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Bi-level optimization model applications in managing air emissions from ships: A review

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ABSTRACT

Ship air emissions are recognized as one of the key concerns of the maritime industry. Competent authorities have issued various regulations to manage air emissions from ships. Although the authorities are policy makers, the effectiveness of policies is up to the shipping industry who operates the vessels and terminals to fulfill maritime transportation works. Given this characteristic, bi-level optimization model has been widely adopted in studies that optimize policy design or evaluate its effectiveness. The framework of a typical bi-level optimization model for ship emission management problem is given to show the basic structure of similar issues. A series of applications of bi-level optimization model in managing ship emissions is reviewed, including cases of Energy Efficiency Design Index, Emissions Control Area, Market Based Measure, Carbon Intensity Indicator, and Vessel Speed Reduction Incentive Program. We hope this paper can enlighten scholars interested in this area and provide help for them.

1. Introduction

As indicated by the latest Review of Maritime Transport by the United Nations Conference on Trade and Development (UNCTAD, 2020), sustainable shipping, decarbonization, and ship pollution control remain priorities of the maritime industry. Abundant attention from academia has been drawn to related topics, including the ship emission reduction technologies and regulations (Wang and Xu, 2015; Wang et al., 2018; Lindstad et al., 2019; Psaraftis, 2019; Zhuge et al., 2021). Currently, with relatively mature green technologies, for example efficient ship engines, alternative fuel powered ships, and advanced desulfurization technology for marine fuels, various regulations have been carried out by competent authorities to promote the application of the technologies (International Maritime Organization, 2011, 2021a,b,c). Although the regulations were enacted with good intentions, the implementation effect is up to the maritime industry including carriers such as shipping companies. They are the ones who conduct the transportation tasks and directly influence the air emission volume. Thus, in the investigation into the optimization problem of regulation design and the analysis of its effect, the bi-level perspective is extensively adopted.

In a bi-level problem, there are two types of decision makers playing on behalf of their own interests. One is the leader who first makes decisions and the other is the follower who makes decisions afterward. The leader's decisions have an impact on the follower's decisions, which in turn, influence the leader's objective function value. In the bi-level problem about the management of air emissions from ships, competent authorities that issue regulations are the leader; the maritime industry including carriers such as shipping companies who fulfill the transportation tasks is the follower that operates on behalf of its own profits.

In this paper, we review the applications of bi-level optimization model in managing air emissions from ships. The remainder of the paper consists of several parts as follows: Section 2 presents the framework of the bi-level model in ship air emission management. Section 3 reviews applications of the bi-level optimization model in maritime transportation. Meanwhile, application at the interface between the maritime and other industries is introduced in Section 4. Lastly, Section 5 sets the conclusions of this review paper and states the possible extension in the area of ship air emission management.

2. Bi-level framework in ship air emission management

In the management of ship air emissions, a typical bi-level problem has the framework shown in this section. We list the notations that will be used in the framework before presenting it.

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2.1. Parameter

B the budget for the regulation implementation (USD).

2.2. Decision variables

x the decision made in the upper level model by the competent authority;

y the decision made in the lower level model by the maritime industry.

The decision maker in the upper level problem is the competent authority, including the government of different countries and areas or nongovernmental organizations such as the International Maritime Organization (IMO). The problem faced by the upper level player can be described as the following model $[MU]$:

$$[\boldsymbol{MU}] \quad \text{minimize}\, f(y^*(x)) \tag{1}$$

subject to

$$g(x, y^*(x)) \le B. \tag{2}$$

In $[MU]$, the objective function (1) aims to minimize the total ship air emissions in the considered area and planning period. It should be noted that the authority is likely to enact multiple regulations or make various decisions related to one regulation, and therefore the notation x is sometimes a vector that represents a series of decisions. Given the authority decision x, the industry reacts in a way that can minimize its own costs, which is denoted by $y^*(x)$. Since the ship air emission volume is directly decided by the reaction of the industry instead of the regulation decisions by the upper level player, function $f(y^*(x))$ is used to represent the emission volume. In addition to the minimization of ship emissions, the upper level player, the government or the IMO most of the time, will also consider the extra cost burden on the lower level players brought by the regulation to ensure that the maritime industry will not be hit badly.

Constraint (2) ensures that the costs of regulation implementation do not exceed the budget allocated. There are circumstances in which implementing a regulation requires an expenditure from the policy maker, such as providing subsidies to encourage the installation of green technologies (Bajic, 2020; Ministry of Finance of the People's Republic of China and Ministry of Transport of the People's Republic of China, 2014). The amount of such expenditure depends on the industry's reaction as well as the detailed rules. For example, a government provides subsidies for ship operators that retrofit their vessels into dual-fueled ships. The total amount of subsidies awarded is closely related to the number of ships retrofitted, which is up to the ship operators, and the subsidy amount for each retrofitted ship, which is decided by the government. Thus, we use the function $g(x, y^*(x))$ to denote the regulation implementing costs, which vary with $y^*(x)$ as well as x. However, in many cases, the implementation expenditure is not strictly constrained by a given budget but considered as a part of the objective function. Thus, the objective function will be

$$[\boldsymbol{MU}] \quad \text{minimize}\, f(y^*(x)) + g(x, y^*(x)) \tag{3}$$

and constraint (2) will be deleted.

The decision maker in the lower level problem is the maritime industry, including carriers such as shipping companies who conduct the transportation works. The problem faced by the lower level player can be described as the following model $[ML]$:

$$[\boldsymbol{ML}] \quad y^*(x) \in \arg\min_{y} c(x, y) \tag{4}$$

subject to

$$y \in Y(x). \tag{5}$$

The objective function (4) means that the industry tries to obtain the decision $y^*(x)$ that can minimize its costs. Similar to the decision variable x in the upper level model, y in the lower level also refers to a series of decisions sometimes. Besides, in most cases, more than one follower should be considered, such as all the shipping companies operating in a certain area. For simplicity, we still use y to represent the decisions in the lower level. The industry makes decisions under the regulation given by the competent authority, and therefore its cost function is denoted by $c(x, y)$, which is related to both x and y. Constraint (5) defines the domain of y, which is denoted by $Y(x)$. The domain is related to the upper level decision x because some regulations are compulsory. For example, the government announced that all ships should be retrofitted into dual-fueled within 10 years from now. Then a shipping company has to obey this regulation and get its ships retrofitted but it can decide when to conduct the retrofitting work.

3. Applications within the maritime industry

In this section we introduce applications of bi-level optimization model in the maritime industry. This section consists of two parts, subsection 3.1 reviews applications related to the ship fleet but not the operation of a particular ship, and subsection 3.2 reviews applications related to a ship's operation.

3.1. Applications related to the ship fleet

Bi-level optimization model has been used to abstract problems in the management of ship air emissions related to the ship fleet. Two examples that involve the ship building and fleet deployment are given in the following.

3.1.1. Energy Efficiency Design Index

The first case is the application of Energy Efficiency Design Index (EEDI) proposed by the IMO. EEDI gives the cap value of the carbon dioxide (CO_2) emission volume per capacity mile (gram/tonne-n mile) for new ships or existing ships that have undergone a major conversion. The index became mandatory in 2011 (International Maritime Organization, 2011), and the highest allowable EEDI value is phase-wise and not sequential. For example, for bulk carriers with dead weight tonnage of 20,000 or above, the highest allowable EEDI value for ships whose construction or conversion started on 1 January 2025 or onwards (phase 3) is 12.5% lower than that on 1 January 2020 to 31 December 2024 (phase 2). The declining cap values ensure the substantial reduction in the emission intensity of existing ships, but such rules not necessarily reduce the emission volume of ships that is going to be built in the near future. The phase-wise EEDI cap values encourage the ship owners to prolong a ship's construction period from 2 years, ranging from 31 December 2028 to 31 December 2030, to 6 years. Then the construction contract as well as the construction work will start on 31 December 2024, which makes the new ship regulated by the EEDI level in phase 2 instead of phase 3. Thus, relatively inexpensive engines with lower energy efficiency can be installed onboard and produce more CO_2 emissions. At the same time, the unnecessarily long construction period will lead to a potential waste of materials and the inefficiency production.

In the case of EEDI, the IMO plays as the upper level decision maker, and the decision x refers to the cap values of EEDI for vessels of various categories and the division of phases. Meanwhile, the ship owners are the followers in the lower level and they determine the start time of the ship's construction contract, the construction period length, and the engines adopted, denoted by y. Besides, despite the freedom of arranging the ship construction, ship engines installed should comply with the EEDI in the corresponding phase, as indicated by $Y(x)$ in constraint (5), which is the domain of decision variable y and depends on x.

Based on an analytical comparison, Lindstad et al. (2019) figure out that the current EEDI also has obvious impact on the ship design. Currently, there are two methods to improve the ship energy efficiency besides the more efficient engines: one is building the vessel in an energy efficient shape and the other is equipping the ship with an anti-fouling design. The energy efficient shape reduces the influence of waves on sailing and therefore improve the energy efficiency. Meanwhile, the anti-fouling design reduces the frictional resistance. The energy efficient shape is more costly but more effective in energy saving, especially with high waves and high sailing speed. Due to the fact that the EEDI test measures the emissions (gram/tonne-n mile) for a fully loaded vessel with the main engine delivering 75% of its maximum continuous power (MCR) at calm water conditions, ship owners tend to build vessels with smaller engines (Lindstad et al., 2019). Considering the high cost of a ship with energy efficient shape and the fact that it is not obviously more energy efficient than ship with anti-fouling design under the scenario of calm water and low speed, ship owners become reluctant to adopt the energy efficient shape, which is actually more efficient in real sea conditions. On the other hand, the small engine power indicates that more ships are needed to be put on the market to match transport demand (Psaraftis, 2019). As a result, the ship emission could potentially increase.

From the perspective of ship design, the decision of upper level model x includes not only the details of EEDI values but also the measuring method of attained EEDI of ships. At the same time, ship owners in the lower level have to take the ship design into considering while building ships, as denoted by y.

3.1.2. Nitrogen emission control area

The second case is related to the establishment of Nitrogen Emission Control Areas (ECAs), namely the North American ECA, the United States Caribbean Sea ECA, the Baltic Sea ECA, and the North Sea ECA. According to ANNEX VI of MARPOL (International Maritime Organization, 2021d), the Tier III regulation sets the cap value of nitrogen oxides (NO_X) emission volume per kWh electricity generated (g/kWh) for ships that have recently installed marine diesel engines with over 130 kW output power. Corresponding vessels have to comply with the cap emission values while operating in the Nitrogen ECAs. Specifically, in the North American ECA and the United States Caribbean Sea ECA, ships whose engines were installed on 1 January 2016 or onwards should comply with the requirement, and the installation date is 1 January 2021 or onwards in the Baltic Sea ECA and the North Sea ECA. Although this Tier III regulation does not apply to engines installed before the particular date, a large number of newly built ships cannot meet the requirement. In order to comply with the Tier III regulation, shipping companies tend to remove the new ships that fail to meet the requirement from the fleet on routes going through Nitrogen ECAs and deploy them on routes that do not involve ECAs. Meanwhile, old ships originally deployed on those routes without ECAs will be reallocated to supplement the capacity of the ECA routes. Due to the aged engines and obsolete design, old ships tend to be more pollution intensive than newly built ships in the aspect of NO_X, CO_2, and particulate matters (PM_X). As a result, the total ship air emission volume within the ECAs may increase, which goes against the initial intention of this regulation in a diametrically opposite direction.

In this case, the upper level decision maker, the IMO, determines the specific NO_X emission volume cap and the situations of engines to which the regulation applies, denoted by x in the model $[MU]$. In the lower level, the shipping companies redeploy their fleets to comply with the regulation, denoted by y in $[ML]$. Given the regulation, represented by x, the fleet deployment decision y has to obey the Tier III requirement in the Nitrogen ECAs, which defines the decision variable domain, denoted by $Y(x)$.

3.2. Applications related to a single ship

Another stream of applications influences the operation of a particular ship, including the sailing route and sailing speed optimization.

3.2.1. Sulfur emission control area

The Nitrogen ECAs mentioned in 3.1.2 are also the Sulfur Emission Control Areas, in which the sulfur oxides (SO_X) emission situation of ships is strictly regulated. According to the IMO's regulation, from 1 January 2020, the upper limit of sulfur content in fuel oils used onboard global-wide is reduced to 0.5% m/m from the 3.5% requirement from 1 January 2012. Meanwhile, ships sailing in Sulfur ECAs are required to use fuel oil with a sulfur content no higher than 0.1% m/m from 1 January 2015 (International Maritime Organization, 2021a). Switching bunker fuel and using fuels in accordance with the regulation, for example marine gas oil (MGO), marine diesel oli (MDO), and ultra-low sulfur fuel oils (ULSFO), while sailing in the Sulfur ECAs is an option that has been frequently adopted by ship operators, especially for existing and aged ships. Since these cleaner fuels are much more expensive than the heavy fuel oil (HFO) and low-sulfur HFO used out of ECAs, ships tend to sail at a low speed in ECAs to save the bunker cost. At the same time, they have to speed up outside the ECAs to guarantee the punctuality. Considering that the ship emission is closely related to fuel consumption which is approximately in a linear relationship to the cubic of sailing speed, this speed rearrangement would drive up the total emission volume of the whole route (Ronen, 1982; Wang and Meng, 2012).

In the implementation of Sulfur ECA, the IMO decides the cap value of sulfur content of fuels used onboard within the ECAs as well as the designation of ECAs in the upper level as x. After that, the ship operators adjust their ship operation plan, including the sailing speed and bunker type used inside and outside of the ECAs, denoted by y in $[ML]$. Meanwhile, the requirements on the sulfur content within ECAs should be met and then form the domain of lower level decision variable y, denoted by $Y(x)$.

3.2.2. Market based measures

Multiple regulations have been carried out regarding the reduction of CO_2 emissions from shipping, including market based measures (MBMs). Currently, there are two main streams of MBMs targeting at the decarbonization of shipping, namely the levy-based and Emission Tradition System (ETS)-based measures (Lagouvardou et al., 2020; Psarafits et al., 2021). In this section, we review the case of Carbon tax, which is a commonly adopted levy-based MBM that levies a fee on the production, distribution or use of fossil fuels based on how much carbon their combustion emits. Carbon tax influences the operations of ships and ports, and brings higher operating costs compared to the scenario without it. Wang et al. (2018) investigate the joint berth allocation and quay crane assignment problem under different carbon emission taxation policies. Considering the carbon tax, the port operator is faced with a higher operating costs and has to pay special attention to the allocation of quay cranes since they are the main source of CO_2 emissions from the port side. Results show that carbon tax can significantly reduce the carbon emissions from the port side.

As for the influence of carbon tax on the ship operating, Wang and Xu (2015) study the sailing speed optimization problem of a voyage chartering ship under different carbon tax policies. The comparison among the results shows that although both taxing emissions that exceed a certain threshold and taxing with a uniform rate for one tonne of emissions are efficient in reducing ship emissions, taxing with a certain threshold achieves the goal at a lower cost of reducing operators' profits.

From the two studies we can see that the carbon tax can reduce the carbon emission significantly at the cost of reducing the profits of port and ship operators. An exorbitant tax rate can surely achieve an obvious emission reduction, but the shipping industry will be hurt. Therefore, the design of carbon tax laws requires thorough investigation from the bilevel perspective.

In the carbon tax case, the upper level player is the tax collector that decides the specific form and rate of the carbon tax, denote by x. Given the tax rules, the lower level players, the port and ship operators, need to consider the carbon tax while making their operating plans and arrangements, denoted by y. Given that the carbon tax is mandatory, the decisions of lower level players, y, is restricted to $Y(x)$, which is closely related to x.

3.2.3. Carbon intensity indicator

Another approach to the carbon emission reduction is the carbon intensity indicator (CII), which measures the carbon emissions per unit transport work for each particular ship (International Maritime Organization, 2021c). Ships that fail to control their CII under the cap value will be asked to go though a revision before returning to the market. There are multiple forms of CIIs, and they mainly differ in the definition of unit transportation work. Under some scenarios, the ship operators choose to sailing empty for unnecessary length to lower the annual average carbon intensity of the vessel and get away with the punishment (Wang et al., 2021). However, such unnecessary empty sailing will increase the total carbon emission volume of the ship, which is contrary to the original intention.

In the problem of CII design and implementation, the IMO in the upper level model decides the specific form and cap value of CII, as denoted by x in $[MU]$. Ship operators have to obey the regulation and operate their vessels complying with it, which is denoted by y in $[ML]$. Apparently, the domain of y, $Y(x)$, refers to the CII regulations issued by the IMO in the upper level.

3.2.4. Vessel speed reduction incentive programs

Another program to reduce ship air emissions within certain areas is the Vessel Speed Reduction Incentive Program (VSRIP), which uses a subsidy to encourage ships to reduce their speed in the proximity of a port so that the emissions can be reduced in the port area. Zhuge et al. (2021) investigate the subsidy plan optimization of such a voluntary program, adopting the bi-level perspective and taking the ship operators' decisions into consideration. In the paper, the government provides subsidies for each ship visit that participates in the VSRIP of a port and conducts slow steaming in the predetermined range. On the one hand, some ship visits will be encouraged by the subsidy and choose to sail at a slow speed in the vessel speed reduction zones and therefore emit less air exhausts. On the other, however, ship visits participating in the VSRIP need to speed up outside the vessel speed reduction zones to catch up with the predetermined ship schedule. Due to the nearly cubic relationship between the sailing speed and the fuel consumption, the air emissions from the route will increase in spite of the slow steaming near the port.

In the VSRIP, the government in the upper level model focuses on how to design the subsidy plan, including the subsidy amount given for each visit participating in the program, denoted by x. And the subsidy budget is represented by B in $[MU]$. For ship operators, the followers in the lower level model, the decision variable y refers to whether the ship visits participate in the VSRIP. Definitely, the ship visits that receive subsidies should reduce their sailing speed in the corresponding zones, and therefore the decision variable y is restricted to $Y(x)$.

4. Application at the interface between the maritime and other industries

Bi-level optimization model is adopted in problems at the interface between the maritime and other industries. Although the maritime industry is not directly involved, such problems are still closely related to shipping transportation and air emissions. In this section, we will introduce the example related to both the maritime and the oil refinery industries.

As mentioned before, the upper limit of sulfur content in fuel oils used onboard global-wide is reduced to 0.5% m/m from from 1 January 2020, and the number is 0.1% m/m for ships sailing in Sulfur ECAs (International Maritime Organization, 2021a). Such a stringent regulation will drive up the demand for low sulfur marine fuels, which raises higher requirements on the global refinery sector. Unfortunately, the desulfurization processes of oil is carbon-intensive and the global refining sector contributes around 4% of the anthropogenic CO_2 emissions (Concawe, 2018). As indicated by Gratsos (2019) and Zisi et al. (2021), the current net CO_2 refinery emissions would increase by at least 15% due to the production of low sulfur fuels required by the IMO. As a result, the regulation that aims to reduce the sulfur emission from the shipping industry will drive up the CO_2 emission volume in an indirect way.

In this case, the upper level player is still the IMO deciding the sulfur content cap values for marine fuels, denoted by x, but the lower level player is the oil refinery industry producing low sulfur marine fuels for the shipping industry. This special case demonstrates that the regulations focusing on ship air emission reduction may influence other related industries, such as the oil refinery industry in this section, and then bring side-effects. Thus, bi-level optimization models is necessary in not only studies focusing on the shipping industry but also those considering other related social sectors.

5. Conclusions

Regulations of various forms play a significant role in ship air emission management. Such regulations are always designed by the competent authorities, for example the government and the IMO, but the implementing effectiveness is up to the maritime industry that operates vessels as well as terminals. The decision process of these two parties, the authorities and the industry, constitutes the bi-level structure of the ship air emission management. Therefore, the bi-level optimization model has been extensively adopted in studies focusing on related topics. To better figure out the common ground of the applications and show the basic bi-level idea behind them, this paper reviewed the applications of bi-level optimization models in the management of ship air emissions regarding a series of emission reduction regulations. Studies related to the implementation of EEDI, ECA, Carbon Tax, CII, and VSRIP were reviewed after the general framework of a typical bi-level problem in these cases. From the systematic review, we can see that the bi-level structure exists in multiple aspects of ship air emission management, including ship fleet management, single ship operation, port operation, and even oil refinery which is closely related to the shipping industry. In addition to bi-level optimization model, machine learning model is also a promising method to assist the ship air emission management thanks to the fast development of computer hardware. Further research on the application of machine learning model in this area should be carried out. It would be a great honor if this review can provide a foundation for scholars interested in this area and inspire them to further investigate optimization problems in ship air emission management.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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