost savings compared to utilizing a fleet of diesel-powered AGVs. While there are several other studies that look at the environmental sustainability of battery-operated vehicles, it is beyond the scope of this work to review studies that do not address the AGV routing problem specifically.

The main methodologies that have been used in the literature for assessing intelligent logistics in a 'port-equipment-containers-AGVs' system relate to: (i) AI techniques; (ii) decision support systems; and (iii) operations research-based algorithms. Thereafter, the environmental impact, across the emissions-energy nexus, of intelligent autonomous vehicles in container port terminals has not been adequately studied. Extant scientific articles focus exclusively on the mathematical modeling and solving techniques of routing algorithms for AGVs in conceptual container port settings, without considering the related environmental footprints. As port authorities and institutions begin to recognize the issue of carbon emissions and energy consumption in ports, the relevant management bodies are likely to promote research into the introduction of AGVs and intelligent operations of container operations management.

In addition to that and considering the interaction between automation and port operations is a relatively new field in the literature, we also opted to seek how topics related to 'AGVs', 'Port Operations' and 'Automation' are clustered together. Using the literature search criteria that were outlined before, we extracted the unstructured part of the publications' metadata (paper abstract, author provided keywords, librarian indexed keywords) and created a topic model using the co-occurrence relationship of the words in the articles' abstract and the semantic distance between the keywords. For each paper, we tokenized the abstract by removing the stop-words and creating word frequency matrixes. For each theme, the ratio of raw frequency counts over total counts was used to estimate the percent of variance accounting for the themes (Figure 1). The dominant topic considers the application of AGVs in ports and the interaction with port operations. As can also be seen in the coloured clustering, the major component concerns the use of AGVs in container terminals and its interaction with algorithmic implementations in either scheduling or routing aspects. The periphery of the main theme also considers the interaction between AGVs with terminal efficiency and port operations.

[Figure 1 about here]

Figure 1. Network map illustrating the relations between key terms in the field of automation in container port terminals.

3. Case Study Description

Design principles to deploy AGVs in non-automated container port terminals would be useful to guide digital-driven infrastructure investments. For our case study, we used the port of Piraeus (United Nations Code for Trade and Transport Locations – UN/LOCODE: GRPIR). This provided several advantages grounded on its strategic role as a major port terminal in the Mediterranean with multiple functions, such as bulk cargo, containers, passengers, cruise ships, etc.

3.1 Case Background

Piraeus port has seen significant growth during the last few years, making it the world's fastest-growing port (Safety4Sea, 2018). Maritime traffic at the Piraeus port has increased in the previous years due to: (i) the expansion of the container terminals; (ii) the continuous development of the cruise market; and (iii) the increasing touristic and passengers traffic owing to the unique landscape of the country and the multiple connections of Piraeus to Greek islands. The strategic role of the port of Piraeus for the international trade has been accredited by the acquisition of 51% of the Port's shareholding by the Chinese company COSCO Shipping Ports in 2016 (Huo et al., 2018). According to AXSmarine's Alphaliner ranking[2], COSCO has the third-largest container fleet in the world with a combined owned and chartered capacity of about 2.94 million TEUs. The

[2] AXSMarine Alphaliner Top 100 – Available at: https://alphaliner.axsmarine.com/PublicTop100/index.php.

company has acknowledged the importance of Piraeus considering its strategic geographical location: "*... as the most advantageous geographical location being the first EU port after crossing Suez Canal, bridging all available transport modes (sea, rail, road, air)*"[2].

The current management of containers in the port of Piraeus is performed via conventional forklift vehicles, resulting in constrained capacity, low efficient and costly procedures. Hence, Piraeus port represents an appropriate case study to explore the impact of adopting and implementing AGVs and their associative workflows in order to quantify the environmental impacts of using them to container port management operations. In addition, air pollution poses a major environmental issue in the Attica region (Mirasgedis et al., 2008), and the port of Piraeus contributes with elevated emissions due to the increasing passenger and container traffic. However, the pollutants' emissions from port activity, as well as the consequent health effects, have been calculated only from the viewpoint of maritime traffic (Chatzinikolaou et al., 2015). In terms of its layout, the port's development started in 1973 with the trapezoid in shape Pier I. In 1978, construction of the second trapezoidal Pier II began at the same location, while Pier III was constructed as an extension. The annual capacity of Pier I is 1,000,000 TEUs. Figure 2 shows the locations of Pier I, Pier II and Pier III.

[Figure 2 about here]

Figure 2. Topology at the container port terminal of Piraeus [*Source*: processed landscape view captured from Google Earth].

In this study, we focus on the import aspect of port operations, as our objective is to explore the benefits of automation and AI techniques on shoreside operations. Regarding the container unloading equipment from cargo vessels, Pier I in total utilizes seven ship-to-shore (STS) cranes; four over Super Post Panamax and (ii) three Panamax twin-lifts. In terms of container storage spaces and yard equipment, in Pier I exist: (i) four rail-mounted gantry cranes (RMG 1^{st} Series) servicing a total area of 26,000 m^2 and 1,302 ground locations; and (ii) four rail-mounted gantry cranes (RMG 2^{nd} Series) servicing a total area of 18,700 m^2 with 924 ground locations.

3.2 Case Parameters

The case study considers that an AGV is installed at Pier I and is used to transport containers from the quayside cranes, which unload a vessel, to the yard cranes, which stack the containers to the

[2] COSCO Shipping iForex Forum Greece – www.coscoshipping.gr.

storage area. The terminal operator's current policy requires that containers be first unloaded from the cargo ship with the quayside cranes, then transported by the AGV to a predefined yard space, and finally unloaded from the AGV and stored in the appropriate space by the yard cranes. Regarding the container sizes, we consider the two most frequently used types of containers in the shipping industry depending on their capacity, i.e., 20-ft and 40-ft. Therefore, these two types of containers are to be unloaded, transported, and stored.

We assume that the containers are initially loaded at respective ship compartments, namely: (i) Ship Compartment 1 – 40-ft containers; (ii) Ship Compartment 2 – 20-ft containers; (iii) Ship Compartment 3 – 20-ft containers; and (iv) Ship Compartment 4 – 40-ft containers. Each Ship Compartment is therefore served by a particular quayside crane: (i) STS SPP No 1 – Ship Compartment 1; (ii) STS SPP No 2 - Ship Compartment 2; (iii) STS SPP No 3 – Ship Compartment 3; and (iv) STS SPP No 4 – Ship Compartment 4. Furthermore, there are two stacking areas based on the container type, namely: (i) Yard Place 40-ft; and (ii) Yard Place 20-ft. Specifically, RMG No 1 is used for handling 40-ft containers in the Yard Place 40-ft, while RMG No 2 is used for handling 20-ft containers in the Yard Place 20-ft. As the focus of this research is to demonstrate the impact of alternative vehicle routing on the gaseous emissions and energy consumption at the shoreside of port terminals, we assume that stacking of mixed containers (e.g., a 40-ft container placed on top of two 20-ft containers and vice versa) at the same yard is not allowed.

Three types of an AGV are investigated, depending on the engine type and fuel, with corresponding environmental emissions and energy consumption factors; these are: (i) 'LPG' – liquefied gas-powered vehicle; (ii) 'ELE' – electric-powered vehicle; and (iii) 'DSL' – diesel-powered vehicle. Regarding the environmental impacts, this research employs the emissions and energy factors provided by Fuc et al. (2016) which had been estimated based on a Life Cycle Impact Assessment applied to forklift trucks with different engine types. The utilized environmental impact and energy consumption indicators are presented in Table A1 in the Appendix.

3.3 Routing Algorithms

To explore the role of AGVs' routing on the gaseous emissions and energy consumption in our study, we develop the following two algorithms: (i) '*Loop Routing*'; and (ii) '*Shortest Distance Loop Routing'*. The first algorithm is used as the reference standard case of automated logistics whereas the second introduces an element of intelligence in automated logistics where routing decisions involve a greater amount of data analysis to inform about the most distance-efficient routing process. These algorithms are to service one quayside crane at a time and unload the cargo vessel. The simulation results are leveraged to articulate design principles for intelligent container handling operations in ports.

3.3.1 Routing Algorithm #1 – 'Loop Routing'

The '*Loop Routing'* allows only the clockwise navigation (monodirectional navigation) of the AGV. In brief, the AGV starts from the central depot and successively visits: (i) STS SPP No 4; (ii) STS SPP No 1; (iii) STS SPP No 3; and (iv) STS SPP No 2. The purpose of this sequence is to unload the containers from the cargo vessel in a rather naive manner, i.e., firstly the 40-ft and then the 20-ft containers for the uniform unloading of the vessel. There is an intersection where the AGV needs to make a routing decision as the two different types of containers have to be unloaded to different stacking spaces. The containers are unloaded with quayside cranes and transported by the AGV to RMG No 1 (stacking 40-ft containers at Yard Place 40-ft) and RMG No 2 (stacking 20-ft containers at Yard Place 20-ft). In case that all containers are unloaded, the AGV returns to the central depot for refuelling/recharging. The algorithm is diagrammatically described in Figure 3, while Figure 4 presents the flowchart of it.

[Figure 3 about here]

Figure 3. Visual representation of the '*Loop Routing*' algorithm.

[Figure 4 about here]

Figure 4. Flowchart of the '*Loop Routing*' algorithm.

3.3.2 Routing Algorithm #2 – 'Shortest Distance Loop Routing'

The '*Shortest Distance Loop Routing*' allows the intelligent routing of the AGV based on the shortest distance required to transport a container from each quayside crane to the suitable yard crane. The algorithm allows the bidirectional navigation of the vehicle, depending on the necessary route to ensure minimum travel distance. In brief, the AGV starts from the central depot and successively visits: (i) STS SPP No 4; (ii) STS SPP No 1; (iii) STS SPP No 3; and (iv) STS SPP No 2. The containers are unloaded with quayside cranes and transported by the AGV to RMG No 1 (stacking 40-ft containers at Yard Place 40-ft) and RMG No 2 (stacking 20-ft containers at Yard Place 20-ft). After each quayside crane unloads a container, the AGV assesses the total required distance of all alternative routes to deliver the container to the suitable yard crane. In total, six decision-making points are recognized where the AGV needs to make a routing decision, based on the different types of the container and the required travel distance. In case that all containers are unloaded, the AGV returns to the central depot for refuelling/recharging. The algorithm is illustrated in Figure 5, while its flowchart is shown in Figure 6.

[Figure 5 about here]

Figure 5. Visual representation of the '*Shortest Distance Loop Routing*' algorithm.

[Figure 6 about here]

Figure 6. Flowchart of the '*Shortest Distance Loop Routing*' algorithm.

Since this research's main objective is to provide evidence regarding the adoption of intelligent logistics for environmentally sustainable container freight management at ports, a further mathematical investigation of the examined algorithms is beyond the scope of this paper. Table 1 presents the experimental design in this research.

Table 1. Design of experiments.

[Table 1 about here]

3.4 Model Setup

The implementation of container terminal management policies is analyzed via simulation that could improve system performance by enabling more efficient port equipment use. Simulation models can be categorized into: (i) continuous process; (ii) discrete-event; and (iii) combined simulation (El-Haik and Al-Aomar, 2006). Discrete-event simulation is the most common type of simulation. In general, it considers the discrete variables and cases where the state of a system changes at discrete points over time. In this study, discrete-event simulation models were developed to study the impact of introducing AGVs in Pier I, container port of Piraeus, in terms of emitted gaseous pollutants and energy consumption.

The simulation models were developed in the WITNESS Horizon (Version 22.5) software environment of the Lanner Group. The basic modeling assumptions are presented in Table 2.

Table 2. Model assumptions.

[Table 2 about here]

We ran the simulation models for a total number of 40 containers with an allocation of 20 containers per type and 10 containers per Ship Compartment.

3.5 Model Validation & Verification

Model validation ensures the accurate representation of the underlying real-world system; so, that the model is structured and behaves realistically (Al-Aomar et al., 2015). To validate the appropriateness of the proposed routing algorithms, the following procedural remedies were followed:

- *Inspection of visual elements* – The validation of the models was performed by monitoring their behaviour during the execution time to ensure the handling the two container types and the AGV's routing were as expected, in alignment also to the topology of Pier I and the simulation assumptions.
- *Control of model input data* – The shop floor design of the port terminal and other data were retrieved from available official sources[3], while the operating parameters of the AGV and other equipment in the model (such as the emissions and energy consumption impact indicators) were retrieved from the scientific literature (Fuc et al., 2016).

Model verification assesses whether a model conforms to the desired conceptual design, logic, and conditions imposed at the beginning of a model's development stage (Al-Aomar et al., 2015). The following techniques were applied to verify the developed simulation analysis:

- *Detailed examination of model inputs* – Each input parameter was studied individually, while multiple simulations were used to ensure that the initial values of the parameters were used correctly during the simulation process. At the end of each simulation, the input parameters were studied to determine that their values did not change involuntarily during the simulation.
- *A thorough study of simulation results* – The simulation results were studied for different input parameter values (e.g., vehicle type, vehicle status, emissions, and energy consumption factors), and we observed the reasonableness of the outputs. In addition, we simulated both routing scenarios for the AGV in terms of a varying number of containers, and we observed the expected linear relation between the number of containers to be handled and the AGV's travel distance (Figure 7).

[3] Piraeus Port Authority - http://www.olp.gr/en/

[Figure 7 about here]

Figure 7. Model verification results.

- *Leveraging the simulation package's visual features* – We leveraged the "animation" features of the used software and visually observed whether the containers were delivered by the AGV to the intended crane and whether these were then stored at the intended stacking area. Moreover, the algorithms' implementation was visually checked to verify that the shortest of the available alternative routes (specifically in Routing Algorithm #2) is actually selected.

4. Simulation Results

This section summarises the simulation results seeking to quantify the environmentally sustainable gains when intelligent operations are adopted at container port terminals. We then discuss the results, focusing on the direct and indirect impact regarding to gaseous emissions and energy consumption that can arise by the potential usage of AGVs and automation in container port terminals.

4.1 Travel Distance

The simulation results demonstrate that the implementation of algorithms and intelligence in AGV routing decisions has a direct impact on the total travel distance that is required in cargo handling operations. Specifically, the total travel distance by the AGV, per vehicle status (i.e., unloaded or loaded) and routing algorithm, is shown in Figure 8.

[Figure 8 about here]

Figure 8. AGV travel distance (in km), per vehicle status (i.e., unloaded or loaded) and routing algorithm.

It is observed that the adoption of intelligent logistics (Routing Algorithm #2) is denoted by an increase in the number of decision-making points during the autonomous navigation of the robot vehicle. This leads the AGV to cover a shorter total distance by 5.6 km (for a total of 40 containers), compared to the reference case of Routing Algorithm #1; i.e., an improvement of about 10% is achieved. Notably, an improvement of around 18% is attained in case the AGV is loaded. Considering the higher emissions factors and energy consumption in the loaded status, the implementation of innovative technologies and AI principles is necessary for reducing the total travel distance that an AGV fleet has to cover in container port terminals regarding the loading, transportation and unloading operations. It should be noted that in the second scenario due to the layout of the shop floor and the possibility of bidirectional routing, the loading and unloading operations do not yield any difference. In the case where a mono-directional layout is imposed, the saving is considerable as can be seen in the first bar group.

In Routing Algorithm #1, there is a single routing decision-making point (Figure 3); in decision point #1 it is sufficient to consider only the capacity of the container where for the delivery of a 20-ft container requires that an additional distance of 110 m is travelled, based on the topology of the operations layout. On the contrary, in Routing Algorithm #2 there are six decision-making points (Figure 5); for the decision points #2-#5, the algorithm needs to consider the total distance from the quayside cranes to the appropriate yard crane. For the decision points #1 and #6, the capacity of the container is the single decision variable. The distance savings in the case of the intelligent logistics could be up to 20% for the delivery of a 40-ft container and up to 15% for the delivery of a 20-ft container.

Overall, intelligent logistics need to consider the scheduling of operations in a ‘port-equipment-containers-AGVs’ system. A solution regarding the routing of AGVs should ensure, in real-time, that the idle time of quayside and yard cranes is minimized while these cranes shall not be occupied when the AGV is ready to receive/deliver a container. This requisite should be fulfilled provided that the ultimate objective of landside operations at port terminals is to support freight vessels and minimize the total time that a vessel is docked to the terminal since containerships are not built for remaining idle in ports. Therefore, both the container transport vehicle’s velocity and the makespan of the cranes, need to be continuously monitored (e.g., via sensors) to inform in real-time the intelligent decision-making over the required operations.

4.2 Environmental Impact

A strong correlation exists between travel distance and carbon emissions and energy consumption (Zissis et al., 2018). Hence, a potential reduction in travel distance results in environmental benefits. Tables 3 and 4 summarise the simulation outcome regarding the environmental impact associated to the examined algorithms, based on the investigated case study.

Table 3. Environmental impact of AGV for Routing Algorithm #1 – '*Loop Routing*' (Total number of containers, C = 40).

[Table 3 about here]

Table 4. Environmental impact of AGV for Routing Algorithm #2 – '*Shortest Distance Loop Routing*' (Total number of containers, C = 40).

[Table 4 about here]

Concerning the environmental aspects, the preferable type of AGVs (regarding the engine) is the electric-powered vehicles (ELE) which is intuitive as such vehicles produce almost zero emissions. An interesting observation about the ELE vehicles is the small increase of the emissions when the respective container transport vehicles are loaded, compared to the unloaded status, while the respective increase is substantial for diesel-powered vehicles (DSL) and liquefied gas-powered (LPG) vehicles. In particular, for Routing Algorithm #1, when an ELE vehicle is used the increased total emissions (in mPt) are around 22% if it is loaded. In contrast, the corresponding increase is 82% for a DSL vehicle and 254% in the case that an LPG vehicle is used. This is more evident for Routing Algorithm #2, in which there is no difference at the emissions between the cases of unloaded and loaded ELE. Still, there is an increase of 50% and 192% between the unloaded and loaded cases when DSL and LPG vehicles are used, respectively.

In addition, Table 5 summarises the simulation results per investigated algorithm and indicates the improvements in the emissions-energy nexus, in terms of the weighted ecological index mPt, emanating from the adoption of intelligent autonomous vehicles in port logistics, per type and status of AGV. We observe that there is a significant improvement, around 18% for loaded vehicles when intelligent logistics (i.e., Routing Algorithm #2) are implemented. This is also in line with the literature and how a potential reduction of travel distance affects the relative emissions and energy consumption (Zissis et al., 2018).

Table 5. Environmental impact improvement of intelligent logistics in terms of the weighted ecological index mPt, by AGV type and status (Total number of containers, C = 40).

[Table 5 about here]

Our results reveal that intelligent logistics for landside operations at container ports can contribute, to a degree, to the directives of the European Union that necessitate the Member States to compose and implement programs to limit their annual emissions. According to the European Environment Agency, poor quality environments contribute to 13% of deaths (EEA, 2020). Therefore, tackling environmental pollution at individual sectors, like container port terminals, will help collectively to save millions of lives whilst bringing several direct and indirect benefits to issues including climate change, improved quality of life and well-being (especially in urban areas), children's development, and equity across the globe.

5. Implications

The discussion of the findings highlights the implications of this study in terms of theoretical as well as practical implications (managerial and policymaking). Following the simulation results, a compilation of the different insights can be summarised in a design framework that encompasses four distinct elements: (i) application insights; (ii) analytical insights; (iii) sensor data acquisition; and (iv) utilization of AI algorithms for feedback loop monitoring through data. When considering the introduction of intelligent logistics in non-automated container port terminals, the design framework summarised in Table 6 can inform technology adoption at theoretical and practical levels.

Table 6. Design principles on intelligent logistics in container port terminals.

[Table 6 about here]

5.1 Theoretical Implications

In the context of containers' handling in the shoreside of port terminals, AI-driven approaches have a demonstratable impact on the operational and environmental sustainability performance of the respective activities, particularly in terms of travel distance, gaseous emissions, and energy consumption. This result adds to an ever-growing stream of literature discussing the productivity gains from investments in production automation (e.g., Acemoglou and Restepo, 2019). Our results are in par with studies in the production research literature that discuss the applicability of AGVs in various areas such as warehouse automation with human pickers (Masae et al., 2020). Nonetheless, when considering digital technologies, such as AGVs in shoreside container port operations, productivity gains are not guaranteed if not optimized accordingly. Such risks are important to be considered since introduction of AI and automation does not automatically warrant a positive outcome and carriers risks which are not easy to overcome (Baryannis, 2019). The design principles outlined here can inform further studies in automation technology acceptance in manufacturing settings where the minimization of environmental impacts from typical container handling and terminal management operations is important.

Furthermore, this study concerns the optimization of an AGV's movement in an environment where operations are constrained by layout configurations and orchestration with other equipment is necessary, thus escaping the typical grid-based routing that is common in production settings. In this regard, selecting appropriate routing algorithms and methods to optimize distances is highly dependent on the quality of sensor data that can be collected by utilizing more extensive sensor arrays. Considering the optimization process results and the parameters of our model, an extension to more granular sensor data can be used for even further adjustments. Therefore, this study also adds in that perspective, the design dimension of sensor requirements in the selection of routing schedules. Such automation approaches are also considered important in other mainstream settings of production research (e.g., Chien et al., 2020) where new hardware platforms are streamlined with human intervention thus enabling coordination through data and sensor augmentation (Sahu et al., 2020).

5.2 Managerial and Policy Implications

The study has a set of practical implications for port operators and policymakers alike. Transitioning to sustainable port container systems requires investments in automation technologies, among others. Notwithstanding the evident financial benefits in terms of productivity and increase throughput considered in a return of investment appraisal, the environmental impact is also an essential parameter that this study highlights. Nonetheless, effective implementation of port automation and/or automation interventions in non-automated ports requires careful planning in both dimensions and particularly in the environmental impact of internal-combustion powered AGVs. This is particularly important considering the high barrier to entry for electrification in freight transport vehicles. Therefore, the need for measuring environmental performance needs to be established since the introduction of AGVs in non-automated port settings can have an increase in emissions from the improvement of operational efficiency at terminals and overshadow the tangible benefits from increased operation (e.g., meeting demand in less time, less docking time of vessels, fewer cases of damaged cargo, fuel consumption efficiency, fewer accidents). Therefore, this derived design principles as presented in Table 6, may inform the implementation decisions of port planners and operators, on how to introduce intelligent logistics and autonomous operations.

Nevertheless, the regulatory landscape needs to also adapt to this new type of technology since the safety procedures for human operators need to adjust to the reliability standards and the data requirements that need to be accompanied in industrial-grade applications of AI (e.g., explanation of the decision-making parameters, human supervision, etc.). Policymakers need to understand the parameters involved in that aspect and incorporate clauses in the regulatory framework of port operations.

In addition to the above, the study also brings a major managerial takeaway in regard to assessing the return on investment of implementing automation in the shoreside part of port operations. A known case of AI adoption barriers is capital expenditure where in some industries such as manufacturing, the capital expenditure is difficult to be justified from productivity gains alone (Pilai et al., 2021). Therefore, incorporating spillover effects from other areas may help incorporate a holistic view about automation, with sustainability been highlighted in this study as a major point. Hence, managers should also consider the long-term environmental sustainability effects when assessing the return on investment of adopting AI and automation in a production setting such as a port.

6. Conclusions, Limitations, and Further Research

In the Industry 4.0 and the Internet of Things era, the digitalization of logistics operations, especially concerning the use of intelligent vehicles for container freight management, can offer a range of economic, environmental and social benefits, including (i) enhanced productivity; (ii) labour cost savings; (iii) reduced gaseous emissions and energy consumption; and (iv) increased levels of safety (Bechtsis et al., 2017). However, to fully leverage the potential and operability of new technological systems in shop floor settings, appropriate analysis approaches and tools are required to assess their efficiency (e.g., mathematical modeling, simulation, emulation) and enable operational efficiency for sustainability (Zissis et al., 2020). This research specifically focused on automated and intelligent container handling through AGVs in port terminals by embracing a novel perspective on environmental impact.

This research argues that AI approaches, which are recommended for intelligent operations in a range of industrial sectors involving complex processes and risk (Giannakis and Papadopoulos, 2016; Baryannis et al., 2019; Sivarajah et al., 2020), are useful for the effective and efficient management that promotes sustainable development. However, the adoption of automated operations in several fields requires data analytics capabilities (e.g., data curation, data processing, etc.), for capturing insightful information and improving operations (Karafili et al., 2018). In this context, we anticipate our work to be beneficial to a wider group of stakeholders such as terminal operators, port authorities, shipping companies and shippers, inland transport providers, and freight forwarders/logistics service providers, particularly considering the global environmental challenges across the emissions-energy nexus.

There are also a number of limitations regarding the outcomes this work that should be considered in future research. The most important one is that our study is based on secondary data in a single port layout. Hence, it is not feasible to compare how different port layouts will affect the results and examine how the size and level of maturity regarding the adoption of AI technology affect the operational performance of the landside operations ports. Therefore, the incorporation of primary data can better inform the design of the developed simulation study. The latter does not examine the scheduling of the terminals' equipment but considers the routing of an AGV along with the relevant environmental ramifications. Finally, the study follows the assumption that unloading policy of the terminal operator requires stacking cranes to be allocated per container type. This may not apply to other ports and terminal layouts and therefore, the model assumptions need to be tested in that regard. Despite the abovementioned limitations, we still believe that our study indicates the benefits that can arise by the implementation of intelligent logistics at container port terminals.

In terms of future research, the possibility of multi-level analysis of AGVs in Pier I, from conceptualization to mathematical modeling, to simulation, to emulation, and to the investigation of testbeds and pilot applications, demonstrates great scientific interest (Tsolakis et al., 2019). Such a modeling and analysis toolkit would facilitate the multi-level analysis of the routing and efficiency of AGVs and could lay the groundwork for the development of 'digital twins' in container port terminals. The continuous flow of data received through sensors can assist in orchestrating synergistic actions in an automated port, thus resulting in improved operational performance which is also sustainable at the same time. In addition, we have not considered the case of transhipment which becomes more and more dominant in container port operations. Finally, an avenue that seems promising, is the development and evaluation of sophisticated routing algorithms for port-oriented landside operations that will allow optimizing the benefits from automation and AI techniques.

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Appendix

Table A1. Gaseous emissions and energy consumption indicators for forklift vehicles with different engine types [*Source*: Fuc et al. (2016)].

[Table A1 about here]