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# Coordinated Approaches for Port State Control Inspection Planning

## Abstract

Port state control (PSC) inspections serve to guard maritime safety and the marine environment. Because port inspection resources are limited, inspection efficiency can be improved if the resources are scheduled more efficiently. Currently, ports worldwide apply a greedy inspection strategy. To improve inspection efficiency, this study proposes two coordinated inspection strategies for both liner and tramp ships, i.e. a self-coordinated port strategy and a fully-coordinated central agent strategy. Extensive numerical experiments indicate that on average the self-coordinated port strategy performs 2.48% better than the greedy strategy, and the fully-coordinated strategy outperforms the greedy and self-coordinated port strategies by 5.02% and 2.48%, respectively. The superiority of the two coordinated strategies is robust to different ratios of liner to tramp ships visiting the ports from 0/100 to 100/0. Therefore, the feasibility and wide applicability of the proposed coordinated strategies are validated. Specifically, when liner ships outnumber tramp ships, the fully-coordinated strategy is more suitable; otherwise, both the self-coordinated port strategy and the fully-coordinated strategy can be used.

## Keywords

Port state control (PSC), coordinated strategies, inspection efficiency, ship deficiency, maritime safety

## 1. Introduction

The shipping industry is the backbone of international trade and globalization. Although maritime transport is relatively safe, losses can be great when accidents occur (Luo and Shin, 2019). For the period between 2011 and 2017, the European Maritime Safety Agency (EMSA) reported 20,616 maritime casualties and incidents causing 6,812 injured persons and 683 fatalities (EMSA, 2018). Meanwhile, the shipping industry produces a heavy environmental footprint due to greenhouse gas emissions and pollutants. To improve maritime safety and reduce the negative environmental effects of shipping, numerous international maritime regulations and conventions are implemented. For example, the International Convention for the Safety of Life at Sea (SOLAS), proposed in 1974, is the principal regulation governing maritime safety. The International Convention for the Prevention of Pollution from Ships (MARPOL), which came into force in 1983, aims to minimize marine pollution.

Ships that fail to follow the various international maritime regulations and conventions are called substandard ships (Xu et al., 2007a, 2007b; Gan et al., 2010). Although the flag state of a ship is the first line of defense against substandard shipping (Luo et al., 2013; Fan et al., 2014), it is believed that some flag states cannot perform their duties well (Li and Zheng, 2008; Wang et al., 2019). Under this condition, port state control (PSC) is implemented around the world (Li et al., 2009; Xiao et al., 2020). PSC refers to the inspection of foreign ships conducted by the port states to verify their condition and ensure compliance with major international maritime conventions. PSC is regarded as the second line of defense against substandard shipping, and its contribution to the IMO's "safer shipping and cleaner oceans" goal is widely recognized by governments, industry, and academia (Li and Zheng, 2008).

To allow information exchange and avoid redundant inspections, Memorandums of Understanding (MoUs) on PSC are signed by neighboring countries and regions. Policy and standards of ship selection and inspection are uniform within an MoU. Some countries and regions, such as the US, establish individual PSC policies and standards without an MoU.

During an inspection, a condition found to be non-compliant with the requirements of a relevant convention is referred to as a deficiency. A ship can be detained by the port state if major deficiencies are found onboard (IMO 2017). In this context, the number of deficiencies of a ship can be viewed as an indicator of ship risk during a PSC inspection. When the port inspection resources, e.g. the number of available PSC officers (PSCOs) or the working hours assigned for PSC inspections, are fixed, inspection efficiency is considered to be improved if more ship deficiencies can be identified (Wang et al., 2019).

On a daily basis, ports apply a greedy ship selection strategy to select higher risk ships for inspection among all visiting ships on a given day. This strategy completely ignores the ships' staying time at the current port, their visits to other ports, and inspection resources at the ports over the following days. Nevertheless, ships are required to report their estimated time of arrival to the ports, sometimes several days in advance. For example, the port of Hong Kong requires all vessels to report their arrival and seek permission from the Director of the Marine Department. The report should be sent no less than 24 hours prior to entering Hong Kong waters (Hong Kong Marine Department, 2020). Furthermore, the number of available PSCOs at a port and the assigned working time for a PSC inspection are predictable over a period and can be treated as known parameters. As a ship may spend more than one day in a port and can be inspected on any of these days, port inspection decisions could potentially apply during a longer planning horizon (e.g. 7 or 10 days) by considering the visiting information and available inspection resources at the ports.

In countries with multiple ports, such as China, the US, India, and Australia, PSC is usually managed by a hierarchy of authorities. In this situation, regional agents are responsible for conducting PSC inspections and a central agent is in charge of the ports in all regions. For example, China has several regional Maritime Safety Administrations (MSAs), such as Fujian MSA, Guangdong MSA, Shanghai MSA, and Shenzhen MSA, all subject to the China Maritime Safety Administration (China MSA, 2020). In the US, the United States Coast Guard is the central PSC agent, with nine district offices in coastal areas in charge of regional PSC inspections (United States Coast Guard, 2019). In India, PSC inspections are conducted by several Mercantile Marine Departments at the ports, supervised by the Directorate General of Shipping (Directorate General of Shipping, 2020). Similarly, the Australian Maritime Safety Authority is responsible for PSC inspections at all Australian ports (Australian Maritime Safety Authority, 2020). Given that foreign liner ships may call at several ports in a country over a given period, a central agent could apply a fully coordinated strategy to maximize the number of deficiencies identified across several ports within this period. This strategy should manage the inspection tasks at all ports by considering ship visiting information and port inspection resources over the whole planning horizon.

Predictive models of ship deficiency numbers have been developed in the literature based on generic factors (Cariou et al., 2007; Cariou and Wolff, 2015; Wang et al., 2019) (e.g. ship age, type, and gross tonnage), dynamic factors (Wang et al., 2019) (e.g. number of ship flag changes), and historical PSC inspection factors (Wang et al., 2019) (e.g. number of deficiencies during the last PSC inspection and detentions during previous PSC inspections). The results of these models could be used to develop optimization-based self-coordinated and fully-coordinated inspection strategies to improve PSC efficiency. However, to the best of our knowledge, no port or regional coordinated ship inspection strategies considering both ship conditions and port inspection resources have yet been proposed or implemented based on mathematical optimization models. There are two main reasons for this. First, most officers in the PSC authorities may lack the relevant mathematical knowledge. Second, even they have such knowledge, the potential improvement in efficiency brought about by applying such models to PSC inspection is unclear and remains to be validated.

This study represents a first attempt to develop mathematical optimization models for coordinated ship inspection strategies to improve PSC inspection efficiency at several ports by maximizing the total number of deficiencies detected. The feasibility of the proposed strategies is verified by numerical experiments. Specifically, strategy 1 is the greedy strategy currently used in ports. The ports make their own inspection decisions each day to maximize the total number of deficiencies detected on that day. In strategy 2, a port applies a self-coordinated inspection strategy based on optimization models to make inspection decisions for the remaining days in the planning horizon. Both ship visiting information and port resources over the following days are considered in the strategy. The goal is to maximize the total number of deficiencies identified at the port for the whole planning horizon. In strategy 3, a central agent applies a fully-coordinated strategy based on optimization models to maximize the total number of deficiencies identified by all ports for the whole planning horizon.

The contribution of this study is as follows. From a theoretical point of view, mathematical optimization models are proposed and validated to improve PSC inspection efficiency by coordinating the inspection resources of several ports over a planning horizon. From a practical point of view, the problems solved in this study are important for maritime policy and port management. Extensive numerical experiments are used to validate the feasibility of the proposed coordinated strategies and their superiority over the current greedy inspection strategy. We therefore believe that the proposed strategies and models may improve the PSC management of port states and central agents by better allocating limited inspection resources to identify as much substandard shipping as possible.

## 2. Literature review

A comprehensive literature review by Yan and Wang (2019) classified the large body of literature on PSC inspection into three main categories: improving inspection efficiency, the influence of PSC, and general comments on the management of PSC MoUs. As only the first category is relevant to this study, recent research on improving the efficiency of PSC inspection is reviewed in this section.

Much of the literature on improving PSC inspection efficiency has proposed models for high-risk ship selection. Yang et al. (2018a) developed Bayesian networks to predict the detention probabilities of bulk carriers in seven major European countries. The key risk factors influencing PSC inspections included deficiency number, inspection type, recognized organization, and vessel age. Based on the Bayesian networks, Yang et al. (2018b) proposed a risk-based game model to derive the optimal inspection rate at port states to improve efficiency. Yan et al. (2020b) developed a random forest-based prediction model of ship detention probability. The prediction model considered the imbalanced distribution of ships with and without detention at the port of Hong Kong. Wang et al. (2019) developed a Bayesian network model to predict the ship deficiency number to target high-risk foreign ships. Numerical experiments showed that the proposed model could identify 130% more deficiencies on average compared with the currently implemented ship selection scheme. By combining past incident and detention information, Heij and Knapp (2019) developed five vessel classification models to effectively target high-risk vessels for inspection.

Some researchers have proposed association rule mining methods to improve onboard inspection efficiency. The relationships between the deficiencies of detained ships and external factors, and the relationships between the deficiencies were identified by association rule mining techniques (Tsou, 2019). Chung et al. (2020) analyzed the association rules between deficiencies detected during inspection and ship characteristics (e.g. ship type, flag, and classification society). Yan et al. (2020c) proposed two onboard inspection schemes describing detailed inspection sequences for inspector reference. The inspection sequences were based on the probable occurrence of the deficiency items and the association rule among them mined by Apriori algorithm. In addition, they proposed and validated PSCO assignment models that consider different categories of ship deficiencies and PSCO expertise (Yan et al., 2020a).

Although the literature on improving PSC inspection efficiency is abundant, the proposed measures mainly focus on improving ship selection and onboard inspection efficiency. No strategies are based on mathematical optimization models to coordinate inspections at several ports over a given period. This study aims to bridge this gap by proposing two coordinated inspection strategies considering the predicted deficiency number of visiting ships and port inspection resources.

## 3. Materials and methods

### 3.1 Problem description

We consider a set of ports $P$ where PSC inspection can be conducted and a planning horizon with length $T$. We set one day as a time unit, denoted by $t$, $t=1,\ldots,T$. During a planning horizon, the set of ships, including liner and tramp ships, that will call at least at one port in $P$ is denoted by $S$. On day $t$, $t=1,\ldots,T$, the set of ships calling at port $p \in P$ is denoted by $S_p^t$. As ships are of different types and sizes, we include the required inspection period (in hours) for each ship, denoted by $\tau_s, s \in S$. A ship can only call at one port or sail at sea in one time unit. The deficiency number of a ship $s \in S$ is denoted by $d_s$. The deficiency number of all ships can be predicted using machine learning models based on the ship's generic, dynamic, and historical inspection factors. We assume that there is a machine learning model that can accurately predict the deficiency number for all ships, and we can use the predicted deficiency number in the optimization models. To avoid delaying the fast turnover of maritime logistics systems, we require that a ship only be inspected once during a planning horizon, but this can take place at any port of call. As inspection resources are limited, at most $m_p^t$ hours of inspection can be conducted at port $p \in P$ on day $t$, $t=1,\ldots,T$.

The objective of the port states is to identify as many deficiencies as possible within the maximum daily working (inspection) hours, as the total number of deficiencies identified can be viewed as the benefit of the PSC inspection. We introduce the binary decision variable $x_{sp}^t$, which equals 1 if ship $s \in S$ is inspected at port $p \in P$ on day $t$, $t=1,\ldots,T$, and 0 otherwise. We also introduce several auxiliary decision variables. The set of inspected ships at port $p$ on day $t$ is denoted by $\hat{S}_p^t$, $\hat{S}_p^t = \{s \mid x_{sp}^t = 1, s \in S_p^t\}$, $p \in P$, $t=1,\ldots,T$. Based on the inspection decision, the total number of identified deficiencies at port $p$ in period $t$ is denoted by $D_p^t$, $D_p^t = \sum_{s \in S_p^t} d_s x_{sp}^t$, $p \in P$, $t = 1,...,T$. The set of ships that are inspected by all ports in $P$ on day $t$ is denoted by $I^t$, $I^t = \{s \mid x_{sp}^t = 1, s \in S_p^t, p \in P\}$, $t = 1,...,T$. The notation is summarized as follows.

| | |
|---|---|
| Sets | |
| $P$ | The set of ports |
| $S$ | The set of ships that visit at least one port in $P$ within planning horizon $T$ |
| $S_p^t$ | The set of liner ships that call at port $p$ in time unit $t$ |
| Indices | |
| $t$ | The index for time units in planning horizon $T$ |
| $p$ | The index for ports in $P$ |
| $s$ | The index for ships in $S$ |
| Parameters | |
| $T$ | The length of a planning horizon |
| $d_s$ | The predicted number of deficiencies of liner ship $s$ |
| $\tau_s$ | The required inspection period of ship $s$ |
| $m_p^t$ | The maximum available inspection hours at port $p$ in time unit $t$ |
| Decision variables | |
| $x_{sp}^t$ | Binary, set to 1 if ship $s$ is inspected at port $p$ in time unit $t$ and 0, otherwise |
| $\hat{S}_p^t$ | The set of inspected ships at port $p$ in time unit $t$ |
| $D_p^t$ | The total number of deficiencies identified at port $p$ in time unit $t$ |
| $I^t$ | The set of inspected ships among all ports in $P$ in time unit $t$ |
| $D_1$ | The total number of deficiencies identified by strategy 1 |
| $D_2$ | The total number of deficiencies identified by strategy 2 |
| $D_3$ | The total number of deficiencies identified by strategy 3 |

### 3.2 Models of the inspection strategies

We designate the inspection strategy currently used in ports as strategy 1, and further propose two inspection strategies, strategies 2 and 3, to maximize inspection efficiency. In strategy 1, on each day $t$, $t = 1,...,T$, port $p$ makes its individual inspection decision for day $t$ by applying a greedy strategy to maximize the total number of deficiencies identified on that day. In strategy 2, on each day $t$, $t = 1,...,T$, port $p$ adopts a self-coordinated strategy to make the inspection decisions for the current day $t$ and the following days in the planning horizon.

The aim is to maximize the total number of deficiencies identified over the period $t, t+1, ..., T$. However, only the decisions for day $t$ are implemented. The decisions for day $\hat{t} = t+1, ..., T$ will be updated on day $\hat{t}$ and then the updated decision will be implemented. In strategy 3, on each day $t$, $t = 1, ..., T$, fully-coordinated inspection decisions for all ports in $P$ regarding all ships in $S$ are generated by a centralized authority. The aim is to maximize the deficiencies identified for all ports in days $t, t+1, ..., T$. However, only the decisions for day $t$ will be executed as the visits of tramp ships may not be confirmed for days $t, t+1, ..., T$; thus strategy 3 requires daily updating. The three strategies are summarized below.

| | Strategy 1 | Strategy 2 | Strategy 3 |
|---|---|---|---|
| Who makes the decisions? | Each port $p$, $p \in P$ | Each port $p$, $p \in P$ | A central agent that coordinates all ports in $P$ |
| When are the decisions made? | Every day $t$, $t = 1,\dots,T$ | Every day $t$, $t = 1,\dots,T$ | Every day $t$, $t = 1,\dots,T$ |
| What ship information is required to make the decision? | Ships that call at port $p$ on day $t$ have not been inspected by any port in $P$ on any day $1,\dots,t-1$ | Ships that call at port $p$ on days $t, t+1,\dots,T$ and have not been inspected by any port in $P$ on any day $1,\dots,t-1$ | Ships that call at any port in $P$ on days $t, t+1,\dots,T$ and have not been inspected by any port in $P$ on any day $1,\dots,t-1$ |
| What decisions are made? | The set of ships to inspect at port $p$ on day $t$ | The sets of ships to inspect at port $p$ on days $t, t+1,\dots,T$ | The sets of ships to inspect at all ports in $P$ on days $t, t+1,\dots,T$ |
| What decisions are implemented? | The set of ships to inspect at port $p$ on day $t$ | The set of ships to inspect at port $p$ on day $t$ (the decisions for day $\hat{t} = t+1,\dots,T$ will be updated on day $\hat{t}$ and then implemented) | The sets of ships to inspect at all ports in $P$ on day $t$ (the decisions for day $\tilde{t} = t+1,\dots,T$ will be updated on day $\tilde{t}$ and then implemented) |
| How to solve? | CPLEX | CPLEX | CPLEX |

### 3.2.1 Strategy 1: greedy strategy

In strategy 1, each port $p$ applies a greedy strategy on day $t$, i.e. among all visiting ships in $S_p^t$, $t = 1,\dots,T$, $p \in P$, a port will always select the set of ships that have not been inspected and have the largest total number of deficiencies for inspection within the maximum working hours. The main steps of strategy 1 are as follows.

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*Strategy 1: Greedy strategy*

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*Input*: The set of visiting ships at each port on each day $S_p^t$, $t = 1,\dots,T$, $p \in P$; the maximum working hours assigned for inspection at each port on each day $m_p^t$, $t = 1,\dots,T$, $p \in P$; the predicted deficiency number $d_s$ for ship $s \in S$; the required inspection time $\tau_s$ for ship $s \in S$.

*Output*: All inspection decisions $\hat{S}_p^t$, $t = 1,\dots,T$, $p \in P$; the total number of deficiencies identified in all ports $D_1$.

Initialize $D_1 = 0$, $\hat{S}_p^t = \varnothing$, $t = 1,\dots,T$, $p \in P$.

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for $t = 1,...,T$
    Initialize $I^t = \varnothing$.
    for $p \in P$
        Step 1: if $t = 1$:
                Set $\bar{S}_p^t = S_p^t$.
            else:
                Update the set of ships that have not been inspected by any port on days $1,...,t-1$ by setting $\bar{S}_p^t = S_p^t - \bigcup_{t'=1,...,t-1} I^{t'}$.
                end if
        Step 2: Make inspection decision at port $p$ for day $\bar{t} = t$ by solving optimization model M1:
        [M1]
                $\max \sum_{s \in \bar{S}_p^t} d_s x_{sp}^{\bar{t}}$    (1)
        s.t.
                $\sum_{s \in \bar{S}_p^t} \tau_s \times x_{sp}^{\bar{t}} \le m_p^{\bar{t}}, \bar{t} = t$    (2)
                $x_{sp}^{\bar{t}} \in \{0,1\}, \forall s \in \bar{S}_p^{\bar{t}}, \bar{t} = t$    (3)
        Step 3: The optimal solution generated by M1 is denoted by $x_{sp}^{\bar{t}*}$. Denote the inspection decision for port $p$ on day $\bar{t} = t$ by $\hat{S}_p^t = \{s \mid x_{sp}^{\bar{t}*} = 1, s \in \bar{S}_p^{\bar{t}}, \bar{t} = t\}$.
        Step 4: Update $I^t = I^t \cup \hat{S}_p^t$.
        Step 5: Inspect all ships in $\hat{S}_p^t$ and record the total number of deficiencies identified $D_p^t$.
        Step 6: Update $D_1 = D_1 + D_p^t$.
    end for
end for
Return $D_1$ and $\hat{S}_p^t$, $t = 1,...,T$, $p \in P$.
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### 3.2.2 Strategy 2: Self-coordinated port strategy

Strategy 2 makes inspection decisions for each port $p \in P$ independently by coordinating the inspection of all ships that call at the port on the current and following days. On day $t$, port $p$ will make inspection decisions for the remaining days in the planning horizon (i.e. days $\hat{t} = t,...,T$) by deciding which of all uninspected ships are to be inspected each day. However, the ships selected for $\hat{t} = t+1,...,T$ by port $p$ may be inspected by other ports before they reach port $p$. In addition, the tramp ships that may call at port $p$ on days $\hat{t}=t+1,\ldots,T$ are unknown on day $\hat{t}=t$. Therefore, only the inspection decision for day $t$ will be carried out and the inspection information will be updated and uploaded to the public website. The inspection decisions will be made on each day for each port based on the updated inspection information. The main steps for strategy 2 are presented as follows.

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*Strategy 2: port self-coordinated strategy*

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Input: The set of visiting ships at each port on each day $S_p^t$, $t=1,\ldots,T$, $p \in P$; the maximum working hours assigned for inspection at each port on each day $m_p^t$, $t=1,\ldots,T$, $p \in P$; the predicted deficiency number $d_s$ for ship $s \in S$; the required inspection time $\tau_s$ for ship $s \in S$.
Output: All inspection decisions $\hat{S}_p^t$, $t=1,\ldots,T$, $p \in P$; the total number of deficiencies identified in all ports $D_2$.
Initialize $D_2 = 0$, $\hat{S}_p^t = \varnothing$, $t=1,\ldots,T$, $p \in P$.
for $t=1,\ldots,T$
    Initialize $I^t = \varnothing$.
    for $p \in P$
        Step 1: if $t=1$:
                Set $\bar{S}_p^t = S_p^t$.
            else:
                Update the set of ships that have not been inspected by any port on days $1,\ldots,t-1$ by setting $\bar{S}_p^t = S_p^t - \bigcup_{t'=1,\ldots,t-1} I^{t'}$.
            end if
        Step 2: Make inspection decisions at port $p$ for day $\hat{t}=t,\ldots,T$ by solving optimization model M2:
        [M2]
            max $\sum_{\hat{t}=t}^{T} \sum_{s \in \bar{S}_p^{\hat{t}}} d_s x_{sp}^{\hat{t}}$        (4)
        s.t.
            $\sum_{\hat{t}=t}^{T} x_{sp}^{\hat{t}} \le 1, \ \forall s \in \bar{S}_p^{\hat{t}}$        (5)
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            $\sum_{s\in \bar{S}_p^{\hat{t}}} \tau_s \times x_{sp}^{\hat{t}} \le m_p^{\hat{t}},\ \hat{t} = t,\ldots,T$    (6)
            $x_{sp}^{\hat{t}} \in \{0,1\},\ \forall s \in \bar{S}_p^{\hat{t}},\ \hat{t} = t,\ldots,T$    (7)
        Step 3: The optimal solution generated by M2 is denoted by $x_{sp}^{\hat{t}*}$. Denote the
            inspection decision for port $p$ on day $\hat{t} = t$ by $\hat{S}_p^t = \{s \mid x_{sp}^{\hat{t}*} = 1, s \in \bar{S}_p^{\hat{t}}, \hat{t} = t\}$.
        Step 4: Update $I^t = I^t \cup \hat{S}_p^t$.
        Step 5: Inspect all ships in $\hat{S}_p^t$ and record the total number of deficiencies identified
            $D_p^t$.
        Step 6: Update $D_2 = D_2 + D_p^t$.
    end for
    Update $I = I \cup I^t$.
end for
Return $D_2$ and $\hat{S}_p^t$, $t = 1,\ldots,T$, $p \in P$.
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### 3.2.3 Strategy 3: fully-coordinated strategy

We consider a central agent in charge of all ports in $P$ and responsible for coordinating ship inspections at each port $p \in P$ on each day $t = 1,\ldots,T$ to maximize the total number of deficiencies identified over the whole planning horizon. As the visiting information on arriving tramp ships keeps being updated during the planning horizon, the central agent needs to make the inspection decisions for all ports on each day. The main steps for strategy 3 are presented as follows.

```
Strategy 3: fully-coordinated strategy
-----------------------------------------------------------------
Input: The set of visiting ships at each port on each day $S_p^t$, $t = 1,\ldots,T$, $p \in P$; the maximum
working hours assigned for inspection at each port on each day $m_p^t$, $t = 1,\ldots,T$, $p \in P$; the
predicted deficiency number $d_s$ for ship $s \in S$; the required inspection time $\tau_s$ for ship
$s \in S$.
Output: All inspection decisions $\hat{S}_p^t$, $t = 1,\ldots,T$, $p \in P$; the total number of deficiencies
identified in all ports $D_3$.
Initialize $D_3 = 0$, $\hat{S}_p^t = \varnothing$, $t = 1,\ldots,T$, $p \in P$.
for $t = 1,\ldots,T$
    Initialize $I^t = \varnothing$.
        Step 1: if $t = 1$:
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                Set $\bar{S}_p^t = S_p^t$.
            else:
                Update the set of ships that have not been inspected by any ports on days $1,\ldots,t-1$ by setting $\bar{S}_p^t = S_p^t - \bigcup_{t'=1,\ldots,t-1} I^{t'}$.
            end if
        Step 2: Make inspection decisions for all ports in $P$ for day $\tilde{t} = t,\ldots,T$ by solving optimization model M3:
        [M3]
            $\max \sum_{\tilde{t}=t}^{T} \sum_{p \in P} \sum_{s \in \bar{S}_p^{\tilde{t}}} d_s x_{sp}^{\tilde{t}}$    (8)
        s.t.
            $\sum_{p \in P} \sum_{\tilde{t}=t}^{T} x_{sp}^{\tilde{t}} \le 1, \forall s \in \bar{S}_p^{\tilde{t}}$    (9)
            $\sum_{s \in \bar{S}_p^{\tilde{t}}} \tau_s \times x_{sp}^{\tilde{t}} \le m_p^{\tilde{t}}, \forall p \in P, \tilde{t} = t,\ldots,T$    (10)
            $x_{sp}^{\tilde{t}} \in \{0,1\}, \forall s \in \bar{S}_p^{\tilde{t}}, \forall p \in P, \tilde{t} = t,\ldots,T$    (11)
        Step 3: The optimal solution generated by M3 is denoted by $x_{sp}^{\tilde{t}\,*}$. Denote the inspection decision for port $p$ on day $\tilde{t} = t$ by $\hat{S}_p^t = \{s \mid x_{sp}^{\tilde{t}\,*} = 1, s \in \bar{S}_p^{\tilde{t}}, \tilde{t} = t\}$.
        Step 4: Update $I^t = I^t \cup \hat{S}_p^t$.
        Step 5: Inspect all ships in $\hat{S}_p^t$ and record the total number of deficiencies identified $D_p^t$.
        Step 6: Update $D_3 = D_3 + D_p^t$.
    end for
    Update $I = I \cup I^t$.
end for
Return $D_3$ and $\hat{S}_p^t$, $t = 1,\ldots,T$, $p \in P$.
```

Intuitively, the differences between strategies 1, 2, and 3 can be explained by the degree of information usage. Strategy 1 uses only the information on the visiting ships and the inspection resources for one port for the current day. The optimal inspection decision is for that port on that day. Strategy 2 takes into account the ship visiting information and port inspection resources from day $t$ to day $T$. The optimal inspection decision is for one port and for the remaining days in a planning horizon. Strategy 3 uses the ship visiting information and inspection resource information for all ports during all the remaining days of the planning horizon.

## 4. Numerical experiments

In the numerical experiments, we consider the top eight ports for total container throughput in 2018 in mainland China (PortEconomics, 2019). From north to south, these are Dalian, Tianjin, Qingdao, Shanghai, Ningbo-Zhoushan, Xiamen, Shenzhen, and Guangzhou, as shown in Figure 1. The distance between each pair of ports is obtained from Netpas Distance[1] software and shown in Table 1. We choose a 10-day planning horizon, i.e. $T = 10$, with a one-day time unit. Given that the cruising speed of a liner ship is usually 15–25 knots, the sailing duration between two ports (rounded up to integers) is presented in Table 1. If the sailing time has more than one value, the sailing duration is randomly selected.

*Insert Figure 1 here*

*Insert Table 1 here*

During a planning horizon, we assume that 50 foreign liner ships and 50 foreign tramp ships will visit at least one of the eight ports. For each liner ship, the set of ports of call and staying time at each port are randomly generated. The information is known at the beginning of the planning horizon by the ports and the central agent. We assume that a liner ship can visit one to three ports during a planning horizon, with 30% of the 50 ships visiting either one or three ports, and 40% visiting two ports. Among the 70% of the liner ships visiting more than one port, 50% visit their ports of call from north to south and 50% from south to north. A liner ship can stay at a port for one, two, or three days with a probability of 20%, 40%, and 40%, respectively. As the routes and schedules of tramp ships are not fixed, their ports of call and staying time are unknown at the beginning of a planning horizon. Instead, the port of call and staying time can only be provided on the morning of the arrival day. According to China's cabotage laws, we assume that a tramp ship can only visit one port during a planning horizon.

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[1] https://www.netpas.net/

A tramp ship may stay at a port for one, two, three, or four days with a probability of 10%, 20%, 30%, and 40%, respectively. As the duration of a PSC inspection can be influenced by ship type and size, and a typical PSC inspection usually lasts about two hours, we assume that 25%, 50%, and 25% of the 100 ships require one hour, two hours, and three hours for an inspection, respectively. Furthermore, the predicted deficiency number of a ship is randomly generated between 0 and 15.

### 4.1 Comparison of the three strategies

For each day at a port, we assume that the total working hours of the PSCO(s) for a PSC inspection range from 0 to 6 hours. As 200 hours are required to inspect all 100 ships, we assume that the total working time for the PSC inspection is 80% of the total required ship inspection time, i.e. 160 hours in a planning horizon. The detailed inspection resources at each port on each day are shown in Table 2. The total number of deficiencies of all ships is 314. The inspection decisions generated by the three strategies are shown in Table 3.

*Insert Table 2 here*

*Insert Table 3 here*

Table 3 shows that strategy 3 can identify 256 deficiencies of the visiting ships and has the best performance, followed by strategy 2 that can identify 249 deficiencies. Strategy 1 performs worst and can identify 245 deficiencies. Strategy 2 outperforms strategy 1 by 1.63%, while strategy 3 outperforms strategies 1 and 2 by 4.49% and 2.81%, respectively. Table 3 shows that given the same port inspection resources and ship visiting information, the distribution of the number of deficiencies identified on each day is different for the three strategies. Nearly 45% of the deficiencies are identified in the first three days in the planning horizon by strategies 1 and 2 (106 and 112, respectively). Meanwhile, no more than 15% and 22% of the deficiencies are identified in the last three days (36 and 54). In contrast, about one third of the deficiencies are identified in the first three days and the last three days of the planning horizon by strategy 3 (78 and 79 deficiencies, respectively). As it is required that each ship can only be inspected once, we can see that the identified deficiencies are most evenly distributed over the planning horizon by strategy 3, followed by strategy 2.

The reason for the difference between strategies 1 and 3 is that, unlike strategy 3 which considers the whole situation, strategy 1 only considers visiting ships on the current day. Thus, for liner ships, strategy 1 ignores their berthing time at the current port and their visits to other ports in the following days. For tramp ships, it ignores their berthing time at the current port in the following days. Consequently, it always chooses the set of ships with the highest total number of deficiencies among all uninspected ships currently in port. The reason for the difference between strategies 2 and 3 is that strategy 2 considers the berthing/visiting of liner ships and the berthing of tramp ships in the following days at all ports in a planning horizon. However, it ignores the fact that liner ships may visit several ports in a planning horizon where they can also be inspected.

In summary, strategy 2 outperforms strategy 1 by self-regulating the inspection strategy at each port in a planning horizon. Strategy 3 significantly outperforms both strategies 1 and 2 by coordinating the inspection strategies for all ports, taking into account that a ship may stay at the same port for several days and visit more than one port in a planning horizon.

## 4.2 Performance of the three inspection strategies

To further compare the performance of the three strategies, we randomly generate 10 instances of visiting ships (50% liner ships and 50% tramp ships) with different ports of call and staying times based on the rules proposed in section 4. We consider five situations in which the total inspection hours are 80%, 70%, 60%, 50%, and 40% of the required inspection time. That is, a total of 160, 140, 120, 100, and 80 working hours respectively are assigned for PSC inspection at all ports in the planning horizon. The number of detected deficiencies for each instance in each situation is presented and compared in Table 4.

*Insert Table 4 here*

Table 4 shows that strategy 3 performs best and strategy 1 worst. On average, strategy 2 outperforms strategy 1 by 2.48% and strategy 3 outperforms strategies 1 and 2 by 5.02% and 2.48%, respectively. In all 50 instances, strategy 2 identifies fewer deficiencies than strategy 1 or the same number in five instances in total. Strategy 3 never performs worse than strategy 1, and both perform the same in one instance. Strategy 3 identifies fewer deficiencies than strategy 2 in six instances, and both perform the same in two instances. The variations are mainly caused by the uncertainty introduced by the 50 tramp ships: although a tramp ship will only visit one port during a 10-day planning horizon, both the port and staying time can only be known when the tramp ship arrives at the port. As a result, the generated decisions need to be updated every day based on the visiting information of the tramp ships and the ship inspection conditions. These uncertainties adversely affect performance.

### 4.3 Sensitivity analysis

In the above analysis, we assume that the 100 visiting ships to the eight ports over the planning horizon consist of 50 liner and 50 tramp ships. In practice, however, the ratio of liner and tramp ships at different ports can vary greatly. To validate the applicability of the proposed strategies to a wider range of ports, we analyze the sensitivity of the ratio between visiting liner and tramp ships. Specifically, we fix the total number of visiting ships at 100 while setting the number of liner and tramp ships to 0/100, 25/75, 40/60, 60/40, 75/25, and 100/0, respectively. We also assume that a liner ship can visit one to three ports during a planning horizon and stay at a port for one to three days. A tramp ship can visit only one port during a planning horizon and stay at that port for one to four days. The number of ports of call and their berthing times are randomly generated. A ship deficiency number can range from 0 to 15, and the inspection period can be one, two, or three hours. The deficiency numbers and inspection periods are also randomly generated. We set the planning horizon to 10 days and assign a total of 160 working hours for PSC inspection at the eight ports in one planning horizon, as in sections 4.1 and 4.2. The performance of the three strategies is shown in Table 5.

*Insert Table 5 here*

Table 5 illustrates that strategy 3 performs best and strategy 1 worst in all situations, regardless of the ratio between liner and tramp ships. As the ratio of liner ships increases, the superiority of strategy 3 over strategies 1 and 2 increases. Specifically, the inspection efficiency of strategy 3 over strategy 1 is doubled when the number of visiting liner ships changes from 0 to 100. Strategies 2 and 3 perform almost the same when all visiting ships are tramp ships. With fewer liner than tramp ships, strategy 3 performs at most 1.5% better than strategy 2. However, when all visiting ships are liner ships, strategy 3 can identify 7.27% more deficiencies than strategy 2.

Table 5 also shows that although strategy 2 always outperforms strategy 1, its advantage fluctuates as the ratio between liner and tramp ships changes. Therefore, we can conclude that 1) under any ratio of liner and tramp ships, the performance of the two proposed coordinated strategies is always better than the current greedy inspection strategy. Thus, they are suitable for a wide range of ports; and 2) when there are more liner than tramp ships, strategy 3 is preferable. Even with more tramp than liner ships, strategy 3 is still the best choice. Nevertheless, as strategy 2 is much easier to apply because it requires less coordination, and strategy 3 has only a slight advantage over it, strategy 2 is also suitable in this situation.

## 5. Conclusion

PSC inspections contribute to the IMO's "safer shipping and cleaner ocean" goal by providing a second line of defense against substandard ships. Currently, port states use a greedy approach to maximize inspection efficiency for the current day, while ignoring ship berthing time and future visiting information over a multi-day period. Furthermore, countries with several ports usually have a central agent in charge of PSC inspections at all ports.

Motivated by the aforementioned facts, two coordinated strategies to schedule port inspection resources for foreign ship inspection are proposed and validated in this study. More specifically, strategy 1, used as a benchmark, is the greedy approach currently used in ports to maximize the total number of deficiencies identified on the current day. Strategy 2 is a self-coordinated mathematical optimization approach for an individual port. The inspection decisions are made for all days in a planning horizon but only the decision for the current day is implemented. Strategy 3 is also based on mathematical optimization. It is proposed for a central agent to maximize the total number of detected deficiencies at all of its ports over a planning horizon.

In the numerical experiments, eight main ports in China and 100 visiting ships (50 liner and 50 tramp ships) are considered with a 10-day planning horizon. The results show that strategy 3 performs best, followed by strategy 2. On average, strategy 2 outperforms strategy 1 by 2.48%, while strategy 3 outperforms strategies 1 and 2 by 5.02% and 2.48%, respectively. The performance of the strategies are validated under different ratios of liner and tramp ships during extensive sensitivity analysis. Based on these results, it is recommended that when liner ships outnumber tramp ships, strategy 3 should be used; otherwise, both strategies 2 and 3 are suitable.

This study represents a first attempt to apply mathematical optimization models to improve PSC inspection efficiency. The results suggest that the performance of the coordinated inspection strategies is superior to the current greedy strategy at ports, regardless of port inspection resources and the ratio of liner to tramp ships. The proposed strategies and extensive numerical experiments offer valuable managerial insights for ports and central PSC management agents.

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