Optimization of The Concurrent Selection of Machinery System and Emission Controls for Green Shipping

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Introduction

Shipping is known for being the most efficient mode of transportation. The world's seaborne trade totalled to almost 9.6 billion tons in 2013, and the maritime shipping industry carries over 85% of globally transported goods.

This imply significant environmental footprints, and a big issue is how to reduce the harmful emissions from ships.

The International Maritime Organization (IMO) has presented several conventions for the reduction of emissions from ships, and some of the latest regulations has given shipowners and operators challenges regarding compliance.

In this thesis, the regulations of CO_2, SO_x and NO_x is considered and challenges related to the stricter regulations applying in special emission control areas (ECAs) is accounted for. The revised Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) is reference for the emission goals for the work presented.

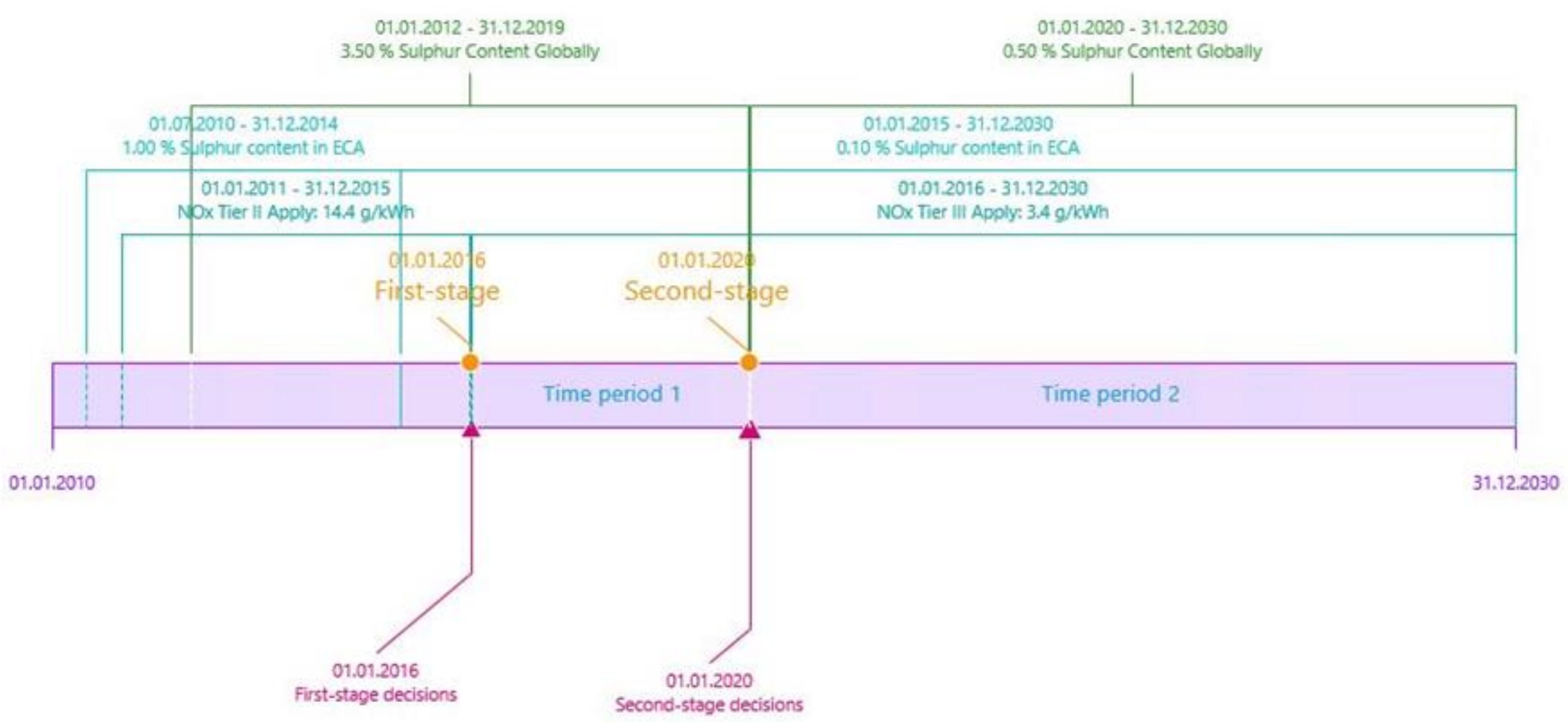
Scope of work

One of the goals with this thesis is to develop a model that will identify a cost-effective combination of machinery system, fuel type and emission controls for compliance with given emission goals or regulations. An emission control is any measure that can be installed on the ship with the intention of reducing emissions. The model is developed from operations research theories.

Issues with uncertain elements in the future are also addressed, using a stochastic optimization model. In the model an objective function minimizes the costs of the selection that is made. The objective function is subjected to a number of constraints. The model is a two-stage stochastic model that in the first-stage use a deterministic case where everything is considered known. The second-stage evaluates scenarios based on uncertain values for the future. The goal of the model is to provide a balanced view of the future in order to make better decisions today.

The conclusions from the stochastic model is compared to a corresponding deterministic model in order to evaluate the value of considering the uncertain elements.

The model is applied to a case with a number of candidate machinery systems, fuel types and emission controls.



Stochastic Optimization Model

Objective function

$$\min\ C^I + \sum_{t\in T_1}\sum_{f\in F} C^F_{tf} D_{tf} \widehat{T}_t x_f + \sum_{t\in T_1}\sum_{i\in I^M} C^E_{ti} y_{it} + \sum_{t\in T_1}\sum_{i\in I^M}\sum_{j\in I^M|j>i} K^C_{tij} u_{ijt}$$
$$+ \sum_{s\in S} p_s \Bigg(\sum_{t\in T_2}\sum_{f\in F} C^F_{tfs} D_{tf} \widehat{T}_t x_{fs}$$
$$+ \sum_{t\in T_2}\sum_{i\in I^M} C^E_{ti} y_{its} + \sum_{t\in T_2}\sum_{i\in I^S} C^E_{tis} y_{its} + \sum_{t\in T_2}\sum_{i\in I^M}\sum_{j\in I^M|j>i} K^C_{tij} u_{ijts} \Bigg) \quad (1)$$

Subject to

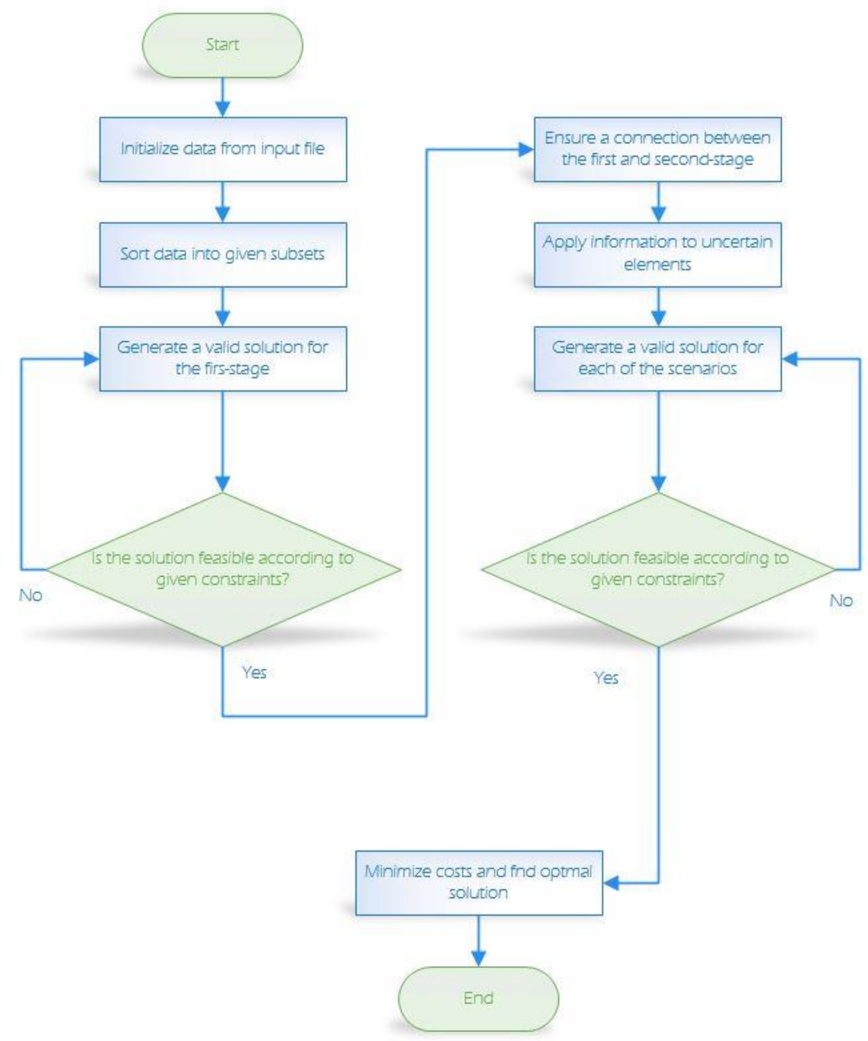
First-stage

$$\sum_{f\in F^M} x_f = 1 \quad (2)$$
$$\sum_{f\in F^M} R_{fe}\, x_f + \sum_{i\in I^M} R_{ie}\, y_{it} - \sum_{i\in I^M}\sum_{j\in I^M|j>i} K^E_{ije} u_{ijt} \geq G^1_e \qquad t\in T_1, e\in E \quad (3)$$
$$y_{it} = \sum_{t`\in \max\{1,t-L_i+1\}} z_{it`} \qquad t\in T_1, i\in I \quad (4)$$
$$y_{it} + y_{jt} \geq 2u_{ijt} \qquad t\in T_1, i,j\in I \quad (5)$$
$$y_{ti} + y_{tj} - 1 \leq u_{ijt} \qquad t\in T_1, i,j\in I \quad (6)$$
$$z_{it} = 0 \qquad t\in T_1 | t>1, i\in I^{NB} \quad (7)$$
$$z_{it} = 0 \qquad t\in T_1, i\in I \setminus I^M \quad (8)$$
$$\sum_{f\in F^{S*}} x_f - \sum_{i\in I^{SECA}} y_{it} \leq 0 \qquad t\in T_1 | \widehat{T}^S_t > 0 \quad (9)$$
$$\sum_{f\in F^{N*}} x_f - \sum_{i\in I^{NECA}} y_{it} \leq 0 \qquad t\in T_1 | \widehat{T}^N_t > 0 \quad (10)$$
$$y_{it} \in \{0,1\} \qquad t\in T_1, i\in I \quad (11)$$
$$z_{it} \in \{0,1\} \qquad t\in T_1, i\in I \quad (12)$$
$$x_f \in \{0,1\} \qquad t\in T_1, f\in F \quad (13)$$
$$u_{ijt} \in \{0,1\} \qquad t\in T_1, i,j\in I \quad (14)$$

Second-stage

$$\sum_{f\in F^M} x_{fs} = 1 \qquad s\in S \quad (15)$$
$$\sum_{f\in F^M} R_{fe}\, x_f + \sum_{i\in I^M} R_{ie}\, y_{its} - \sum_{i\in I^M}\sum_{j\in I^M|j>i} K^E_{ije} u_{ijts} \geq G^2_e \qquad t\in T_2, e\in E, s\in S \quad (16)$$
$$z_{tis} = z_{ti} \qquad t\in T_1, i\in I, s\in S \quad (17)$$
$$y_{tis} = \sum_{t`\in \max\{1,t-L_i+1\}} z_{t`is} \qquad t\in T_2, i\in I, s\in S \quad (18)$$
$$y_{its} + y_{jts} \geq 2u_{ijts} \qquad t\in T_2, i,j\in I, s\in S \quad (20)$$
$$y_{its} + y_{jts} - 1 \leq u_{ijts} \qquad t\in T_2, i,j\in I, s\in S \quad (21)$$
$$z_{tis} = 0 \qquad t\in T_2 | t>1, i\in I^{NB}, s\in S \quad (22)$$
$$z_{tis} = 0 \qquad t\in T_2, i\in I \setminus I^M, s\in S \quad (23)$$
$$\sum_{f\in F^{S*}} x_{fs} - \sum_{i\in I^{SECA}} y_{its} \leq 0 \qquad t\in T_2 | \widehat{T}^S_t > 0, s\in S \quad (24)$$
$$\sum_{f\in F^{N*}} x_{fs} - \sum_{i\in I^{NECA}} y_{its} \leq 0 \qquad t\in T_1 | \widehat{T}^N_t > 0, s\in S \quad (25)$$
$$y_{its} \in \{0,1\} \qquad t\in T_2, i\in I, s\in S \quad (26)$$
$$z_{its} \in \{0,1\} \qquad t\in T_2, i\in I, s\in S \quad (27)$$
$$x_{fs} \in \{0,1\} \qquad f\in F, s\in S \quad (28)$$
$$u_{ijts} \in \{0,1\} \qquad t\in T_2, i,j\in I, s\in S \quad (29)$$

Flow Chart Illustrating The Overall Dynamics of The Model



Computational study

In the study it is vital how the different machinery systems are defined as this decides fuel consumption, emission goals and compatibility with different emission controls.

Sets of emission controls are given with the reduction effect of each emission type. Additionally, interaction effects can be present if installing two different emission controls and the model accounts for this. An example of interaction between controls, is the use of both selective catalytic reduction (SCR) and a sea water scrubber (SWS) that both cleanses the exhaust gas and reduces the emissions on NO_x and SO_x respectively. Both controls require large spaces for installation and if they are installed and used on the same ship, they would both lower the temperature of the exhaust gas making it necessary to heat up the exhaust again for the control that comes second in line.

Uncertainty is essential for the development of the stochastic programming model in this thesis. Many elements can be subjected to uncertainty as you cannot be completely certain of any parameters for the future. However, due to modelling and computational issues, the number of elements dependent on scenarios must be limited.

The fuel prices are subjected to uncertainty in this thesis, as they are one of the most important factors to consider when evaluating the expenses for a ship in operation. Fuel trends given in the project report "Shipping 2020" by DNV (2012) is used as basis for scenario generation.

The fuel types HFO, MGO and LNG are used for evaluation as the relative price development of these can represent the future fuel price market in a good way. Scenarios are generated with different projections of HFO, MGO and LNG from 2020 to 2030. A high, reference and low fuel trend is considered for each fuel type as a basis for the generation of scenarios.

In the scenario generation a dependence between the development of HFO and MGO price is taken into account while the price development of LNG is considered independent. This result in a total of 18 scenarios to evaluate.

Implementation and running of the model has been done in FICO Xpress Optimization Suite 7.7 with a Intel Core I5-4200U 1.60GHz processor and 4GB RAM.

Projection of Fuel Trends