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Sustainable maritime inventory routing problem with time window constraints

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ABSTRACT

Maritime inventory routing problem is addressed in this paper to satisfy the demand at different ports during the planning horizon. It explores the possibilities of integrating slow steaming policy as mentioned in Kontovas et al. (2011) and Norstad et al. (2011) within ship routing. A mixed integer non-linear programming model is presented considering various scheduling and routing constraints, loading/unloading constraints and vessel capacity constraints. Non-linear equation between fuel consumption and vessel speed has been incorporated to capture the sustainability aspects. Several time window constraints are inculcated in the mathematical model to enhance the service level at each port. Penalty costs are incurred if the ship arrives early before the starting of the time window or if it finishes its operation after the ending of the time window. Costs associated with the violation of time window helps in maintaining a proper port discipline. Now, owing to the inherent complexity of the aforementioned problem, an effective search heuristics named Particle Swarm Optimization for Composite Particle (PSO-CP) is employed. Particle Swarm Optimization – Differential Evolution (PSO-DE), Basic PSO and Genetic Algorithm (GA) are used to validate the result obtained from PSO-CP. Computational results provided for different problem instances shows the superiority of PSO-CP over the other algorithms in terms of the solution obtained.

1. Introduction

Maritime logistics sector is considered to be the most important mode of transportation involving 9.6 billion tons of world trade in 2013 as reported in UNCTAD (2014). Maritime transportation comprises of around 80% of the international trade as mentioned in UNCTAD (2013). It is estimated that around 65–85% of total global trade is carried using seaborne shipping as mentioned in Christiansen et al. (2007). Volume of the global seaborne shipments expanded by 3.4% in 2014 as reported in UNCTAD (2015). Containerized trade contributes about 15% share to the international seaborne trade. Containerized trade volume is estimated to have increased by 5.3% in 2014, taking the total to 1.63 billion tons. Increasing level of international trade using sea-route has led to greater attention in the domain of ship routing and scheduling. In this paper, a particular ship routing and scheduling problem is studied considering the aspects of containerized trade. Although it is observed that maritime transportation leads to a significant consumption of fuel. Hence, it is essential to achieve greater sustainability by considering several environmental friendly policies such as slow steaming, speed optimization, fuel efficient vessels etc.

International shipping emitted around 2.7% of carbon di oxide in 2007 on the basis of 2nd International Maritime Organisation (IMO) GHG Study 2009 as mentioned in Buhaug et al. (2009). ICS (2009) addressed the issue of green-house gas emissions in maritime transportation and estimated that short-sea shipping contributes around 25% of GHG emissions. Furthermore, this percentage may drastically increase if no possible measures are adopted to curb the emissions. In recent years, environmental issues pertaining to seaborne shipping and increasing fuel prices have given vessel speed a newer perspective. As stated in UNCTAD (2015), practice of speed optimization in container shipping helps to counter high fuel prices. Ship speed has a non-linear relationship with fuel consumption as mentioned in Norstad et al. (2011). Therefore, speed optimization or ideally slow steaming can be implemented as an operational measure to depict the amount of fuel consumed. The research work presented in this paper addresses the sustainability aspects in maritime transportation by considering vessel speed optimization strategy. Slow steaming policy has been adopted to estimate the total amount of fuel consumed in sea and port. Fuel cost

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incurred in sea is computed using the relationship between vessel speed and fuel consumption.

Maritime transportation faces different challenges of lowering the fuel consumption and minimizing the transportation cost. Also increased amount of maritime traffic volume requires efficient routing and scheduling of ships. Container shipping is concerned with the distribution of multiple containers of different types from one port to another using a heterogeneous fleet of ships. Each port has its storage capacity or demand on the basis of whether it is a production or consumption port. Designing the schedules and routes for the fleet of ships on the basis of number of containers to be loaded or unloaded is an important aspect to be taken into account. Reducing the total transportation cost for each vessel without interrupting the supply and demand remains one of the primary challenges. The work presented in the paper performs efficient routing and scheduling of vessels such that the demand and supply of containerized cargo could be met at different ports.

There is an increasing interest to explore the possible ways for improving the service level at port. The issue pertaining to the time spent by a ship at a port can be addressed by considering a time window concept. Each ship should carry out its loading/unloading operations within the time window of the port. Violation of time window takes place when the ship finishes its operation outside the specified time window. Furthermore, the vessel can arrive much before the starting of the time window. In such a situation, it will remain idle till the beginning of the time window. There are different challenges encountered in implementing the time window concept in a port. Several measures need to be taken in order to counter the scenarios of early arrival of a ship as well as violation of the time window. The paper incorporates time window concept to enhance the service level at the port. Multiple vessels arriving before the allotted time window range may lead to congestion at the port. Such scenarios are countered in this paper by imposing penalty cost per hour of waiting before the starting of the time window. Certain vessels may fail to finish its operation within the allotted time window range, thereby incurring penalty charges per hour as considered in the paper.

Now, a shipping company generally operates on heterogeneous fleet of vessels having different carrying capacities, speeds, physical dimensions and operating costs. The ship transports multiple types of containers from production ports to consumption ports and ensures a check in the capacity of the port. The challenge lies in determining the ideal distribution policies such that scheduling and operating costs are minimized. Simultaneously, it is essential to keep a track on the ship's inventory and port's capacity for maintaining it within a certain limit. Proper inventory management decisions are important in the context of maritime transportation as it can be beneficial for port operations. The objective of the paper is to elaborately study a sustainable maritime inventory problem considering different shipping operations such as ship routing and scheduling, time window concept at ports, multiple ships operating at a port due to the presence of number of available berths, loading unloading operations at port, speed optimization strategy for computing the fuel consumed by the ship. In view of the objective of the paper, a novel mathematical model addressing sustainable maritime inventory routing problem is presented aiming to minimize the fuel cost of the shipping company and penalty charges associated with the violation of the time window, docking cost and variable cost pertaining to the loading and unloading operation at the port.

The contributions made in this paper are of interest for other researchers working in the domain of sustainable maritime transportation. The novelty of the paper lies in integrating different maritime operations such as ship routing and scheduling, loading/unloading of containers at ports, time window concept considering penalty costs to deal with violation and fuel consumption associated with different vessels. De et al. (2016) considered different shipping operation and presented a generic mathematical model for a sustainable ship routing and scheduling problem. They primarily focussed on transportation cost, set up cost and penalty cost associated with the violation of time window in their objective function and overlooked the fuel cost at port and sea as well as variable cost at the port depending upon the number of containers loaded/unloaded. A robust mathematical formulation developed in this research work aims to minimize the total cost of the container shipping company considering fuel cost at port and sea, fixed and variable cost at port and different penalty cost for violating the time window. The model incorporates slow steaming strategy to estimate the fuel consumption at sea, routing constraints, time window constraints and ship's capacity related constraints. Time window constraints improves the service level at the port by imposing penalty cost for two different scenarios of vessel arriving early before the starting of the time window and the vessel finishing its operation outside the specified time window. As slow steaming policy increases the total voyage time of a ship, hence it is essential to consider time window concept in the model for keeping a check on the arrival and departure time of the vessel. Fixed cost associated with performing a loading/unloading operation at a port and variable cost related to the number of containers loaded/unloaded are considered in the model to compute the overall operation cost of a vessel. Predominantly, Heavy Fuel Oil (HFO) is employed to run the ship's main engine while sailing in sea and at port Marine Diesel Oil (MDO) is used to run vessel's auxiliary engine. The fuel consumption for each vessel is computed keeping this practicality in mind and corresponding average fuel prices considered are 463.50 USD/ton and 586 USD/ton for HFO and MDO respectively (Kontovas and Psaraftis, 2011). Fuel prices generally keep fluctuating with time but for computational experiment it is assumed to be constant in this paper. The study successfully integrates speed optimization policy along with fuel prices to estimate the total fuel cost and address the sustainability aspects in maritime transportation domain. Fuel cost incurred at a port is computed by taking into account the total operating time and the fuel consumed by the vessel at a port per hour. Moreover, the model considers the simultaneous operation of multiple numbers of ships in a period as in practicality each port contains numerous berths.

The rest of the paper is organized in following manner: Section 2 provides a brief literature review on relevant studies related ship routing and scheduling problem. In Section 3, the problem environment is discussed in an elaborate manner. In Section 4, the mathematical formulation and the descriptions of the objective function and constraints are presented. The proposed solution approach for the problem is mentioned in Section 5. The implementation of particle swarm optimization for composite particle (PSO-CP) algorithm is illustrated over here. Section 6 is devoted to the results and discussions of the extensive computational study carried out. Conclusions are given in Section 7. It also includes the managerial implications and future scope of the problem.

2. Literature review

Maritime inventory routing problems involves transportation of several products between different ports and constant monitoring of the inventory level for all the products at the ports. This section provides a brief review on the relevant studies in the domain of basic maritime inventory routing problem (MIRP). Christiansen and Nygreen (1998) dealt with a MIRP for routing several vessels and performing the inventory management at different ports. Their model comprises of inventory pick-up and delivery of a single product to different ports using a fleet of ships for short-term planning horizon. Christiansen (1999) examined a maritime transportation problem of a single product (ammonia) between several production and consumption facilities. The product is produced and stored in inventory facilities and later transported using a fleet of ships to several ports. The aim of this problem is to design appropriate shipping routes and schedules for minimizing the total costs associated with transportation without