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Composite particle algorithm for sustainable integrated dynamic ship routing and scheduling optimization

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ABSTRACT

Ship routing and scheduling problem is considered to meet the demand for various products in multiple ports within the planning horizon. The ports have restricted operating time, so multiple time windows are taken into account. The problem addresses the operational measures such as speed optimisation and slow steaming for reducing carbon emission. A Mixed Integer Non-Linear Programming (MINLP) model is presented and it includes the issues pertaining to multiple time horizons, sustainability aspects and varying demand and supply at various ports. The formulation incorporates several real time constraints addressing the multiple time window, varying supply and demand, carbon emission, etc. that conceive a way to represent several complicating scenarios experienced in maritime transportation. Owing to the inherent complexity, such a problem is considered to be NP-Hard in nature and for solutions an effective meta-heuristics named Particle Swarm Optimization-Composite Particle (PSO-CP) is employed. Results obtained from PSO-CP are compared using PSO (Particle Swarm Optimization) and GA (Genetic Algorithm) to prove its superiority. Addition of sustainability constraints leads to a 4–10% variation in the total cost. Results suggest that the carbon emission, fuel cost and fuel consumption constraints can be comfortably added to the mathematical model for encapsulating the sustainability dimensions.

1. Introduction

In maritime transportation domain, carbon emission is a topic of intense debate in the world shipping community. According to the United Nations Framework Convention on Climate Change – UNFCCC (1997) Kyoto protocol, definite measures have to be taken in order to curb Carbon emission. Its main motive lies in restraining the increase of the greenhouse gas emissions worldwide. Buhaug et al. (2009) stated that throughout the world, 4100 container carrying fleets operate, out of which only 4% are registered. Still 70 million metric tons (Mmt) of fuel was consumed in 2007 and 230 Mmt of CO_2 emitted. This number shows that 22% of carbon emission and energy consumption are attributed to international shipping. According to International Chamber of Shipping (ICS), 25% of the greenhouse gas emissions in maritime industry are contributed by short sea shipping (ICS, 2009). Now, this percentage may rapidly increase if there is no counteractions taken in order to lower the emission rate (IMO, 2009c). International Maritime Organization (IMO) is exploring the possible measures which may help to reduce carbon emission from the available vessels by 20–50% (IMO, 2009c).

IMO has already developed two measures EEDI (Energy Efficiency Design Index) for new vessels and EEOI (Energy Efficiency Operational Indicator) for existing vessels (IMO, 2009a, 2009b, 2009c). IMO suggested several other measures like vessel size enlargement, voyage speed reduction, etc. In general, greenhouse gas emissions can be lowered in three distinct ways. Technological measures mainly involve the usage of alternative fuels such as biofuels, using energy-saving engines, more efficient ship propulsions, ship scrubbers which generally trap exhaust emissions and several other technologies that aim to reduce power consumption, etc. There are two popular policies exist to account for carbon trading viz emission trading and carbon levy schemes. IMO has been working extensively on the introduction of these policies in the

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context of maritime transportation. Operational measures include speed optimization by ideally slow steaming, optimal fleet, route planning and other transportation based measures. Now all these effective measures can be implemented while addressing an equally important issue that deals with the increase in shipping costs.

Shipping costs primarily includes transportation costs, fuel costs, operating costs, hiring cost, etc. To capture the carbon emission and bring sustainability issue into shipping operations, there is a need to combine carbon emission and maritime costs. In operational context, vessel speed optimization is an ideal strategy to reduce emissions and fuel consumption for a sustainable environmental condition. In high fuel price and low freight rate situation, it's logical to employ slow steaming as a prime strategy. Ronen (1982) used this strategy and stated that emission is proportional to fuel consumption which in turn is a cubic function of vessel speed. This relationship holds good approximation after a certain speed limit.

There is an increasing interest to investigate the possible ways to reduce the time spent by the ship in port. This issue can be addressed by considering a time window concept at each port. Most of the ports have definite operational restrictions during certain period of the day. Hence, port operations should categorically be carried out during that pre-defined time window. Port operations primarily involve loading/unloading of the products. Generally speaking, operating time at a port comprises of setup time and loading/unloading time. Fixed loading/unloading time is considered for each product. Port operation begins with the start of the time window. However, a vessel has to wait if it arrives much before the start of the time window. There is a possibility that the ship may finish its operation after the ending of the time window. In such cases a penalty cost is imposed depending on the total time operated outside the time window. Such measures help in maintaining port discipline and enhance the port management facilities.

Most liner shipping started to adopt the slow steaming policy from 2010 onwards. This strategy is useful in minimizing the total amount of CO_2 emitted for a current maritime logistics scenario with low freight rates and high fuel prices. It's already observed that if voyage speed is decreased by 20%, then carbon emission and fuel consumption can be reduced by 20% and 40% respectively.

A mathematical model is developed keeping in mind the advantages of ship speed relationship with fuel cost and fuel consumption. In a realistic scenario, two types of fuel oils are considered for each vessel. Engine of the vessel is operated on Heavy Fuel Oil (HFO) while it is at sea. While operating on ports, it runs on Marine Diesel Oil (MDO). There is a need to develop an emission coefficient for predicting the amount of CO_2 generated for both types of fuel. From IMO 2000 study, it is concluded that emission coefficients of 3.082 and 3.021 can be considered for MDO and HFO respectively. Buhaug et al. (2009) have used similar emission coefficient in their paper.

Keeping in mind the slow steaming relationship with fuel cost, it is obvious to consider an appropriate fuel price coefficient for calculating the fuel cost. Fuel prices keep fluctuating from time to time as being market dependent. It can be assumed constant for computational benefit and for this paper average price considered for HFO and MDO are 463.50 USD/ton and 586 USD/ton respectively (values are taken from Kontovas and Psaraftis (2011)).

In recent past, shipping lines are focusing more on mitigating ship emissions and fuel consumption in the prescribed sailing period. Fuel cost has become one of the most influential part of the total cost associated with maritime transportation. Already discussed earlier that slow steaming policy is a widely adopted operational measure to address sustainability aspects. A shipping company aims to lower the emission even when the vessels are operating at the port. Another objective is reducing the ship's waiting time at the port in order to improve the service level. However, it is observed that the terminal's operational plan depends on the schedule of the vessels of the shipping lines. The expected ship arrival times and departure times are regulated on the basis of shipping schedule and it gets disturbed owing to port congestion as mentioned in Notteboom (2006). Hence, for keeping proper coordination between the shipping lines and ports, vessel speed optimization can be considered as an ideal operational measure.

The contribution in this paper includes development of a new mathematical model considering planning horizon whereas in other papers only ship routing, loading/unloading operation are taken into account. The model predominantly deals with varying supply and demand rate for different products at each ports. It successfully integrates ship routing, scheduling along with slow steaming, carbon emission and fuel consumption. Slow steaming policy is incorporated for capturing the intricacies associated with sustainability in ship routing and scheduling. It is identified as an essential strategy for addressing the issues related to carbon emission. Different types of fuel oils are considered to map the realistic scenario in ports. This study integrates decision pertaining to fleet routing, multiple time window horizon and carbon emission associated with each vessel. An effective and intelligent search algorithm named PSO-CP is put to use for optimizing the developed mathematical model.

The rest of the paper is organized as follows: Section 2 presents the literature review. Section 3 describes Problem environment. In Section 4, the problem is mathematically formulated and the notations are provided. In Section 5, the proposed solution approach is mentioned. PSO-CP algorithm is described over here and it is followed by the description of the implementation of the algorithm. In Section 6, the result and discussions are presented. Here, the sensitivity analysis for the parameters of the algorithm is provided and the results obtained from different instances are mentioned. Section 7 comprises of the conclusions and future scope of the research.

2. Literature review

In the context of maritime logistics, researchers are showing keen intent in resolving the intricacies of carbon emission while dealing with mathematically grounded models.

2.1. Scheduling and routing models and methods

Christiansen (1999) examined a fleet of ships transporting a single product (ammonia) between several production and consumption facilities. Here, the product is produced and stored in inventory facilities and later transported using a fleet of ships to several ports. The problem aims to design routes and schedules for a fleet of vessels in order to minimize the total transportation costs without any interruption of operations at the ports. Inclusion of time window concept in the model appears to be a possible scope of improvement. In subsequent years several articles related to inventory and routing problems are reported. Ronen (2002) dealt with a maritime inventory routing problem considering multiple products. Their formulation addressed the intricacies associated with port inventory management. The routing part is missing in their formulation and it may affect the real life application of the model. Al-Khayyal and Hwang (2007) studied a maritime inventory routing problem for multiple products and presented a mathematical model accordingly. They considered different compartments in the ship for accommodating multiple types of products. Song and Furman (2013) proposed a new