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Emission reduction measures ranking under uncertainty

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HIGHLIGHTS

- Propose a ranking algorithm with a new criterion to rank emission reduction measures.
- Propose a ranking under uncertainty method taking into account the input uncertainties.
- Apply to the ranking of emissions reduction measures for shipping industry.

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ABSTRACT

Shipping is a major contributor to global CO_2 emissions. Various operational and technical measures have been proposed to reduce ship emissions. However, these emission reduction measures may not be all economically feasible to implement. Therefore, it is important to rank all these measures and select the most cost-effective measures for emissions reduction. Moreover, there are various uncertainties in evaluating emission reduction measures, such as uncertainties of implementation cost, fuel consumption, abatement potential and fuel price. These uncertainties may significantly influence the ranking of the emission reduction measures, which further result in an inappropriate selection of the measures for implementation. In this paper, a ranking algorithm with a new criterion is proposed to rank all the emission reduction measures by considering the preference between cost and abatement. Furthermore, a ranking under uncertainty method is developed which takes into account various uncertainties of the impact factors. This method can support policy makers in ranking and selecting emission reduction measures more appropriately by better quantifying and reflecting the uncertainties.

1. Introduction

With increasing concerns about the climate change and global warming, considerable attention has been given to improving the shipping efficiency in order to reduce the total greenhouse gas (GHG) emissions. In view of the current environment concerns, many organizations have proposed and implemented various measures to reduce CO_2 emissions from shipping [1–3]. The IMO MEPC 62 report [4] identified 50 possible operational and technical measures and conducted a comprehensive study on 22 measures. However, it may not be economically feasible to implement all the measures. Policy makers are then confronted with the challenge of ranking and selecting suitable and cost-effective ways to reduce carbon emissions. To rank and select emission reduction measures, there are two objectives to be considered, which are cost and abatement (emission reduction amount). Lower cost and larger abatement measures are desired. However, these two objectives are often conflicting. That is, a measure with larger abatement may also have higher cost, and a measure with lower cost may also have lesser abatement. In such situations, it is not easy to determine which measure is preferred. In order to rank and select measures more appropriately, it is important to consider the trade-off between these two objectives. The marginal abatement cost curve (MACC) has been widely used to illustrate and rank the economic feasibility of the emission reduction measures [5–7]. These curves represent the relationship between the cost-effectiveness (CE) and the amount of emission reduction for various abatement options, and the cost-effectiveness criterion, which considers the trade-off between the two objectives, is typically used with it to rank the emission reduction measures.

Although MACCs are commonly applied for policy making, they have some limitations. One flaw of the MACC is that it is inappropriate to rank the negative CE measures [8–10]. For instance, the measure with larger abatement (better) and smaller negative cost (better) may still be less preferred to the measure with smaller

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abatement (worse) and larger negative cost (worse). Hence, alternative ranking methods have been proposed to rank the negative CE measures, such as the ranking method based on 'benefit' [9] and the Pareto front method [8]. The Pareto front method essentially belongs to the class of multi-objective ranking methods. However, these methods are proposed only for the negative CE measures. Although the Pareto front method can be further applied to both negative and non-negative CE measures, there is still no clear approach to rank among the Pareto optimal measures (the definition of the Pareto optimal is given by Definition 2 in Section 4.1). In order to support policy makers in selecting the most feasible set of emission reduction measures, it is important to rank all the measures appropriately and evaluate their cost-effectiveness. For general multi-objective ranking problem, there are also many other multi-objective ranking methods (see the literature review in Section 3). However, these methods cannot be easily applied to rank the emission reduction measures. This is because these methods usually require weights to be assigned to the different objectives, but it is often not practical or straightforward to assign weights between cost and abatement for the ranking of the emission reduction measures. In this paper, we propose a multi-objective ranking method for emission reduction measures. More specifically, we apply the Pareto front method to rank measures and further propose a new criterion which incorporates the policy makers' preferences between cost and abatement to rank the measures on the same Pareto optimal level. This criterion compares the increased cost over the increased abatement amount from one measure to another. This approach of trade-off follows similar idea of the marginal cost in economics [11]. With the proposed new criterion, we further propose a ranking algorithm which can be applied to rank all measures effectively and efficiently. This method can provide ranking results for policy makers to determine more appropriate set of emission reduction measures for implementation.

The ranking of the emission reduction measures depends on the evaluation of the cost and abatement for each measure. The computation of the cost and abatement relies on various input factors such as the abatement potential, fuel price projection, and discount rate estimation. As these input factors are usually highly uncertain, the ranking of the emission reduction measures are also inevitably uncertain [12]. Therefore, to enable better ranking and selection of the emission reduction measures, it is important to place emphasis on the uncertainty quantification related to the input assumptions, so that policy makers are more aware of them and account for them in their decisions.

Various uncertainty quantification methods have been applied for emissions estimation [13–17]. However, little attention has been paid to quantify the uncertainty for the ranking of the emission reduction measures. Even for the widely used MACC, one of its shortcomings is the lack of uncertainty assessment [18,19]. When the MACC is used to prioritize mitigation measures, the simple way to quantify the uncertainty in ranking provided by the IMO MEPC 62 report [4] is to compute the cost-effectiveness and emission reduction for "optimistic" and "pessimistic" cases. A similar approach can be found in [20]. However, this approach only provides limited scenarios for the ranking, and assumes equal likelihood for all inputs across the scenarios. This can result in several significantly different ranking orders, all with the same possibility. This becomes a challenge for policy makers when deciding which ranking order should be used to select measures to implement or encourage. A systematic way is provided in [21] to quantify the uncertainty in emission reduction amounts based on a selection of measures. They however do not address the issue of ranking of the measures. Moreover, all the measures ranking methods that are based on the CE values may not be appropriate for ranking the negative CE measures. For other ranking methods proposed for the negative CE measures [8,9], the uncertainty of the input assumptions are not considered. This lack of uncertainty consideration may lead to inappropriate and different ranking results. In this paper, we not only propose a ranking method which can be applied to rank all the emission reduction measures, but also further develop this ranking method to account for the uncertainty in the input factors. This method provides more complete information for policy makers to rank and select emission reduction measures by better reflecting the uncertainties. It can also help shipping companies to take CO_2 emission abatement more seriously and support them in making their own decisions on maintenance, fleet planning, etc.

The rest of the paper is organized as follows: Section 2 defines the two-objective ranking problem with model formulation. A literature review of the multi-objective ranking methods is then given in Section 3. In Section 4, the proposed ranking criterion is described and the ranking algorithm is provided. The ranking under uncertainty method is then proposed in Section 5. A case study is given in Section 6 to illustrate the proposed methods and major findings and conclusions are provided in Section 7.

2. Problem formulation

To rank the emission reduction measures, two objectives are compared, which are cost and abatement. The measure with smaller cost and larger abatement amount is preferred. Therefore, this is a two-objective ranking problem. In the following subsections, the two objectives are described in detail.

2.1. Cost

The cost function of implementing a new technology (see Eq. (1) in [21]) can be defined as

$$C(x) = NRC(x) + RC(x) + OC(x) - CS(x) \tag{1}$$

where for each emission reduction measure x, all terms can be defined as follows [21]

C is the additional cost of installing the technology/implementing the measure;
NRC is the non-recurring cost (i.e. annualized capital cost of implementing the measure);
RC is the recurring cost (i.e. operating cost for the measure);
OC is the opportunity cost while implementing the measure;
CS is the amount of fuel cost saved from implementing the measure, which is calculated by

$$CS = FC \times FP \times AP$$

where
FC is the fuel consumption before implementing the measure;
FP is the fuel price;
AP is the abatement potential.

2.2. Abatement

The abatement for each emission reduction measure x is represented as

$$A(x) = EF(x) \times FC(x) \times AP(x) \tag{2}$$

where EF is the carbon emission factor, which is defined as the average amount of GHG emissions per metric tonne of the fuel consumed [21].

The ranking of the emission reduction measures requires the comparison of both cost and abatement. If there is only one objective function, for example cost, it is easy to rank the measures by ordering the cost from the smallest to the largest. However, for