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Digitalization in Penang Port: Infrastructure, Analysis and Perspectives for Sustainable Logistics

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Abstract. Penang Port is one of the largest container ports in Malaysia, as it handled 1.42 million TEUs in 2024. As in many large seaports, modernization, innovation and sustainability have become key strategic priorities for Penang Port authorities. In this context, a long-term strategy has been defined to achieve these objectives. Port digitalization plays a central role in this strategy by enabling data-driven monitoring and optimization of operations. In particular, the digitalization of cargo handling relies on a data acquisition system and ICT technologies deployed within the terminal. The system relies on sensors installed on a fleet of five trucks operating the containers between the yard and the berth. These sensors provide detailed information on travel times, distances, and routes. An analysis of the collected data over the period from May to August 2025 reveals that the trucks traveled a total distance of 22,631 kilometers, resulting in estimated CO2 emissions ranging from 19 to 27 tons. Furthermore, the trucks remain idle approximately 20% of their operating time, mainly due to congestion within the terminal. To address these issues, we address the problem of designing an efficient pickup-and-delivery planning framework as well as the route of the trucks such that the traffic jam and total travel time are minimized. We propose a genetic algorithm for solving the problem whose aim is to reduce both CO2 emissions and travel distances, compared to the actual situation on Penang Port. We finally conclude with some discussions on the perspective offered by the digital system for reducing total GHG emissions of Penang port.

1 Page layout

Ports play a key role in worldwide supply chains and economic activities. Actually, all the ports,from small-size to huge ones, are facing several challenges. First, the strategic importance of maritime transportation and the increase of maritime shipping forces the ports to differentiate themselves from their concurrent. Also, policy makers impose to ports a stronger consideration of sustainability issues. The European Green Deal and the European Commission's Sustainable and Smart Mobility Strategy, require that ports meet environmental, safety and policy standards. These challenges lead the port authorities to invest in innovative technologies and frameworks in order to reach both economic performance and sustainability goals. Digitalization of port logistic activities is considered as a major tool for reaching these objectives. Digitalization in port receives a significant interest from port managers during these last years. Indeed, digital transformation of ports provide numerous advantages including real-time monitoring and a smart management of logistic activities, and a better monitoring of the environmental impact of logistics in port areas. The literature review shows that in few years, several initiatives have been developed for engaging digital transformation of seaports. Also, several research works point out the scientific challenges raised by digitalization of ports. In [1], Kosek et al. studied the digital transformation of three major ports in Poland. They showed that each of these three ports have a different approach to digital innovation, and that this transformation improves their connectivity with other European ports. Shamshol Bahri et al. [2] conducted a study on sustainable port operations and environmental initiatives in Malaysia. They showed that integrating digital technologies and automation into port logistic operations represent a significant opportunity for improving both operational efficiency and environmental performance in Malaysian ports. Similarly, Klein and Spychalska-Wojtkiewicz [3] investigated the role of digitalization for achieving sustainability goals in small and medium-size ports in South Baltic Sea. Digitalization in port is also determinant to improve the management of several issues like logistic performance, resilience, congestion, pollution and environmental impact, innovation and governance. Zhang et al. [4] examined shipping frameworks involving digitalization and innovation in green ports. They showed that a stronger cooperation in logistic operations is necessary for implementing efficiency in green port activities and that digitalization is determinant for enabling such collaboration. Narimane et al. [5] developed a framework based on block chain technology to secure transactions between different stakeholders in a smart port network. Ziar et al. [6] investigated the interest of block chain technology for sustainable shipping in several Asian ports. Finally, Sirajuddin et al. in [7] proposed a governance model based on digital ports and evaluate the performance of such framework. In this work, we are interested in using digitalization for optimizing both logistic performance and environmental impact in ports. We consider the container terminal of Penang port as a case study and investigate how digital tools can be used to improve vessel handling time while minimizing CO2 emissions due to container movement on the terminal. Here, the CO2 emissions are correlated with congestion on the container terminal. Digitalization is used to reduce such congestion and minimize the total CO2 emissions. The paper is organized as follows. First, in Section 2, we present the logistic context which is studied as well the sustainability issue which is considered. We also describe the optimization framework for optimizing simultaneously the logistic performance and the total CO2 emissions for a given time period. Then, in Section 3, we describe the digital infrastructure supporting the decision system. Finally, in Section 4, we give some perspectives and concluding remarks.

2 Decision Making Tool: a conceptual optimization frame-work for containers transportation

In this section, we propose a first decision-support framework to improve the efficiency of container transportation, within the terminal. The objective is to reduce travel time, limit the impact of congestion, and decrease CO2 emissions. The problem is modeled as a pickup-and-delivery problem with unit capacity and time-dependent travel times.

2.1 Problem description

We consider a set of transportation requests, each corresponding to the movement of a single container from a pickup location (e.g., quay) to a delivery location (e.g., storage yard). A fleet of straddle carriers is available to perform these operations. Each vehicle has a unit capacity, meaning that it can carry at most one container at a time. Container availability, vehicle movements, and congestion are inherently time-dependent. We therefore consider a time-dependent pickup-and-delivery problem with unit capacity, in which each request r is associated with a release time are corresponding to its availability at the pickup location. Service times may also be considered at pickup and delivery points. The terminal is represented as a directed graph G = (V,A), where nodes correspond to operational areas (storage zones, quays, intersections) and arcs represent feasible travel paths between them. Given the structure of the terminal, this network can be approximated by a small grid-like topology. The objective is to assign and sequence the transportation requests on the available vehicles, while accounting for time-dependent travel conditions and minimizing both operational and environmental costs.

2.2 Congestion modelling

Time-dependent vehicle routing problems have been extensively studied to capture congestion effects through travel times that vary with departure time [8]. In line with this approach, congestion within the terminal is modeled as an exogenous phenomenon through time-dependent travel times. Time is discretized into periods, and each arc (i,j) ∈ A is associated with a nominal (free-flow) travel time $\overline{\tau}_{ij}$ and a time-dependent congestion-induced delay Δij(t) ≥ 0. The effective travel time when departing at time t is thus given by

$$\tau_{ij}(t) = \overline{\tau}_{ij} + \Delta_{ij}(t).$$

We assume that congestion conditions remain constant during the traversal of a path, i.e., they depend only on the departure time. This assumption allows us to compute, for each time period, shortest paths between relevant origin-destination pairs with respect to different criteria such as distance, travel time, or emission-related costs. These precomputed path metrics are used within the decoding procedure to efficiently evaluate routing decisions. In particular, the congestion-related duration along a path can be naturally defined as the cumulative excess travel time with respect to nominal conditions. This allows us to capture variations in traffic conditions across different areas of the terminal and time periods, based on data collected by the monitoring system.

2.3 CO2 Emission estimation

Environmental considerations have increasingly been integrated into vehicle routing problems, leading to various emission models of different levels of complexity, see [9]. In this work, we adopt a simplified yet expressive formulation consistent with the available data. We distinguish three components: regular motion, idle periods, and congestion-induced effects. Total emissions are estimated as:

$$E = Q^m t^{move} + Q^i t^{idle} + Q^c t^{cong}$$

where t^{move} denotes the time spent in motion under nominal conditions (i.e., excluding congestion-induced delays), t^{idle} the total idle time, and t^{cong} the additional time induced by congestion. The coefficients Q^m, Q^i, and Q^crepresent average emission rates associated with these three components. For a given path P traversed at time t, the congestion-related duration can be computed as

$$t^{cong}(P,t) = \sum_{(i,j)\in P} \Delta_{ij}\,(t)$$

which corresponds to the cumulative excess travel time with respect to free-flow conditions.

This formulation makes the emission model directly compatible with the time-dependent routing framework, while remaining simple enough to be used within an optimization procedure. The coefficients can be calibrated from the literature or from future field measurements. More refined models, for instance incorporating nonlinear relationships between speed and emissions, could be considered in future work.

2.4 Optimization Objective

The optimization problem aims to determine routes and schedules for the vehicles that minimize operational and environmental costs. We consider an aggregated objective function combining travel time and emissions:

$$min\lambda_1(TotalTravelTime) + \lambda_2(E),$$

where λ_1 and λ_2 are weighting parameters. They represent the priority given to Total Travel Time or to Emission, when computing the solution of the problem.

This formulation takes into account both the impact of congestion through both travel times and emission components. Thus, it allows a possible balance between efficiency and sustainability objectives.

2.5 Genetic Algorithm Framework

To solve the problem, we propose a genetic algorithm (GA) approach. Given the limited fleet size and the combinatorial nature of the routing and scheduling decisions, meta-heuristic methods provide a flexible framework for exploring the solution space. Random-key genetic algorithms, and in particular biased variants (BRKGA), have proven effective for solving complex combinatorial optimization problems due to their flexible decoder-based structure [10]. This makes them well suited for integrating time-dependent travel times and emission evaluation within a unified framework. Each individual in the population encodes a vector of random keys associated with the transportation requests. A decoding procedure first builds a sequence of transportation requests from the weights, then assigns these requests to vehicles and selects feasible routes relying on precomputed path metrics. The fitness of each solution is evaluated based on the objective function, which incorporates both travel time and emissions. Standard genetic operators such as crossover and mutation are used to explore new solutions, while a selection mechanism promotes high-quality individuals. This approach allows us to handle the complexity induced by time-dependent travel times and to integrate multiple performance criteria in a unified framework

3 Digital Infrastructure and Data Acquisition System

Figure 1 illustrates the overall digital architecture deployed at Penang Port to support the monitoring and optimization of container handling operations. This system provides the technological foundation upon which the optimization framework presented in this work relies on. The architecture is structured around three interconnected layers. The first layer corresponds to the physical infrastructure of the terminal, which encompasses the quays, storage yards, gate areas, and the fleet of trucks operating within the terminal. Each truck is equipped with embedded sensors that continuously capture operational data, including travel distances, travel times, and idle periods. These sensors constitute the IoT layer of the system and provide the raw data stream upon which all subsequent analyses are performed. The second layer is a real-time centralized database, which aggregates and stores the data transmitted wirelessly by the on-board sensors. This server acts as the central node of the digital infrastructure, enabling real-time data access and processing. The database is accessible to multiple stakeholders involved in port operations: port staff can monitor operational performance indicators in real time, while customs authorities can query the system to track container flows and streamline administrative procedures. External logistics companies also interact with the system to coordinate freight delivery schedules and reduce dwell times at terminal gates.

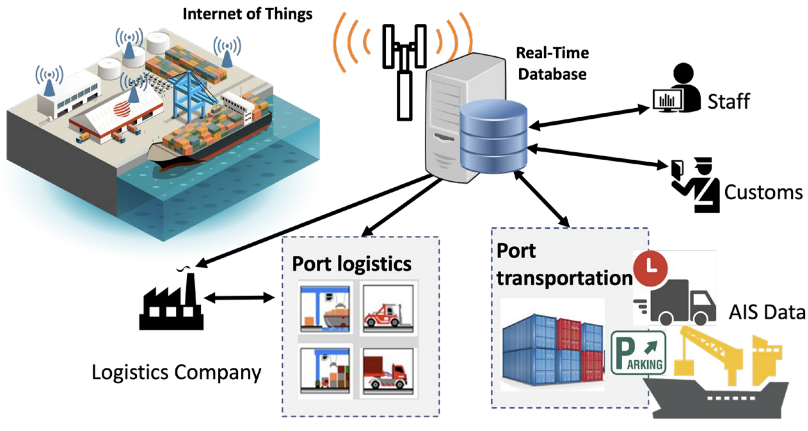

Fig. 1. Digital Port Infrastructure.

4 Numerical results

In this section, we present some computational results obtained from Penang Container Terminal as case study. The Figure 2 below shows the structure of Penang Container Terminal and the possible paths used by the trucks to convey containers between the berths and the yard.

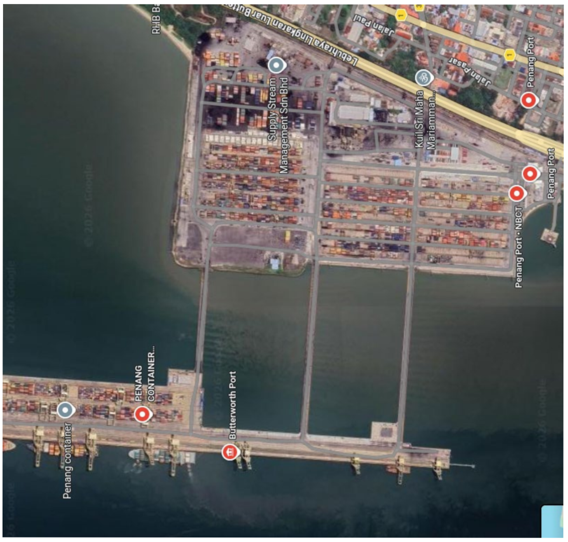

Fig. 2. Penang Container Terminal and the paths used by the trucks to convey containers.

The objective of the test phase is to compute the optimal pickup-and-delivery sequence that minimizes both makespan (the time taken to complete all the tasks) and the emissions. Recall that here a task corresponds to the transfer of a container between the berth and the yard. The aim is to assess the impact of the chosen solution on both makespan and emission. Also, remind that both makespan and emissions are influenced by the congestion on the terminal.

The algorithm compute solutions in two configurations, that are when congestion is allowed on the terminal and when it is not allowed. Since the genetic algorithm is a randomize algorithm, we run the algorithm several times for each configuration and analyze the trends. The numerical results are presented by Figures 3. Each point of the this figure presents a solution computed by the algorithm. Figure 3 shows, for each solution, the makespan versus the total distance traveled.

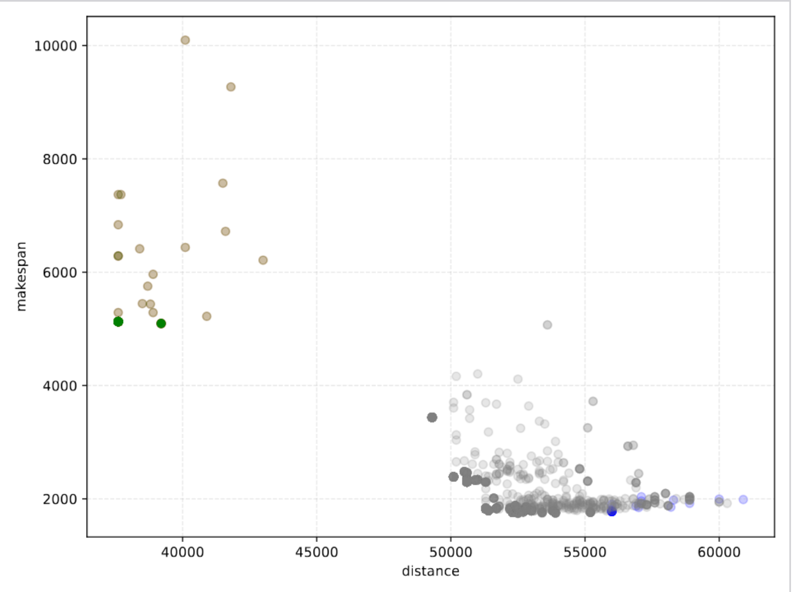

Fig. 3. Makespan versus total distance measured.

First, notice that in each configuration, several solutions are displayed. This is because the genetic algorithm is randomized, and because of the variation in the priority given to makespan or to CO2 emission during the optimization. Figure 3 clear shows two groups of solutions. The left-up group of solutions corresponds to solutions when congestion is allowed. The right-bottom group corresponds to solution when congestion is not allowed. Notice that when the congestion is allowed (left-up group), the makespan is increased. The analysis of the two groups of solution shows that the idle time of the trucks due to congestion impact more significantly the makespan than the increasing of the distance traveled by the trucks. Thus, completely removing congestion by rerouting the trucks implies a decrease of the CO2 emissions, but also a significant increase of the makespan

5 Conclusion and discussions

Digitalization of port activities is recognized as major tool for improving both operational performance and sustainability of ports [3]. However, design and implementation of relevant digital framework still remain a challenge. In this paper, we have presented a digital framework designed to monitor logistic activities while minimizing the CO2emssions related to container handling. Our framework combines different IoT systems implemented within a digital twin of the container terminal. The framework also implements an optimization algorithm for allowing relevant management strategies in terms of sustainability. The digital framework we have developed introduces several opportunities in terms of innovation and in terms of research perspectives. First, in terms of innovation, it is recognized that for a better management of the maritime and port supply chain, the different port management system should cooperate with each others. This raised several challenges in systems interoperability and in governance. Also, the data collected through the digital system may allow better modeling of various indicators which are important for both performance and sustainability issues. For instance, a relevant monitoring of CO2 emissions in a Port require to assess the values of the coefficients Q^m, Q^i and Q^c, introduced in Section 2.3.

The numerical results on the container terminal of Penang shows that reducing CO2 emissions while keeping operational competitiveness is challenging task. A better strategy for improving sustainability main not rely only on truck congestion management.

Finally, it is important to propose relevant models joining logistic operations with sustainability indicators. As notice above, the data gathered through the digital framework may help in building such models.

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